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A suggestion and a contribution for the improvement of Axiomatic Design

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ABSTRACT

Design methodologies aim to systematize the design process in order to make the practice more efficient and effective. One such methodology is Axiomatic Design. However, this design theory still has some difficulties and is not completely formalized. In this paper, the new issue for the non-linear design is suggested and the representation of system architecture by flow chart is modified accordingly.

Keywords[1]: Variation of Design Parameter, Flow Chart, End of Decoupling

1 INTRODUCTION

The mid-1980s has been notable in terms of prominent engineering design failures. The Union Carbide chemical plant failure in Bhopal, India, killed more than 2,000 people; the nuclear power plant accident in Chernobyl, Soviet Union, has showered many European nations with radioactive elements; the failure of an O-ring on the NASA Space Shuttle rocket booster killed seven astronauts and demoralized an entire nation; and the Three Mile Island Nuclear Power Plant accident, although minor compared to the other accidents, realized the worst fears of nuclear power opponents [1].

Poor design practice also results in high cost and long delivery times, and these can be as devastating to a firm or nation as the failure of products and structures. Many smaller problems that we encounter with our cars and home appliances may also be attributed to inadequate design. Poorly designed products often cost more, because they use more materials or parts than well-designed products. They are also often difficult to manufacture and to maintain. Poor designs originate from the current dependence on trial and error, intuition, empiricism, and the so-called handbook method. Though many failures could not have been anticipated, some might have been averted by a more systematic, scientific and rational approach to design [1].

Axiomatic Design is the engineering design theory that has been developed at MIT since the 1980's. This aims to establish a scientific basis for design and improves design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools [1-2]. However, Axiomatic Design still has some problems and is not yet completely formalized. Therefore, in this study, the new issue for the non-linear design is proposed and the representation of system architecture by flow chart is modified accordingly.

2 SUGGESTION FOR IMPROVEMENT OF AXIOMATIC DESIGN

Consider a design with one Functional Requirement (FR) and one Design Parameter (DP), for which the design equation may be written as

$$FR_1 = A_{11} DP_1 \tag{1}$$

or in differential form as

$$dFR_1 = \frac{\partial FR_1}{\partial DP_1} dDP_1 \tag{2}$$

The relation between A_{11} and $(\partial FR_1 / \partial DP_1)$ is obtained by differentiating Eq. (1) with respect to DP_1 and comparing

$$\frac{\partial FR_1}{\partial DP_1} = A_{11} + \frac{\partial A_{11}}{\partial DP_1} DP_1 \tag{3}$$

Equation (2) may be now written as

$$dFR_1 = \left(A_{11} + \frac{\partial A_{11}}{\partial DP_1} DP_1 \right) dDP_1 = \frac{\partial FR_1}{\partial DP_1} dDP_1 \tag{4}$$

In the case of a linear design, A_{11} is constant and equal to $(\partial FR_1 / \partial DP_1)$, i.e.,

$$A_{11} = \frac{\partial FR_1}{\partial DP_1} = \text{constant} \tag{5}$$

In the case of nonlinear design, A_{11} and $(\partial FR_1 / \partial DP_1)$ will vary as a function of DP_1 [2].

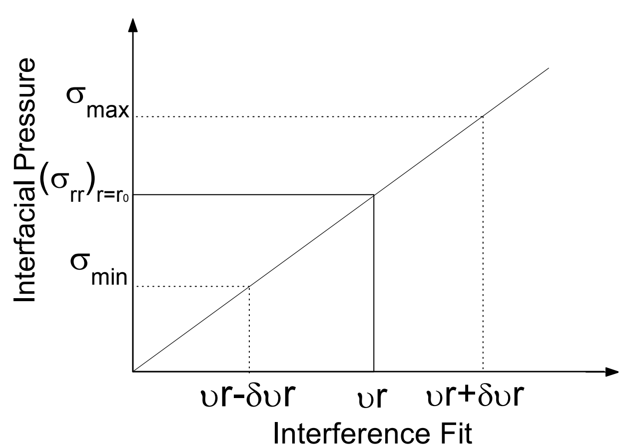

Figure 1 Interfacial pressure vs. interference fit [2]

