AXIOMATICALLY DESIGNED ROBUSTNESS

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ABSTRACT

While Taguchi methods allow engineers to adjust control factors in a design to increase robustness to noise, obtaining good performance via these methods requires the design to contain suitable control factors. Axiomatic design is a methodology that forces the engineer to address each functional requirement of a system with an associated design parameter that may be adjusted to satisfy the functional requirement. By minimizing the number of explicitly stated design parameters, axiomatic design may be though to decrease the flexibility for Taguchi optimization. However, by addressing known noise factors as functional requirements for robustness, axiomatic design produces systems with better responses to Taguchi methods. This paper highlights the method for considering noise factors in axiomatic system design such that Taguchi methods may have maximum impact. Specific consideration during system design ensures both sufficient and effective control factors. Examples are drawn from various sources including a wafer polishing machine used in semiconductor fabrication and automobiles.

1. INTRODUCTION

1.1 Axiomatic Design

The axiomatic design process is centered on the satisfaction of functional requirements (FRs). FRs are defined as the minimum set of independent requirements that completely characterize the functional needs in the functional domain. The goal of the design is to satisfy the FRs, and this is done by creating a system that uses design parameters (DPs) to affect the behavior such that the FRs are satisfied [1].

Given a set of FRs, the designer conceives of a physical embodiment containing a DP that may be adjusted to satisfy the FR. When embodiments and DPs are selected for the design, they are chosen according to the two design axioms:

- The Independence Axiom – Maintain the independence of the functional requirements.
- The Information Axiom – Minimize the information content of the design.

The design matrix relates the FR vector to the DP vector. It is used to note the effects of DPs on FRs. An example design matrix is contained in the following design equation:

$$\begin{Bmatrix} FR\,1 \\ FR\,2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \begin{Bmatrix} DP\,1 \\ DP\,2 \end{Bmatrix} \tag{1}$$

where A_{11} denotes the effect of DP1 on FR1, A_{21} denotes the effect of DP1 on FR2, etc. When the design equations represent conceptual levels of the design, it is common for the elements of the matrix, A_{ij} to be represented with an 'X' if there is an effect, and an 'O' if there is no effect. To satisfy the Independence Axiom, the design matrix must be either diagonal or triangular. The triangular matrix in Equation 1 represents a decoupled design. For correct implementation of such a design, it is necessary to set the value of DP1 before setting the value of DP2. If the matrix in Equation 1 were diagonal, the design would be uncoupled, and the DPs may be set in any order.

Axiomatic design begins with the most general requirements of the system, and decomposes these into sub-requirements. The goal of decomposing an FR/DP pair is to develop a combination of elements that, used together, result in the parent. As the system is decomposed, it is necessary to specify a set of FRs, move to the physical domain by conceiving of a design solution, and then proceed back to the functional domain to add a level of detail. This process of moving from the functional to physical domains, and progressing from a general to a detailed description is called zigzagging.

The hierarchical collection of FRs and DPs generated during the zigzagging process is termed the system architecture. Zigzagging is repeated until it is possible to construct the system from the information contained in the system architecture.

As most DPs are invariably associated with random variations, the complexity of a decoupled system increases with the number of layers of decomposition, since the allowable variations of DPs decreases.

1.2 Robust Design

Robust design is the general term used to describe a process initiated by Taguchi as quality engineering [2]. Taguchi aimed to reduce production variance by creating a quality loss function, and optimizing the product to minimize the loss function. The methods have been expanded and developed, and are commonly termed robust design or Taguchi methods today [3]. The premise of robust design is that product variance is caused by noise factors, which may come from many places, throughout the life of the product, and through experimentation it is possible to make the product and production process less sensitive to sources of variation, so it may always achieve its desired purpose.

Taguchi defines five stages of product and production process design: system selection/design, parameter design, tolerance design, tolerance specifications, and quality management for the production process [4]. While these stages are sometimes expanded, the stages of system design, parameter design, and tolerance design are inherent to robust engineering practice [3]. Unfortunately, little is said of system design – also known as conceptual design – besides mentioning that it is necessary. Taguchi states that the engineer must consider all possible systems to perform the desired functions, and then arrive at a final choice based on judgment and discussions [2,4]. While this is compatible with the most basic goals of axiomatic design – the satisfaction of functional

requirements, it does not say anything about considering the robustness of a design during the conceptual design stage.

