A Basic Study of the Automated Generation of Machine Structures*

(2nd Report, Generation Method of the

Functional Structure of Machine)

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As a basic study for the establishment of the methodology for computer aided or automated design of machine structures, this report deals with an algorithm and a computer program for the automated generation of the functional structures of power transmitting or motion transmitting machines, such as machine tools, measuring apparatus. The machines are considered an aggregation of motion transmitting elements, such as gear mechanism, screw driving mechanism, cam mechanism, and their functional structures are generated automatically using these elements. In computer the functional structure of a machine is described using an adjacency matrix and transformation vectors of all motion transmitting elements. In the adjacency matrix each matrix element corresponds to the relation between two elements such as fixed, sliding or motion-transmitting.

Key Words: Machine Design, CAD, Automated Design, Design Engineering, Machine Structure, Graphical Description of Machine

1. Introduction

For the establishment of a methodology for computer aided or automated design of machine structures, the authors have proposed a method of graphical description of the functional structures of machines. Focusing their interest on the motion transmitting functions of power machinery or motion transmitting machines, they regard machines as aggregations of motion-transmitting elements such as gear mechanism, screw mechanism, etc. and present a method of graphical description of machine structures, in which the nodes correspond to the motion-transmitting elements (hereafter abbreviated as ME) and the edges correspond to the relations between two adjacent MEs. This graph, which is called "function structure graph," is described as combination of fundamental motion graph and transformation vectors. To advance this study a problem of automated generation of this function structure graph needs to be solved.

The process to implement the automated generation of machine structures is: (1) generate basic graph from basic specification, (2) expand this basic graph into three-dimensional function structure graph, (3) generate basic configuration structure of motion-transmitting system, (4) generate

basic configuration structure of the parts other than motion-transmitting system, and (5) flesh out this basic configuration structure. This second report deals with the method of automatization of the steps (1) and (2) in the process.

2. Generation Method of the Functional Structure of Machine

In this chapter, the method of expansion of basic graph to a three-dimensional function structure graph is described. The basic graph is the most primitive one of the fundamental motion graphs.

2.1 Input of the basic specifications The basic specifications, which are necessary for the generation of a three-dimensional function structure graph, are summarized in Table 1. The data include kinds and direction cosines of input motions, kinds and direction cosines of output motions and their dependencies on input motions. In this study rotation is adopted as input motion. This means that ME of ER type shall be used as power sources. The direction cosine of input motion denotes the direction cosine of rotating axle of power source in the global coordinate system. Generally machines can fulfil their functions by the relative motions of two moving parts such as axles and tables. Hence two series of output motions are prepared as output motions in this study. In the same series of output motions, the motion with a larger serial number is superposed on the motion with a smaller serial number. In the case of this Table 1, output motion is motion 1 + motion 2. If motions are superposed on rotation, direction cosines of these motions

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can not be determined. In this case they are determined at appropriate positions. "Source" in the rows of outputs denote the dependency on input, that is, it denotes by what power source the output motion is driven.

2.2 Generation of basic graph of a machine which gives desired output motions

In computer the basic graph is described by an adjacency matrix. Hence the generation of basic graph corresponds to the generation of adjacency matrix. Adjacency matrix of X-Y table is shown in Fig. 1. In the first row and column, the names of MEs are written. In the rest of the matrix are written the possibility of motion transmission from MEs in the first row (called active ME here) to MEs in the first column (called passive ME here), and the relations, such as fixed or sliding, of input and output axes of passive MEs to output motions of active MEs. Adjacency matrix corresponding to basic graph is called "basic matrix."

Unlike the idea given in the first report, basic matrix, and hence basic graph are generated using the algorithm and procedure explained in the following.

In an example of generation of basic matrix which satisfies the specification in Table 1, generation process of basic matrix will be explained as follows. Let output A be explained in the first place. A vacant matrix, in which necessary active and passive MEs are written, is prepared (step 0). Here, because ER type ME is adopted as power source, MEs except S element and power source element shall be MEs with R type motion as input motion. Next, relations of motion transmission are written in such that the data in Source column of Table 1 are satisfied (step 1). Moreover, at (RR1, RDA2) "2" can be written, because RR1 can transmit motion to RDA2. But in this place "1" must be written afterwards, so this case is impossible and omitted here.