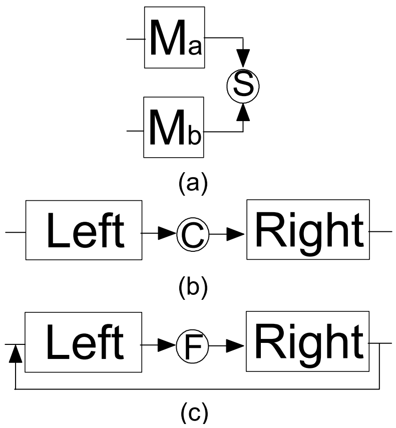

Figure 2 Representation of the design at each junction of a flow chart (a) Summing junction (uncoupled design) (b) Control junction (decoupled design) (c) Feedback junction (coupled design) [2

So far, Axiomatic Design has not considered the case that the design equation varies as a function of the variation of DP (δDP). In this case, the design should be regarded as the nonlinear design because the design equation is not a constant. Such designs should also be studied physically to be settled and systematized. Below is an example of the design in which the design equation itself varies with δDP.

A part for a machine used in harsh environments is made of a 7075-T6 aluminum tube pressed on a 1020 steel rod. The part must maintain a tight fit in the temperature range from –30°C to +70°C. The machining accuracy of the mass-production machines selected to make these parts is ±0.0254 mm. The required interference fit between the rod and the tube is 4.0 to 8.0 MPa. The FR is now the compressive stress $(\sigma_{rr})_{r=r_0}$ between the steel shaft and the aluminum tube and the DP is the interference fit υr (i.e., the difference between the nominal value of the shaft and the nominal value of the cylinder). Random variation of the interference fit, $\delta(\upsilon r)$, will occur due to the manufacturing variability of the shaft diameter and the inner diameter of the tube, and also during service by temperature fluctuations [2].

The design equation is

$$\begin{aligned} FR_1 &= A_{11} DP_1 \\ (\sigma_{rr})_{r=r_0} &= f(r_0, t)\upsilon r \end{aligned} \tag{6}$$

In reference [2], this design was analyzed as a linear design as shown in Fig. 1 since A_{11} does not depend on DP_1. However, in this case, Eq. (6) can be written at the two bounds of the interfacial stress as

$$\begin{aligned} 8\,\mathrm{MPa} &= f(r_0, t)(\upsilon r + \delta(\upsilon r)) \\ 4\,\mathrm{MPa} &= f(r_0, t)(\upsilon r - \delta(\upsilon r)) \end{aligned} \tag{7}$$

By solving Eq. (7), we obtain

$$f(r_0, t) = 2/\delta(\upsilon r) \tag{8}$$

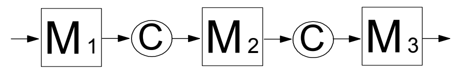

Figure 3 Flow chart of Eqs. (10.a) and (10.b)

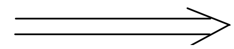

Figure 4 Notation of the end of decoupling

Therefore, this design should be treated as nonlinear because the design equation is a function of the variation of DP_1, $\delta(\upsilon r)$, and is not a constant.

3 CORRECTION OF THE FLOW CHART

In Axiomatic Design, a flow chart is often used as a representation of system architecture. To construct the flow chart, a module is defined as the row of the design matrix that yields an FR when it is provided with the input of its corresponding DP, and it is adopted the relationship between modules, as shown in Fig. 2. Consider the following design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} a & 0 \\ b & c \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{8}$$

The modules M_1 and M_2 are given by

$$\begin{aligned} FR_1 &= aDP_1 + 0DP_2 = M_1 \times DP_1 \text{, where } M_1 = a \\ FR_2 &= bDP_1 + cDP_2 = M_2 \times DP_2 \text{, where } M_2 = b(DP_1/DP_2) + c \end{aligned} \tag{9}$$

In an uncoupled design, because the 'child' FRs are independent of each other, their parent FR is satisfied by combining all the outputs of its child modules in any random sequence. This is represented by the summation junction with the modules parallel to each other, as shown in Fig. 2(a). When the design is decoupled, the parent FR is determined by combined the child modules in a given sequence indicated by the design matrix, which is shown as a serial arrangement of modules. In this case, the output of the left-side module is controlled first and then the right-side module is executed next, as shown in Fig. 2(b). For a coupled design, the feedback junction requires that the output of the right-side modules be fed back to the left-side module, requiring a number of iterations until the solution converges, if it converges, which is shown in Fig. 2(c). Some feedback junctions may never converge. When there are feedback junctions, especially at the higher level of the system hierarchy, we should stop and seek an uncoupled or decoupled design [2].