1.3 Robustness in Axiomatic Design

Axiomatic design currently addresses robustness in two areas. By nature of the two design axioms, robustness is improved. The independence axiom results in systems with reduced internal interactions. By designing a system with minimal interaction between elements, one source of internal noise is reduced. Noise that is introduced into one element of the system will not propagate into other areas, therefore improving robustness. This is a feature of axiomatic design that does not need to be separately addressed by the designer to achieve robustness. If the first axiom is followed, and independence is maintained as much as possible, then the system will be as robust as possible to degradation of performance from interactions.

The information axiom also has repercussions for robustness, as discussed by Suh [1]. This may be illustrated as shown in Figure 1. Shown are two alternate designs, one with a higher "stiffness" than the other. The tolerance on the allowable FR range, and random variation (noise) of the DP is the same for each system. In design A, the stiffer system, it is apparent that the noise-induced variation of the DP causes the FR to move beyond its allowable limits. However, in the case of design B, the same amount of variation allows the system to remain within tolerance. Therefore, axiomatic design is prepared to deal with variation in the selected design parameters.
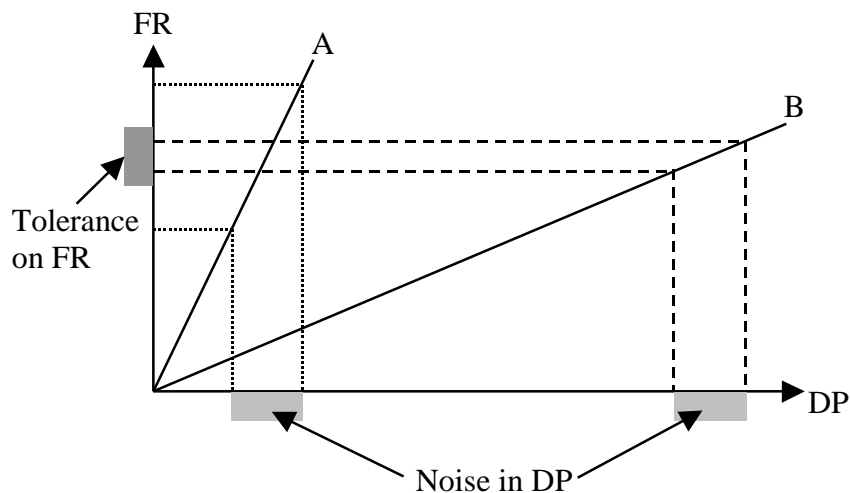

Figure 1: System robustness to noise in design parameters is increased by reducing the system stiffness.

2. CONCEPTUAL ROBUSTNESS

Andersson proposes both a qualitative and semi-analytic approach to achieving robustness during conceptual design [5,6]. His overall idea is that robustness should be considered as early as possible in the product design process, where experimentation is not possible. By setting the stage for parameter design, system design is the key to the

possibilities for robustness. A system that is designed to be robust during conceptual design will still improve with parameter design – it will improve to a level beyond the system in which robustness was not considered during system design. While Andersson has captured the key idea for conceptual robustness, he does not mention how to go about making sure that the correct ideas are used. He lists many sources of design information that can be applied in the conceptual design phase, and will improve robustness. The important step is the ability to identify the need for a particular solution and understand how it can fit into the rest of the system. This is where axiomatic design may be very useful.

2.1 Identification of Noise Factors

While axiomatic design already considers robustness to variation in design parameters and to internal noise, there are many other sources of noise in a system. The current approach of axiomatic design is to consider all the additional noise sources as a single entity. Then, the allowable variation due to DPs is found by subtracting the sum of the variance due to noise from the total permissible FR variation. This approach may work in many circumstances, but the resulting allowable tolerance of DPs may be expensive or difficult to achieve. This is particularly true when the noise introduced from other sources is very large.

