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AN APPROACH TO MODULAR MACHINE REDESIGN WITH CONSIDERATION OF FLUID FLOW

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ABSTRACT

The ever increasing need to develop new product range has forced industry to adopt new design and manufacturing strategies in order to response to customers need. One of the most powerful strategy is in the adoption of modular approach in machine redesign in order to achieve better parts commonality and integrity. This paper describes an approach in modular design for machine redesign by taking into account parts interaction and fluid-flow within a machine to derive a module, which fits assembly requirement and minimum leak arrangement. The approach uses product structure and product decomposition to identify components. Components interaction based on assembly direction is used to construct the interaction matrix. The fluid flow within the structure is also constructed and the fluid interaction matrix is then combined with the interaction matrix. Clustering is then applied simultaneously using the extended triangularization algorithm. Interaction density is used as a measure of module preference and this is done by rearranging the components so as to achieve high interaction density module. This approach enables the designer to adopt new method in redesign where other factors are considered apart from assembly. An example of electrodepositing machine redesign is used to further describe the approach.

Keywords: *Modular design, interaction matrix, cluster identification, electrodeposition.*

1.0 INTRODUCTION

1.1 Motivation and Objective

The current manufacturing industry has moved from low variety production to high variety and high quality production. This shift is embodied in agile manufacturing concepts with customization, rapid production, upgradable new products with dynamic reconfiguration for production processes [1]. Modular design approach is one of the solutions to the need of higher variety and complexity of products using product family design that allows shared product platform to produce variant [2]. Therefore modular design is seen as one of the essential competencies in implementing agile manufacturing concept. Modular design is also one of the efficient means for meeting new customer requirements and introducing new technology and at the same time allows for structured approach to dealing with complexity [3]. It is a part of the overall product architecture that enables modular product architecture to be developed. It is a more recent aspect, which must be considered even after the product architecture has been developed for redesign and reengineering. There are various examples in the use of modular platform, which can result in economies of scale [4]. Among the famous examples are platform designs by Sony using three platforms to support hundreds of the Walkman variants, scalable motor platform by Black and Decker and V-8 engine family by Ford [5]. The reader is referred to the excellent compilation of several reports on the industry adoption of modular design by Whitney [6].

With any connections or assembly involving fluids, leakage is one of the main factors to be considered. Leakage is usually prevented by some means of seal or gaskets for static applications. Spurious leaks also known as fugitive leaks account for no less than a third of total organic emissions from chemical plants [7]. The visible cost is direct material loss. Other losses associated with leakages are labour and material to repair, wasted energy and plant inefficiency, environmental clean-up, environmental fines and claims for personal injury when hazardous materials are involved. Mechanical seals are used where conventional packed stuffing boxes are inadequate in service life or leakage. A typical mechanical seal may consist of nine components and installation and repair associated with defective seal is laborious and costly. Troubles related to seal joints might, among others, because by worn packing, worn seal, loose packing, damaged o-ring and corrosion. Adding to this is the need to provide cooling circulation to the mechanical seal. All these add up to cost and assembly time and later in the product life and maintenance cost. [8]

Modularity or combining the structure allows for integration of the fluid-joints and can prevent the occurrence of leaking. Usually assembly joints of the conduits are also the liquid joints for fluid flow system. In cases which involve flow networks, distribution of the correct amount of fluid is important to ensure homogeneity within the production unit. Typical examples are when chemicals are required at various stations of processes (mixing, dispensing, electroplating etc.). Thus, for a machine there will be dry joints where the assembled parts are not related to the fluid flow and fluid joints. For the dry joints an interaction matrix can be constructed with consideration for assembly direction. However for the fluid joints there is the leakage and flow integrity issue. Combining these parts must now look into the sealing construction, the design of which is dependent upon the pressure, type of fluids, kinematics (sliding or rotating joints) and other parameters. Obvious benefits arising from the deleting of fluid joints are reduced number of parts and possible elimination of leakage.