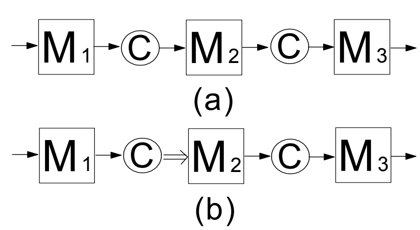

Figure 5 Independent flow charts (a) Eq.(10.a) (b) Eq.(10.b)

However, the design equations for all systems are not independent according to the notations in Fig. 2. Consider the following design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (10.a)$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (10.b)$$

The flow charts for Eqs. (10.a) and (10.b) are same as shown in Fig. 3. In Eq. (10.a), DP_1 affects FR_2 and FR_3. Hence, M_1 becomes decoupled from M_2 and M_3. In Eq. (10.b), DP_1 affects FR_2 but does not affect FR_3. Hence, M_1 becomes decoupled to M_2, but uncoupled to M_3. However, it is impossible to represent that M_1 becomes a decoupled relationship with M_2, but uncoupled with M_3 by previous notations of flow chart. Therefore, the notation of Fig. 4 that indicates the end of decoupling is inserted to represent that. The end of decoupling makes the decoupled relationship of M_1 finish at M_2. Hence, M_3 becomes a uncoupled relationship with M_1. As a result, the design equations are independently represented by the flow chart shown in Fig. 5.

4 CONCLUSIONS

We have raised a new issue for nonlinear design in Axiomatic Design and correspondingly modified the representation of system architecture by a flow chart. Therefore, the following conclusions have been drawn:

(1) The design in which the design equation varies with the variation of DP (δDP) should be regarded as a nonlinear design and should be further studied physically.

(2) When system architectures are represented by a flow chart, all systems can be independently represented by the notation of the end of decoupling.

5 ACKNOWLEDGMENTS

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7 APPENDICES

Flow charts for a design that has three FRs and three DPs are represented. There are total 64 kinds of design equation, and these are classified into 15 equivalent groups through arrangement. Among these groups, groups 6 and 7, groups 8 and 9, and groups 11 and 12 are distinguished by the notation of the end of decoupling.

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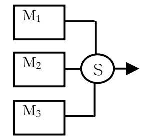

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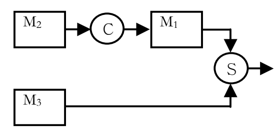

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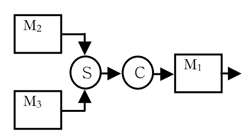

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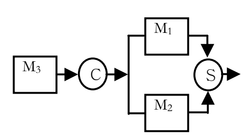

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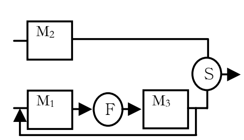

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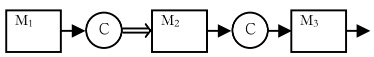

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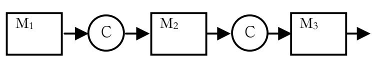

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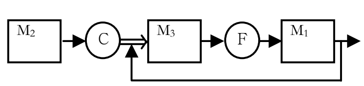

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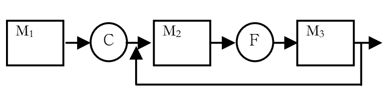

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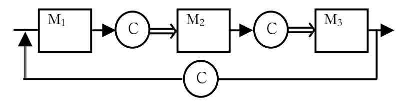

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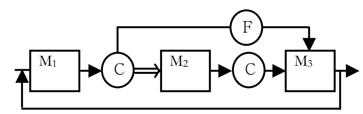

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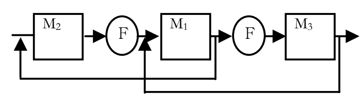

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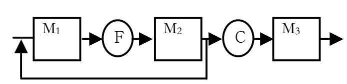

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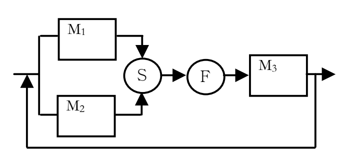

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