The strategy proposed is to identify major sources of noise, and then specifically target them within the conceptual design of the system. Noise factors may come from several sources; Taguchi defines three types of noise – external, internal, and unit-to-unit [2]. Knowing categories of noise can help the designer predict which may play a factor in the system under consideration. This is an area in which past experience will be important. Information stored as a database may also be used to predict which noise factors are likely to contribute to the behavior of the system.

2.2 Creation of Functional Requirements

Once noise factors have been identified, those which are believed to contribute significantly to variation in the desired FR behavior should be selected. For each selected noise factor, a functional requirement is created to minimize the system response or susceptibility to the noise factor. The general form of the FR, in concurrence with standard axiomatic design practice, should express the requirement as a verb, e.g. "Prevent errors due to thermal fluctuation," or "Allow variation in stock material." Examples of specific robustness functional requirements will be given in following sections.

2.3 Mapping to Design Parameters

Once functional requirements exist that explicitly address noise factors, the standard methods of axiomatic design apply. Since there is a design solution to satisfy the fundamental set of FRs, one possibility may be to select some parameter of the existing solution and use that as the DP to control system response to a noise factor. If this is not possible, a new embodiment may be added to the system to provide a parameter that may be used as the DP to control response to the noise factor.

The design solution may be to reduce sensitivity to noise, or to shield the system from the noise. Such an example may be a precision machine tool or measurement tool, where the noise is thermal variation in the environment. Since this is a known source of noise, the design solution may be to create a temperature controlled enclosure in which the machine will operate. On the other hand, if the requirement exists at a lower level of the design, such as a measurement scale, then the design solution may be to use a material with a low coefficient of thermal expansion, and therefore reduce the system sensitivity to the thermal noise.

The need for suitable design parameters to satisfy the newly created functional requirements is significant. While a designer's experience may often allow the specification of appropriate solutions, other sources are useful. This is an area where computer databases of design information may be applied. Work is being done to develop systems with collections of case-based conceptual design information [7]. The information in such a system could be indexed with noise factors, therefore allowing a search to find potential solutions to a particular noise problem.

Often, a design parameter at high levels of the design will require decomposition. For instance, in the case mentioned above, if a thermally controlled enclosure were used, the FR/DP pair would be decomposed into a subsystem to enable the enclosure to be created. This is the natural process of axiomatic design, and moves the system from conceptual design into configuration design and parameter design. In the parameter design stage, when values are set for leaf level DPs, the traditional techniques of Taguchi Methods may be used. Since the system has been designed for robustness from the conceptual stage, it is guaranteed to have the flexibility needed for successful optimization. The control factors to be used for parameter design experiments have already been explicitly placed into the system for the purpose of affecting response to noise.

3. EXAMPLES

3.1 CMP Pressure Application

As an example of designing robustness into the system during conceptual design, the design of a chemical mechanical polishing (CMP) machine will be used. This machine was developed as part of a research program at MIT, and has demonstrated advanced capabilities to polish silicon wafers for semiconductor fabrication [8]. During the development of the system, robustness was designed into the concepts of the machine. Examples of robustness FRs will be demonstrated from two subsystems. First is the application of pressure to the wafer being polished. Here the parent FR is Apply normal pressure and the DP is Interface pressure. These are decomposed as shown in Table 1. The prefix "x" in the FR/DP numbering designates the subsystem's existence within a larger design. The design equation is Equation 2, and shows that the system is decoupled. A schematic of the system is shown in Figure 2. The FR/DP pairs that were created to improve the system robustness are x.3 and x.5.

Table 1: FR/DP x.5 decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
x.1	Provide pressure	Nominal compartment pressure
x.2	Create local pressure variation	Pad surface modulus $E_{PAD-TOP}$
x.3	Accommodate wafer form variation	Stack stiffness $(Eh^4)_{mem} + (E_{bulk}/h)_{PAD}$
x.4	Transmit pressure to interface	Membrane area
x.5	Accommodate machine misalignment	Isolation bellows stiffness
x.6	Support normal loads	Normal load support chain