Following this are written in all relations between input and output axes of all MEs except S element (step 2). The input and output axes of ER element and RR element are fixed to S element. The input axis of RD element is fixed to S element, because it is directly driven by ER element. The output motion is R+D, so axis of RD element is fixed to output motion of RR element. The adjacency matrix generated by this procedure does not contain unnecessary MEs and then this becomes the basic matrix for output A. As for output B, adjacency matrix is completed from step 0 to step 2. In this case, output motion is RB1+RB2, and input and output axes of ER2 and RRB2 elements are both fixed to the output motion of RRB1, because RRB2 element is directly driven by ER2 element. The adjacency matrix thus generated contains unnecessary MEs such as RRB1 and RRB2 elements, and these shall be removed (step 3). So far the basic matrix for output B is completed. Then, combining this matrix with one for output A, a basic matrix which satisfies basic specification is completely generated. Adjacency matrix which contains unnecessary elements is called "semi-basic matrix."

So far the authors, using the basic specification in Table 1 as an example, have

Table 1 Example of basic specification

	Serial No.		Motion	Direction	Source
Input	IN1		R	(0,1,0)	
	IN2		R	(0,0,1)	
Output	A	1 2	R D	(1,0,0) (0,1,0)	IN1 IN1
	B	1 2	R R	(0,1,0) (1,0,0)	IN1 IN2

	S	ER _x	ER _y	RD _x	RD _y
S		00		01	
ER _x				2	
ER _y					2
RD _x			00		01
RD _y					

0: fixed, 1: sliding,
2: motion transmitting

Fig.1 Basic graph and adjacency matrix of X-Y table

(I) OUTPUT-A		(II) OUTPUT-B	
(1) STEP 0	S ER1 RR1 RDA2	(1) STEP 0	S ER1 ER2 RRB1 RRB2
S		S	
ER1		ER1	
RR1		ER2	
RDA2		RRB1	
		RRB2	
(2) STEP 1	S ER1 RR1 RDA2	(2) STEP 1	S ER1 ER2 RRB1 RRB2
S		S	
ER1	2 2	ER1	2
RR1		ER2	
RDA2		RRB1	2
		RRB2	
(3) STEP 2	S ER1 RR1 RDA2	(3) STEP 2	S ER1 ER2 RRB1 RRB2
S	00 00 0*	S	00 00
ER1	2 2	ER1	2
RR1	*1	ER2	
RDA2		RRB1	00
		RRB2	00
(4) STEP 3	No processing	(4) STEP 3	S ER1 ER2
		S	00
		ER1	
		ER2	00

Fig.2 Generation process of basic matrix which corresponds to Table 1

explained the process of generation of basic matrix. Next they will explain the rules which must be followed in the writing of relations of motion transmissions or of input and output axes of MEs in a vacant square matrix. Of course, these rules are not applicable to general cases, and it is possible to generate machine structures which do not obey these rules.

In this report output motions are in the form of

$$M_1 + M_2 + \dots + M_n + \dots$$

where $M_1 - M_n$ are fundamental motions.

Accordingly, MEs are denoted by $RM_1 - RM_n$. This report does not deal with other forms of motions than this.

Writing the relations of motion transmission is carried out under the rules explained below:

(I) The rules for writing the relations of motion transmission:

- (1) For RM_1-RM_1 elements, "2" is written in the row of ER_1 element. Same procedures are carried out for ER_2 and ER_3 .
- (2) In the same group there can be ME, which is not ER element and directly drives a ME. For example, if RM_1 and RM_2 are both RR type ME, the former can drive the latter. For such a case, generate all square matrices which are different from (1) and in which "2" is written in appropriate places.
- (3) Combining (1) and (2), generate all variations of square matrices.