From the various approaches reviewed there is a potential for extending the modular design approach to machines with fluid-flow network within. The main contribution of this paper is to extend the existing modular design methods by integrating parts design and fluid-flow within a machine to create coherent and common modules thus benefiting from assembly and better flow integrity.

1.2 Related Work

There has been active research in the modular design methodology. A very methodical and systematic approach to modular design with known parts list has been presented by Huang and Kusiak [9] with the use of interaction matrix and suitability matrix. The approach requires the designer to know the assembly of the product and interpret the suitability of combining those assemblies to form module.

Dahmus et al. [10] also employs clustering of various components in the system architecting to identify effective modules. The approach established limits of the product family that can share common modules by the union of multiple product function structure in a single family function structure and then constructing the modularity matrix. The matrix is different from [9] as it is based on function versus product. Shared functions are the target for modularization as common functions and shared columns allow for multiple function to be incorporated into one product. This enables decision to be made on the basis of product or portfolio architecture.

Salhieh and Kamrani [11] have introduced a systematic approach to design for modularity, which involves need analysis, product requirement analysis, product/concept analysis and product integration. They employ system level specification based on decomposition of the product hierarchy and general function requirement and assess its impact on each other based on the need analysis. Degrees of association between different components are used to determine similarity index, which is based on the system level specification. The similarity indices associated with components are arranged in components versus component form to obtain the similarity matrix. The p-median model is then used to rearrange the similarity matrices into independent modules.

2.0 APPROACH

The approach taken here is to include the possible leak joint where fluid flow exists within the machine structure (for example air intake manifold, pumps etc.). The methodology used in this work is based on the work of Kusiak et al. [9] but extended to include in the analysis of fluid-flow within the system. The approach is to construct the product structure as used by Dahmus [11] and then carry out product decomposition to come out with components listing. The component interactions are identified and presented in matrix form based on assembly with numbers representing the interactions based on parts incidence. Cluster identification is then carried out to identify the possible modules from interaction matrix. The flow of fluid within the structure is analyzed and flow path identified. The flow path is then used to construct the flow interaction based on the flow incidence. As the flow must also pass through the parts it is then possible to construct the parts and flow interaction matrix side-by-side and these are then subjected to cluster identification. The preferred results are based on creating modules which is common to parts incidence and flow incidence, combining both assembly and flow problem. If the modules are not common the adjustment should be made either to the flow or to the parts to enforce common module.

2.1 Problem Statement

Consider a machine with m number of components. Let the row I and the column set of J correspond to the component set C={1......m}. The interaction matrix $\mathbf{M_A}=[a_{ij}]_{mxm}$ is a component incident matrix where a_{ij} is the number of possible assembly direction between component i and component j, i and j $\in$ C.

The flow matrix $\mathbf{M_F}=[f_{ij}]$ is flow incidence matrix within a flow network in the machine connecting component i and component j where f_{ij} is the fluid flow incident. The value of f_{ij} is either 1 or 0, that is for components interfaces where the fluid passes through a value of $f_{ij}=1$ is enforced or zero otherwise.

The leakage matrix $\mathbf{M_L}=[l_{ij}]$ is to map the possible leak locations within the machine and identifiable in the flow network at interfaces of component i and component j where usually seal is being used or locations where leak tests are necessary to determine assembly integrity. The flow-leakage matrix is then defined as

$$\mathbf{M_{FL}} = \mathbf{M_F} + \mathbf{M_L}$$

The overall assembly and flow-leakage matrix can now be viewed by arranging the interaction matrix and the flow-leakage matrix side by side to form a 2m x m matrix.

$$\mathbf{M} = [\mathbf{M_A} \mid \mathbf{M_{FL}}]_{2m \times m}$$

The problem is to form clusters within the overall matrix M to create maximum interaction within the cluster allowing it to be minimally dependant on other unit which is one of the major criteria for creating modular unit. This is achieved by reordering the matrix using the extended triangularization method. Generally the clusters within $\mathbf{M_A}$ and $\mathbf{M_{FL}}$ is not similar and the interaction density or the group efficacy can be used to determine the cluster with the higher interaction.