$$
\begin{Bmatrix} FR\ x.1 \\ FR\ x.2 \\ FR\ x.3 \\ FR\ x.4 \\ FR\ x.5 \\ FR\ x.6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & X & X & O & O & O \\ O & O & O & X & O & O \\ O & O & X & O & X & O \\ O & O & O & X & O & X \end{bmatrix} \begin{Bmatrix} DP\ x.1 \\ DP\ x.2 \\ DP\ x.3 \\ DP\ x.4 \\ DP\ x.5 \\ DP\ x.6 \end{Bmatrix} \tag{2}
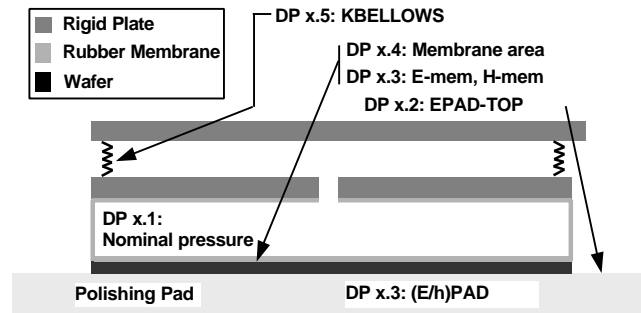$$

Figure 2: FR/DP x decomposition schematic

DP x.1: Compartment pressure is the pressurized gas supplied to the bladder compartment. With the extremely flexible membrane used in this design, uniform pressure is easily obtained.

DP x.2: The pad surface modulus is what creates preferential removal of the high features compared to the low features – the process of planarization. At the length scale of the features being polished (less than one micron), macroscopic features of the pad have little effect. The pad surface modulus affects FR x.3 because a higher modulus will, to some extent, reduce the ability of the system to tolerate wafer form variation.

DP x.3: $(E/h)_{PAD}$ is the stiffness of the pad in the vertical direction. The membrane modulus, E_{mem}, combined with the membrane thickness, h_{mem}, describes the bending stiffness of the planar membrane. The total stack stiffness of the pad and membrane controls how the pressure will respond to wafer form variation. A low stiffness will accommodate a large wafer form variation without creating large pressure variation. Due to the high compliance of the membrane used to apply pressure to the wafer, the primary

concern here is from the pad side of the wafer. Generally, the pad thickness may be used to control the stack stiffness in a way that will not influence polishing at a local level. Most pads used in commercial processes use a multi-layer stack, so that the surface presented to the wafer is of the desired modulus to satisfy DP x.2, and then an additional lower layer may be used to reduce the overall stack stiffness to a value suitable for robustness to incoming wafer variation. The stiffness affects FR x.5 because low stiffness reduces requirements for misalignment, as low pad stiffness creates less pressure variation due to misalignment.

DP x.4: Membrane area is the overall area of the membrane; It should match the wafer area. Membrane area affects FR x.6 because a change in area will change the applied loads that the system must support. The area does not change during operation of the machine, so creates no problem.

DP x.5: The isolation bellows stiffness is the tip-tilt stiffness of the bellow used to decouple the wafer carrier membrane from the rest of the wafer carrier. Thus, any misalignment in the wafer carrier itself will not translate into a pressure variation on the wafer surface. This decoupling bellows has the benefit of isolating the normal loads on the wafer, i.e. the polishing pressure, from frictional loads that are supported by the wafer carrier. This is a major advantage over some earlier CMP systems, in which a strong coupling exists.

DP x.6: The load support chain is the series of machine elements that allows a load to be present at the wafer-pad interface without undue deflection. These are primarily load ratings of the various hardware components used in the mechanical system, and have little influence on the wafer carrier itself.

Both of the robustness FR/DP pairs used in the design of the pressure subsystem use an increase in compliance to improve the system robustness. Rather than using parameter design to optimize the values of compliances that might have been part of the design, the compliance was put in the most beneficial position. It is still possible to use parameter design to optimize the values.

3.2 CMP Pad Conditioner

Another subsystem of the CMP machine is the pad conditioner. The pad conditioner uses an abrasive disc to remove material from the surface of the polishing pad, and therefore maintain the surface characteristics of the pad. As the pad conditioner is decomposed, one requirement is to apply normal force. Table 2 shows the decomposition of the parent pair, FR: Apply normal force & DP: Pivoting arm force system. Equation 3 is the associated design equation. Figure 3 shows an overall schematic of the subsystem, and Figure 4 shows a more detailed view of the conditioner head configuration. The FR/DP pairs y.2, y.3, and y.4 are all created to improve system robustness.