So far are generated all square matrices in which the relations of motion transmission are written. Next all the relations of input and output axes are written in the matrices. The rules for this processing are explained in the following.

(II) The rules for writing the relations of input and output axes of MEs:

- (1) ER_1 element is fixed to S element as "00."
- (2) ER_2 element is fixed to output motion of RM_1 element as "00." ER_3 element is fixed to output motion of RM_m element as "00." Same procedures are repeated for the following ER elements.
- (3) RM_1 element is fixed to S element as "00" or "01" or "10."
- (4) The input axes of RM_i elements in group 1 are fixed, as ER_1 element, to S element as "0*" or "1*." Output axes are fixed to output motion of RM_{i-1} element as "*0" or "*1." Same procedures are repeated. Here, * means vacancy.
- (5) If the motion transmission such as $RM_1 \rightarrow RM_i$ is in a same group, output axis of RM_i element and input axis of RM_j element are fixed to output motion of same element. But if the motion of input axis of RM_i element is D, $\bar{D}$, this rule is not applicable, because connection by spline shaft is possible.

Following these rules the writing of the relation of input and output axes is carried out. But, midway in the process, if any situations, which do not satisfy next conditions, happen, stop the writing and abandon the square matrix under generation.

(III) The conditions for the existence of machine structures:

- (1) MEs except S element have one "0" or "1" in each input and output of one column.
- (2) In an element of matrix, "2" and "0" do not coexist.
- (3) MEs in a narrow sense have one "2" in column.

The condition (3) does not apply to general cases. For example, tandem articulated type or double locked train type marine gears do not satisfy this condition.

The semi-basic matrix can be generated by the procedures explained above, but it may contain unnecessary MEs. This is due to the fact that the power sources are ER type elements and MEs in a narrow sense are

elements whose input motions are R type. Removal of unnecessary MEs is carried out when the following three conditions are all satisfied.

(IV) The conditions for removal of MEs:

- (1) MEs are RR type elements.
- (2) MEs are fixed to output motion of other MEs as "00."
- (3) After removal of MEs, right rearrangement of various relations of MEs can be carried out.

Following these conditions and after removing MEs, a basic matrix is generated. But, a semi-basic matrix and unnecessary MEs are stored and retained for later use.

2.3 Expansion of basic graph into three-dimensional function structure graph
By introducing transformation vectors, a basic matrix can be expanded into a three-dimensional function structure graph. Adjacency matrix corresponding to the three-dimensional structure graph is called

"fundamental motion matrix." Fundamental motion matrix is generated from basic matrix in such a way that the directions of three-dimensional motion transmissions between MEs can be adjusted properly by insertion of RR type MEs, whose axial angles can be set at arbitrary values. But, in reality a fundamental motion matrix is generated from semi-basic matrix for reason of ease.

In a semi-basic matrix are prepared serially numbered MEs which correspond to all fundamental motions appearing in the basic specification. These MEs are driven directly by ER elements, because their input motions are all R type.

Let us first take the case that ER drives directly other elements as

$ER \rightarrow RM$, where S element is omitted. All the cases in Fig. 2 apply to this case. In the table of basic specification, direction cosines written in the rows of "Input" are direction cosines of axes of ER elements. These are also direction cosines of input axes of RM elements. And, direction cosines in the rows of "Output" are those of output axes of RM elements.

As in the first report, the coordinate system is a right-hand and rectangular one. Let the direction cosines of input and output axes relative to a global coordinate system O-XYZ be $l_i, m_i, n_i, l_o, m_o, n_o$. In the local coordinate system o-xyz, the input axis coincides with x-axis and the output axis lies on X-Y plane. If x-axis coincides with Z-axis, let y-axis coincide with X-axis. And as in the first report, let the angles between output axis and each axis of local coordinate system be $\theta_x, \theta_y, \theta_z$. Angles θ_x and θ_y , and vectors $[\cos\theta_x \cos\theta_y \cos\theta_z]^T$ are called axis angle, attitude angle, and transformation vector respectively. In each element, the positive direction of input axis is toward the element, and the output axis is directed outward from the element.

