Failure Analysis of Mechanical Systems Based on Function-cum-Structure Approach

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Abstract: This paper suggests failure analysis of mechanical systems using function-cum-structure approach. Operational parameters of system function are identified and their relationships are developed. The predicates, which comprise of components of the system and their properties as their attributes, i.e., type of connectivity (fixed or sliding contact) and functions (transmit torque, and transmit force etc.) represent the facts. The facts are modelled in terms of functional-cum-structure graph. By analysing interaction of a failure function i.e., function of a failed component in the graph with other functions, the failure cause-function is identified. The problem can either be solved by removing the cause-functions or by modifying the failure function. A critical function is also identified from function set on the basis of importance of a function. Appropriate parameters for in-situ design provision for condition monitoring of the system are also identified. Various steps of the methodology are illustrated by means of an example.

Key Words: Failure Analysis, Mechanical Systems, Design for Maintenance, Condition Monitoring, Function and Structure Analysis

1. Introduction

A designer is conversant with functional requirements of a system and these are derived from its specification. These functional requirements are crucial in the development of a product. Suh [1,2] has developed axiomatic design theory based on function and structure of the system. Krischman and Fadel [3] have discussed the use of function for development of product design in systematic design. Pahl and Beitz [4], Ullman [5], Kim and Suh [6] and Harutunin et al. [7] have used function and structure in the design and development of product of a system. Umeda et al. [8], Umeda and Tomiyama [9], Hodges [10], Schmekel [11] and Qian and Gero [12] have used knowledge of structure and function for improving the existing design, obtaining innovative design solution and evaluation of design concepts. Moreover, structure and function knowledge has also been used for fault diagnosing of systems. Milne [13] has used topological representation of components at various hierarchies for obtaining complete knowledge of the system for strategic diagnosis. Ishida et al. [14], Biswas et al. [15], Padalker et al. [16] and Tazafestas

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M. F. Wani and O. P. Gandhi

[17] have developed procedure for fault diagnosis on the basis of structure and function knowledge of the system. Hawkins and Wollens [18], Bellinger [19] and Kapur [20] have used Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) are used for improving the system reliability and the safety based on function and structure approach at design stage. FMEA is useful for identifying critical components and assemblies considering their failure effects. The use of FTA is restricted because each fault tree is specific only to the identification of system elements and events that lead to one desired event. Yoshikakwa [21] has developed a methodology for the evaluation of reliability of mechanical systems based on structure properties. In this study, fixed and assembly branches have not been considered, as these do not contribute in geometric motion. Bradshaw and Young [22] and Sanseverino and Cascio [23] have used the knowledge of function and structure for predicting behaviour of the system at design stage. Chittaro and Ranon [24], Chittaro et al. [25], Chittaro [26], Nakakuki et al. [27], Davis [28], Dekleer and Williams [29], Genesereth [30], and Dvorak and Kuipers [31] have proposed methodologies for the diagnosis of mainly electrical and electronic systems using structure and function of the system. Keuneke [32] has proposed that functional knowledge can be more useful to understand the behaviour of a system than physical knowledge.

It is evident, from above that researcher have made numerous attempts to use knowledge of structure and function for diagnosing the system failures and these have been mainly applied to electrical and electronic systems. Moreover, in these, emphasis has been more on structure than function. These measures often provide not so complete solutions to the failure of components and in many instances a larger problem within the system goes unchecked. The reason is that the failed components in many cases are only a symptom of deeper malfunction. Therefore, an emphasis on the component failure tends to dilute attention away from any attempts at pinpointing the exact root causes of a failure. The components in a given system are expected to perform appropriate function(s) to attain desired output. The output of a given system depends upon how beset individual components perform. The malfunctioning of a system is attributed to improper functional interaction between its components and sub-systems. This means a function specifies intended behaviour of an individual components or sub-system. Moreover, the structure of a system is important for understanding the connectivity of its components and subsystems. Therefore, both function and structure are the key entities in failure consideration as a whole. However, to analyse the failure causes of mechanical systems it is indispensable to consider the functional and structural interactions of the system at the design stage with more emphasis on function. This exercise aims at minimising operational failures and can be implemented at design stage and in particular, at its conceptual stage if appropriate procedures based on this approach are made available to a designer.