Table 2: Decomposition of CMP conditioner force system

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
y.1	Apply force	Bellows pressure
y.2	Prevent force variation from drag loads	Vertical offset of arm pivot from conditioning point
y.3	Prevent pressure distribution from drag loads	Vertical offset of head pivot from conditioning point
y.4	Prevent pressure distribution from misalignment	Tip/tilt compliance of conditioner head
y.5	Support applied force	PAFS support structure

$$\begin{Bmatrix} FR\ y.1 \\ FR\ y.2 \\ FR\ y.3 \\ FR\ y.4 \\ FR\ y.5 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & O & X & O & O \\ O & O & O & X & O \\ X & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ y.1 \\ DP\ y.2 \\ DP\ y.3 \\ DP\ y.4 \\ DP\ y.5 \end{Bmatrix} \tag{3}$$
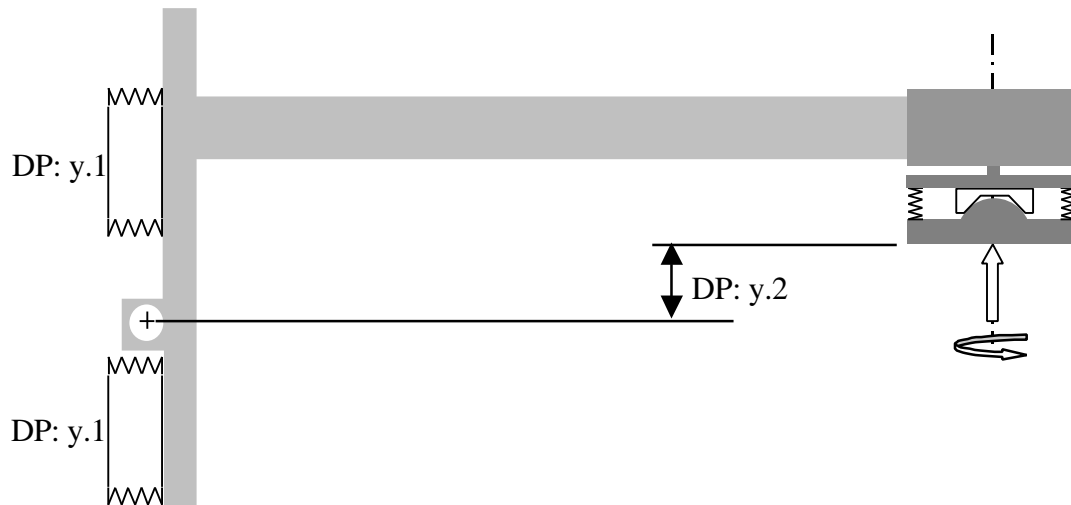

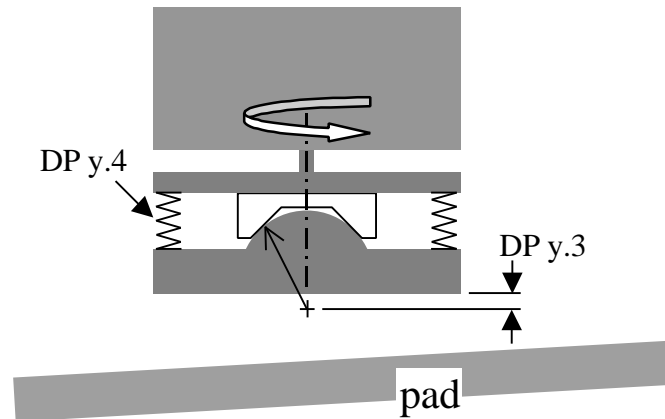**Figure 3: Schematic of CMP conditioner system**

Figure 4: Detailed schematic of CMP conditioner head

DP y.1: Bellows pressure is the pressure applied to the bellows which pivots the arm up or down, as shown in Figure 3. The difference between the top and bottom bellows is the effective DP. DP y.1 affects FR y.5 because the amount of force that must be supported is a function of the applied pressure.