When these input and output axes are considered, a relation in the form of

$$\begin{bmatrix} l_o \\ m_o \\ n_o \end{bmatrix} = T(l_i, m_i, n_i) \begin{bmatrix} \cos\theta_x \\ \cos\theta_y \\ \cos\theta_z \end{bmatrix} \dots\dots\dots (1)$$

is satisfied. Here, $T(l_i, m_i, n_i)$ denotes a matrix whose elements are functions of

variables l_i, m_i, n_i , and this matrix is the same as that in Eq.(1) and (2) in the first report. Solving Eq.(1) leads to angles $\theta_x, \theta_y, \theta_z$. If RM element under consideration takes this θ_x as its axis angle, direction of motion transmission is adjustable. The cases of RRA1 and RRB2 in Fig.2 apply to this case. Even if the direction is adjustable, an element, which is an unnecessary element with $\theta_x=0$, is removed. RRB1 in Fig.2 applies to this case and it is removed in Fig.3.

If RM element does not take θ_x as its axis angle, some RR type elements must be inserted between ER and RM elements. This relation is written graphically as

ER $\longrightarrow$ RR $\longrightarrow$ RM, where S element is omitted.

In this case, the following equation holds,

$$\begin{bmatrix} l_o \\ m_o \\ n_o \end{bmatrix} = T \left\{ T(l_i, m_i, n_i) \begin{bmatrix} \cos \theta_{zRR} \\ \cos \theta_{yRR} \\ \cos \theta_{xRR} \end{bmatrix} \right\}$$

$$\begin{bmatrix} \cos \theta_{xRM} \\ \cos \theta_{yRM} \\ \cos \theta_{zRM} \end{bmatrix} \dots \dots \dots (2)$$

Direction cosines $l_i, m_i, n_i, l_o, m_o, n_o$ are known values and axis angle θ_{xRM} is also known. Then two transformation vectors can be determined such that output axis of RR element lies on X-Y plane. The case of RDA2 element applies to this case. Rearrangement of the relations of motion transmissions and of input and output axes is carried out by insertion of RR element as shown in Fig.3. In this case, cam mechanism with 90° is taken for RDA2. Transformation vectors are as follows:

$$\begin{aligned} \text{RRA1} &: [0 \ -1 \ 0]^T, & \text{RRA2} &: [0 \ 1 \ 0]^T, \\ \text{RDA3} &: [0 \ -1 \ 0]^T, & \text{RRB1} &: [0 \ 1 \ 0]^T. \end{aligned}$$

Secondly, let us consider the case that a ME is driven indirectly by ER element through RR MEs which are prepared in a semi-basic matrix. This case is written graphically as

ER $\longrightarrow$ RR $\longrightarrow$... $\longrightarrow$ RM, where S element is omitted.

In this case, direction cosines of output axes are all given in basic specification table and they become the direction cosines of MEs which follow these MEs. Hence all values are known and it becomes possible to check the adjustability of directions of motion transmission. And then if necessary, RR type MEs are inserted and necessary processings are carried out.

Using the procedures explained so far, a fundamental motion matrix, which corresponds to a three-dimensional function structure graph, and transformation vectors can be generated.

3. Examples of Generation of Function Structures of Machines

3.1 Summary of limitations Using the techniques and procedures explained so far, the authors have written a "Function Structure Generation Program," which is written in FORTRAN, the number of statements being about 1300. The limitations in the application of this program are summarized as follows:

(I) OUTPUT-A					(II) OUTPUT-B				
(5) STEP 4					(5) STEP 4				
S	ER1	RRA1	RRA2	RDA3	S	ER1	ER2	RRB1	
	00	00	00	0*		00	00	00	
ER1		2	2		ER1				
RRA1				*1	ER2				
RRA2				2	RRB1				
RDA3									

Fig.3 Fundamental motion matrix corresponding to Table 1

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① [ The number of ENERGY inputs = 2
    IN1 ER1 : ( 0.0 1.00 0.0 )
    IN2 ER2 : ( 0.0 0.0 1.00 )