3.0 IMPLEMENTATION

The current study will look into the modularization based on assembly and flow connectivity. Simultaneous clustering is applied to the flow network to identify any possible modular unit.

Case Study – Electrodepositing Machine

This machine is used in the manufacturing of the leadframe which forms the metal interconnect base for the chip. The die pad area is the central area on the leadframe where the silicon chip is mounted before wiring and packaging is done. In the flow network in electrodepositing process of leadframe, there are several critical defect parameters, which are bleeding and seepage. Selective electrodepositing is essentially electrodepositing on the target area (die pad) which is achieved by containing the electrolyte within the desired area using elastomeric mask [12]. Leakage in minor quantities resulting in a plated area projecting out from the die pad area whereas major quantities spread over a relatively large area does not result in plated area but surface blemish. Both of these surface defects are not acceptable. The existing design uses a fibre reinforced polymer plate where a network of vertical and horizontal troughs is machined to create the flow network within. These network of channels 2,3 are to receive the incoming electrolyte 1 and distribute it to each die pad area 4 bounded by the mask and the pressure pad, both of which are made from elastomer. After passing through the die pad area the electrolyte is directed to the outlet channel 5 to flow down into a sump below as shown in the flow structure of figure 1. Defect sometimes occurs when the mask and pressure pad did not match properly due to some operational reason such as variation in the pressure distribution at the interface.

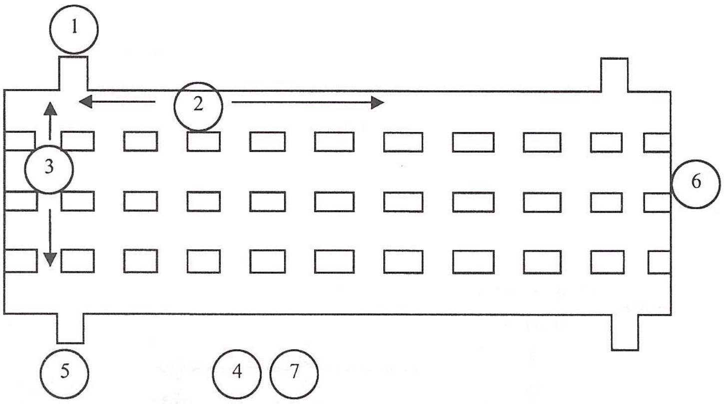


Figure 1 Schematics of the electrodepositing machine

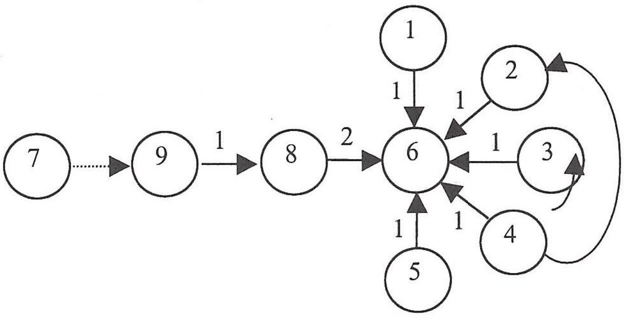
Physical decomposition is carried out and 9 major components can be identified which are listed as below:

1. Inlet pipe
2. Horizontal channel
3. Vertical channel
4. Die pad area

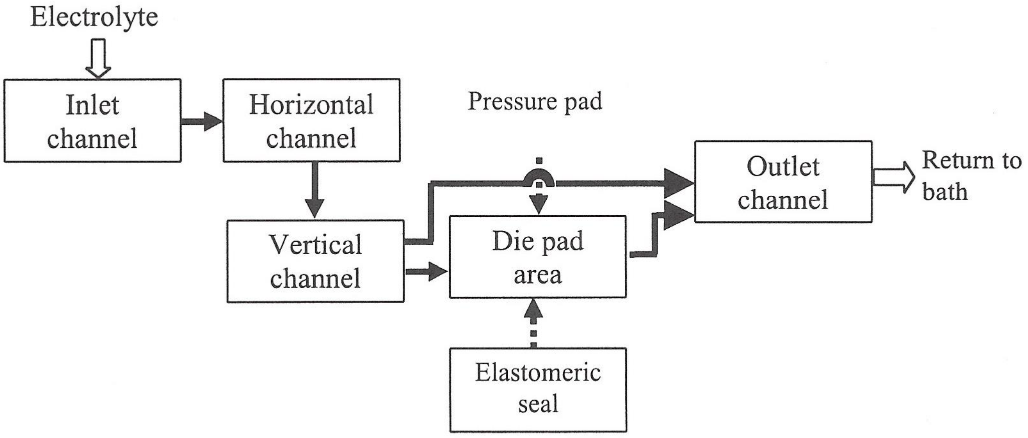
5. Outlet channel
6. Base body
7. Pressure pad
8. Window
9. Line seal

The construction of the assembly digraph showing how the components are assembled allows for evaluation of the interaction of the components with the numbers of assembly direction indicated on the arrows as shown in figure 2(a). This information is necessary as it forms the input value for the interaction matrix.

The physical decomposition also allows for the flow interaction to be clearly shown at components level and the location of the interface where leak can possibly take place shown as dashed lines in figure 2(b). This is to indicate that it is not the primary flow.



(a)



(b)

Figure 2 (a) assembly digraph and (b) the flow networks after physical decomposition

4.0 RESULTS

The interaction matrix $\mathbf{M_A}$ is constructed using the information from the assembly digraphs of figure 2(a) and is shown in figure 3. The matrix is generally sparse, as the assembly interaction between the components is limited. Similarly using the flow network chart the flow matrix $\mathbf{M_F}$ is constructed as shown in figure 4 which indicates that the flow matrix is also sparse with smaller flow interaction between the components as compared to the assembly interaction matrix. This is understandable, as the flow must occur within the assembly therefore the flow matrix must be a smaller matrix than the assembly matrix. The leakage matrix $\mathbf{M_L}$ is shown in figure 4(b) and it is the most sparse matrix as leakage in this particular case only occurs at the interface of two components within the larger flow network. Adding the flow matrix and the leakage matrix, the resulting matrix $\mathbf{M_{FL}}$ is similar to the flow matrix except that the values of the interaction at the two components interface where leak can occur are bigger f l_{34} = f l_{43}= 2. Arranging the assembly matrix and the flow-leakage matrix side by side results in the overall matrix $\mathbf{M}$ as shown in figure 5. This allows for direct inspection of the assembly and flow interaction of the components and comparison made for any modification or design changes.

$$\begin{array}{c|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & x & 1 & 1 & & & 1 & & & \\
2 & 1 & x & 1 & 1 & & 1 & & & \\
3 & 1 & 1 & x & 1 & & 1 & & & \\
4 & & 1 & 1 & x & & 1 & & & \\
5 & & & & & x & 1 & & & \\
6 & 1 & 1 & 1 & 1 & 1 & x & & 1 & \\
7 & & & & & & & x & & \\
8 & & & & & & 1 & & x & 1 \\
9 & & & & & & & & 1 & x
\end{array}$$

Figure 3 Assembly interaction matrix, $\mathbf{M_A}$

$$\begin{array}{c|ccccccccc}
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & x & 1 & 1 & & & & & & \\
2 & 1 & x & 1 & & 1 & & & & \\
3 & 1 & 1 & x & 1 & & & & & \\
4 & & & 1 & x & & 1 & & & \\
5 & & 1 & & & x & 1 & & & \\
6 & & & & 1 & 1 & x & & & \\
7 & & & & & & & x & & \\
8 & & & & & & & & x & \\
9 & & & & & & & & & x
\end{array}
\qquad
\begin{array}{ccccccccc}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
x & & & & & & & & \\
 & x & & & & & & & \\
 & & x & 1 & & & & & \\
 & & 1 & x & & & 1 & & 1 \\
 & & & & x & & & & \\
 & & & & & x & & & \\
 & & & 1 & & & x & & \\
 & & & & & & & x & \\
 & & & 1 & & & & & x
\end{array}$$