DP y.2: Vertical offset of arm pivot from conditioning point is shown in Figure 3. If there is any offset from the point of force application, a moment is created which tends to pivot the arm. The moment will be balanced by a change in the normal force on the conditioner, since the pressure in the bellows is constant. DP y.1 would ideally be set near zero, but has been shown with a non-zero value for the purposes of illustration.

DP y.3: Vertical offset of head pivot from conditioning point is shown in Figure 4. If there is any offset from the point of force application, a moment is created in the lower member of the conditioner that must be balanced by a resulting pressure distribution at the surface of contact between the conditioner and pad. DP y.2 would ideally be set near zero, but has been shown with a non-zero value for the purposes of illustration.

DP y.4: Tip/tilt compliance of conditioner head is also shown as a bellows in Figure 4. The bellows provides lateral stiffness to support the conditioner lower member, but allows it to assume the correct orientation to make contact with the pad without a pressure distribution due to misalignment.

DP y.5: Pivoting Arm Force System Support Structure is the collection of machine elements that allows the arm to apply force at the conditioner.

3.3 Vehicle Design

There is a large push for robustness vehicles. Particularly with vehicles operated on public roads, the conditions of usage vary widely. Many features of robustness have been incorporated into vehicle design as it progressed from generation to generation. For example, the use of detonation sensor, or knock sensor, allows gasoline engines to run on a wide variety of fuel octane content without problems. Detonation, or knock, is a condition where the fuel-air mixture in a cylinder combusts while the piston is still moving upwards to compress the mixture. The combustion is in opposition to the upward moving cylinder, and therefore creates a loss of power. By sensing detonation in the engine, the sensor provides information to the engine management computer that causes it to retard the ignition timing, therefore allowing the piston to begin moving downward

before the mixture is ignited. High octane fuels are less prone to pre-ignition, and therefore prevent knock. With the sensor and control system, the engine has been made robust to gasoline variation through the inclusion of a subsystem to change ignition timing.

Also, vehicles must be robust with respect to the profile and conditions of the road surface. For instance, undulations in the road surface should not disturb the directional stability of the vehicle. Road undulations cause vertical motion of the suspension relative to the frame of the vehicle; the wheel alignment parameters are a function of the suspension position. For this purpose, the suspension kinematics are carefully designed for the desirable characteristics. The FR in such a case might be as follows: Prevent wheel alignment changes due to road surface undulation, and the DP could be: Suspension kinematics.

Additionally, the tire tread pattern is designed to make the vehicle robust against water or other fluids on the road surface. With the proper tread pattern design, the tire is able to remove water from under the contact patch between the tire and road. Each of these design features, planned during the conceptual design phase of development, directly addresses a known source of noise facing the system.

4. SUMMARY AND CONCLUSIONS

The need to address robustness during the conceptual design stage has been demonstrated. Parameter design and tolerance design, while useful practices, can only provide as much improvement as allowed by the system as specified in conceptual design. As a design methodology, axiomatic design provides a good framework for performing conceptual design in a structured manner, to insure that necessary functional requirements for a system are met. While axiomatic design does address certain types of robustness, there are likely to be additional noise factors that influence the overall performance of the system. If these can not be dealt with by reducing design parameter variation, another method is needed.

By creating functional requirements for robustness, it is possible to directly address individual sources of noise with parameters of the design to have maximum effect. Not only does this provide a system with the increased flexibility that is a benefit to parameter design, it increases the likelihood that such optimization will be maximally effective. The results of the proposed method are difficult to quantify without a more thorough investigation. The specific benefit of robustness features added during conceptual design could be demonstrated by comparing two systems – one that has no such features, and undergoes Taguchi methods, and another that has been designed for conceptual robustness, and then undergoes Taguchi methods. The authors believe that the system designed for conceptual robustness will show a better response to the optimization and therefore will have superior robustness to the noise factors that have been targeted during conceptual design.

Examples of the proposed method have been shown, such that a number of noise factors could be dealt with. The CMP machine used as an example has been successful in its designed task and performed well without careful assembly and debugging, largely due to the robustness built into the system during conceptual design.

5. ACKNOWLEDGEMENTS

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