② [ The number of elements in A-group = 2
    A1 : R IN1
    A2 : R IN1
    R1-B1

③ [ A1 : ( 1.00 0.0 0.0 )
    A2 : ( 0.0 1.00 0.0 )
    CAUTION!
    A2
    variable

④ [ The number of elements in B-group = 2
    B1 : R IN2
    B2 : R IN2
    R1-R2
    B1 : ( 0.0 1.00 0.0 )
    B2 : ( 1.00 0.0 0.0 )
    CAUTION!
    B2
    variable

```

Fig.4 Display of input data corresponding to the basic specification in Table 1

- (1) "Stiff" machines are dealt with, where the direction cosines of the output axes of the preceding MEs become the direction cosines of input axes of following MEs.
- (2) The number of outputs is not more than 2 series.
- (3) In each series, the number of superposable motions is not more than 3.
- (4) ER type power sources are adopted.
- (5) Plural MEs do not drive "one" element.

3.2 Input method of basic specification
The basic specification of machine can be input interactively or by prepared data set. For example, input data are displayed on CRT as in Fig.4, and after all input data are judged as right, next process is carried out. Here, B denotes D. The user must input the data underlined in Fig.4. In ① the number of power sources and the direction cosines of output axes are input. In ② are input the number, kind and sources of fundamental motions included in output A. In ③ is output the state of the superposition of fundamental motions. In ④ direction cosines of fundamental motions in ② are input. In ⑤ are output the motion numbers with variable direction cosines to inform the user. In ⑥ processes ② - ⑤ are repeated for output B.

3.3 Examples of generation of function structures A gear shaper and an involute compass are selected as examples.

As the basic specification for gear shaper, the data in Table 2 are adopted. Let the global coordinate system be the same as one shown in Fig.3 of the first report. Gear type tool and work are set to output motions A and B respectively. Output motion A is composed by superposition of relief motion in the X-positive direction, rotation and up-down motions in the Z-negative direction. By implementation of this program for this specification the results as shown in Fig.5 can be generated. This is the case that one structure is generated. In Fig.5 are listed from the top to the bottom, semi-basic matrix, basic matrix, semi-fundamental motion matrix,

fundamental motion matrix, transformation vectors respectively. In semi-basic matrix, it is seen that ARRI element is inserted for the direction adjustment of RBAL. Here, character "A" means that this element belongs to output "A" and figure "1" does that this element is inserted for the direction adjustment of "first" element of output A. In fundamental motion matrix, it is seen that the rearrangement of MEs and necessary processing are carried out. In Fig.6 are shown a basic graph and a fundamental motion graph generated from these matrices. The basic graph is the same as the basic graph shown in Fig.6 of the first report, if ER and DD elements are omitted. This fundamental motion graph is quite different from one shown in Fig.4 in the first report. This is due to the fact that the fundamental motion graph in this report considers only directions of motion transmissions, whereas in real machines various variables, such as distances between input and output axes and lengths of axles between MEs, must be considered. Introduction of these variables shall be described in the following reports.