(a) (b)

Figure 4 (a) Flow interaction matrix $\mathbf{M_F}$ and (b) leakage incidence matrix $\mathbf{M_L}$

$$
\begin{array}{c|ccccccccc|ccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & x & 1 & 1 & & & 1 & & & & x & 1 & 1 & & & & & & \\
2 & 1 & x & 1 & 1 & & 1 & & & & 1 & x & 1 & & 1 & & & & \\
3 & 1 & 1 & x & 1 & & 1 & & & & 1 & 1 & x & 2 & & & & & \\
4 & & 1 & 1 & x & & 1 & & & & & & 2 & x & & 1 & 1 & & 1 \\
5 & & & & & x & 1 & & & & & 1 & & & x & 1 & & & \\
6 & 1 & 1 & 1 & 1 & 1 & x & & 1 & & & & & 1 & 1 & x & & & \\
7 & & & & & & & x & & & & & & 1 & & & x & & \\
8 & & & & & & 1 & & x & 1 & & & & & & & & x & \\
9 & & & & & & & & 1 & x & & & & 1 & & & & &
\end{array}
$$

Figure 5 Overall interaction matrix $M = [\mathbf{M_A}|\mathbf{M_{FL}}]$

$$
\begin{array}{c|ccccccccc|ccccccccc}
 & 1 & 2 & 3 & 4 & 6 & 5 & 8 & 9 & 7 & 1 & 2 & 3 & 4 & 6 & 5 & 8 & 9 & 7 \\
\hline
1 & x & 1 & 1 & & 1 & & & & & x & 1 & 1 & & & & & & \\
2 & 1 & x & 1 & 1 & 1 & 1 & & & & 1 & x & 1 & & & 1 & & & \\
3 & 1 & 1 & x & 1 & 1 & & & & & 1 & 1 & x & 2 & & & & & \\
4 & & 1 & 1 & x & 1 & & & & & & & 2 & x & 1 & & 1 & 1 & \\
6 & 1 & 1 & 1 & 1 & x & 1 & 1 & & & & & & 1 & x & 1 & & & \\
5 & & 1 & & & 1 & x & & & & & 1 & & & 1 & x & & & \\
8 & & & & & 1 & & x & 1 & & & & & 1 & & & x & & \\
9 & & & & & & & 1 & x & & & & & 1 & & & & x & \\
7 & & & & & & & & & x & & & & & & & & & x
\end{array}
$$

Figure 6 The overall interaction matrix after clustering

4.1 Clustering and Module Identification

The overall matrix is then subjected to clustering by reordering the matrix using the extended triangularization algorithm [13]. The final overall matrix is shown in figure 6. There are two sets of clusters identified which can be candidates for module development, which are:

Assembly criteria	**Flow criteria**
Module 1a (assembly): {1,2,3,4,6}	Module 1b (flow-leakage): {1,2,3,4}
Module 2a (assembly): {8,9}	Module 2b (flow-leakage): {5,6}

Module 1a and module 1b consist of the same component thus can be accepted as one module. The interaction density of module 1a is 4/6, which is lower than the interaction density for module 1b, which is 6/6, which is a full matrix. This indicates the flow interaction is stronger than the assembly interaction in this module.

Module 2a consists of the components 5,6 and 8 and the cluster is different from the module 2b, which consists of components 4,5 and 6. The interaction density for both modules 2a and 2b is 4/6. The decision to select which module is more suitable must now rely on the judgement of the designer.

5.0 CONCLUSIONS

In this paper, the matrix representation of the modularity problem is presented by taking into account the interaction matrix and the flow of fluid within the structure. The fluid flow interaction is used to map the leak locations and to identify and prioritize those areas as a good candidate for module development. The modules are identified from the interaction matrix developed from the product decomposition carried out on the initial design. The identification was carried out using the extended triangularization algorithm. The approach highlights the designer of the possibility of eliminating leak and seal problems by adopting integral design. The most feasible module is selected on the basis of interaction density.

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