Next, let us consider the case of involute compass. Its output motion is R+D, where D is linear motion, the direction of which is tangential to a base circle. For this motion, let the basic specification in Table 3 be given. The fundamental motion matrices and transformation vectors are listed in Fig.7. From this basic specification two structures are generated. If a planetary gear mechanism is adopted for RRA1 element, these two structures are realized.

So far, the authors have explained the generation results of function structures of gear shaper and involute compass. Having obtained expected results, the authors have confirmed the validity of this computer program.

4. Concluding Remarks

As a basic study for the establishment of the methodology for computer aided or automated design of machine structures, the authors have dealt with the automated generation of the functional structures of machines and developed an algorithm for it. Here, the machines are considered an aggregation of MEs, and transformation vectors of each element are automatically determined and if necessary the insertion of MEs and

MATRIX(11) is as follows:
The FUNDAMENTAL MOTION MATRIX is as follows:

S	ER1	RRA1	RRA2
S	00	00	00
ER1	00	20	20
RRA1	00	00	01
RRA2	00	00	00

ELEMENT TRANSFORMATION VECTOR

ELEMENT	TRANSFORMATION VECTOR
RRA1	(1.00 0.0 0.0)
RRA2	(0.0 1.00 0.0)

MATRIX(21) is as follows:
The FUNDAMENTAL MOTION MATRIX is as follows:

S	ER1	RRA1	RRA2
S	00	00	00
ER1	00	20	20
RRA1	00	00	01
RRA2	00	00	00

ELEMENT TRANSFORMATION VECTOR

ELEMENT	TRANSFORMATION VECTOR
RRA1	(1.00 0.0 0.0)
RRA2	(0.0 1.00 0.0)

Fig.7 Parts of generated results of the functional structure of involute compass

Table 2 Basic specification for gear shaper

	Serial No.		Motion	Direction	Source
Input	IN1		R	(1,0,0)	
Output	A	1	B	(1,0,0)	IN1
		2	R	(0,0,-1)	IN1
		3	D	(0,0,-1)	IN1
	B	1	D	(-1,0,0)	IN1
		2	R	(0,0,1)	IN1

MATRIX(11) is as follows:
The semi BASIC MATRIX is as follows:

S	ER1	RBA1	RRA2	RBA3	RDB1	RRA2
S	00	01	00	00	01	00
ER1	00	20	20	20	20	20
RBA1	00	00	00	00	00	00
RRA2	00	00	00	01	00	00
RBA3	00	00	00	00	00	00
RDB1	00	00	00	00	00	00
RRA2	00	00	00	00	00	00

The BASIC MATRIX is as follows:

S	ER1	RBA1	RRA2	RBA3	RDB1	RRA2
S	00	01	00	00	01	00
ER1	00	20	20	20	20	20
RBA1	00	00	00	00	00	00
RRA2	00	00	00	01	00	00
RBA3	00	00	00	00	00	00
RDB1	00	00	00	00	00	00
RRA2	00	00	00	00	00	00

The semi FUNDAMENTAL MOTION MATRIX is as follows:

S	ER1	RBA1	RRA2	RBA3	RDB1	RRA2	ARR1
S	00	01	00	00	01	00	00
ER1	00	20	20	20	20	20	20
RBA1	00	00	00	00	00	00	00
RRA2	00	00	00	01	00	00	00
RBA3	00	00	00	00	00	00	00
RDB1	00	00	00	00	00	00	00
RRA2	00	00	00	00	00	00	00
ARR1	00	00	00	00	00	00	00

There are no unnecessary elements.
The FUNDAMENTAL MOTION MATRIX is as follows:

S	ER1	RBA1	RRA2	RBA3	RBA4	RDB1	RRA2
S	00	01	00	00	01	00	00
ER1	00	20	20	20	20	20	20
RBA1	00	00	00	00	00	00	00
RRA2	00	00	00	01	00	00	00
RBA3	00	00	00	00	00	00	00
RBA4	00	00	00	00	00	00	00
RDB1	00	00	00	00	00	00	00
RRA2	00	00	00	00	00	00	00

ELEMENT TRANSFORMATION VECTOR

ELEMENT	TRANSFORMATION VECTOR
RRA1	(0.0 1.00 0.0)
RBA2	(0.0 -1.00 0.0)
RRA3	(0.0 0.0 -1.00)
RBA4	(0.0 0.0 -1.00)
RDB1	(-1.00 0.0 0.0)
RRA2	(0.0 0.0 1.00)

Fig.5 Generated results of the functional structure of gear shaper

Fig.6 Basic graph (upper) and fundamental motion graph (lower) of gear shaper

Table 3 Basic specification for involute compass

	Serial No.		Motion	Direction	Source
Input	IN1		R	(0,0,1)	
Output	A	1	R	(0,0,1)	IN1
		2	D	(1,0,0)	IN1

the determination of their transformation vectors are carried out automatically. Using the algorithm, the authors have written a FORTRAN program and applied it to the generation of function structures of machines. Having obtained expected results, they have confirmed the validity of this program.

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