In order to minimise the system failures of mechanical systems, a procedure based on function-cum-structure approach is proposed in this paper. This is obtained by identifying the relationship between various functions in a system on the basis of its operational parameters. The functional and structural relationships are modelled in terms of a function-cum-structure graph. The interaction between various functions helps in identifying the cause of a failure in the system in terms of a cause-function. A critical function of the system is also identified on the basis of its importance and appropriate condition monitoring parameters are proposed on the basis of parameters of the functions.
2. Structure and Function Representation

Structural knowledge means information about the components, assemblies or sub-systems of a system and their connectivity. The connectivity implies connection between the components, assemblies or sub-systems of the system e.g., a sliding contact between two mating gears, bearing and shaft at the component level, pipe joint between pump and reservoir at the sub-system level, etc. Functional knowledge means how the components, assemblies or sub-systems interact with one another to achieve a desired output. A function interacts through its operational parameters and these are specified by their nomenclature such as force, torque, speed etc. and their value. The functions e.g., transmit torque, support load, develop flow have parameters force and diameter, force and volume respectively.

The different functions which are related to this analysis are classified under the following categories:

Overall function: Function which represents the desired output of the system is called overall function.

Primary function: The basic important action performed by the function is called the primary function.

Secondary function: A secondary function is other useful function performed by the component/assembly

It has already been discussed that function and structure plays a significant role in the failure analysis of a system. An appropriate representation of structure and function is therefore, required to carry out this. This is discussed considering a hypothetical example of a system whose structure and function are given in Table 1. In this Table, C_1, C_2, C_3 and C_4 represent four components of the hypothetical system. F_{11}, F_{21}, F_{31} and F_{41} are the primary functions performed by C_1, C_2, C_3 and C_4. F_{12} and F_{22} are the secondary functions performed by C_1 and C_2. The components C_3 and C_4, however, have no secondary functions.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Component</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Component (C_1)</td>
<td>Primary function (F_{11}), Secondary function (F_{12})</td>
</tr>
<tr>
<td>2</td>
<td>Component (C_2)</td>
<td>Primary function (F_{21}), Secondary function (F_{22})</td>
</tr>
<tr>
<td>3</td>
<td>Component (C_3)</td>
<td>Primary function (F_{31})</td>
</tr>
<tr>
<td>4</td>
<td>Component (C_4)</td>
<td>Primary function (F_{41})</td>
</tr>
</tbody>
</table>

Characteristics of a component, connectivity and functions are called attributes and are represented by a predicate. A predicate as defined in the object oriented programming in artificial intelligence refers to either properties or relations. A predicate name is followed by attributes as arguments. Predicate for a component is represented as:

*Component (attributes)*

For component C_1 of the hypothetical system, its attributes are sliding and fixed contact, and functions F_{11} and F_{12} and these are its arguments. Its predicate is therefore, represented as:

C_1 (Sliding contact, fixed contact, F_{11}, F_{12})

Similarly, the other predicates for the hypothetical system are:

C_2 (Fixed contact, F_{21}, F_{22})
C₃ (Sliding contact, fixed contact, F₃₁)
C₄ (Fixed contact, F₄₁)

These predicates represent facts of the hypothetical system. As already discussed the function and structural knowledge form important entities in the failure cause analysis. This is further substantiated in the following.

2.1 Function-cum-Structure Graph

The relationships between the predicates of components of a system are modelled in terms of a graph and this is called Function-cum-Structure Graph. For the hypothetical system (Table 1), this is shown in Fig.1. The nodes C₁, C₂, C₃ and C₄ in the graph represent the components of the system and the connections between these nodes represent their connectivity. A connection in dash line shows a sliding contact, while a solid line shows a fixed contact. The sub-nodes of a node in the graph represent various functions of the component representing the node and the connections among the sub-nodes represent the functional interaction/relationship.

Fig.1: Function-cum-structure Graph of a Hypothetical System

The function-cum-structure graph of a system gives a visual picture of a network of relationship between the functional and structural characteristics of the system. This helps to understand the failure cause-function. This means if a failure of the system is reported, then cause can be obtained by analysing the functional interaction along with the structure using the function-cum-structure graph. The failure-cause-function is obtained from function-cum structure-graph, and this is the function of the adjacent component, which causes the failure in the failed component. For example, if component C₃ fails then cause function is obtained from F₁₁ or F₁₄. F₁₁ and F₁₄ are related to the function (F₃₁) of failed component C₃. These relationships (functional and structural) assist in deriving the rules- simulated (i.e., directly derived from facts) and inference (i.e., indirectly derived from facts) for obtaining the failure cause function. The logic for derivation of simulated rule is:

IF
A ∩ B = C
THEN B ∩ A = C

The logic for derivation of inference rule is:
IF
A ∩ B = C,
B ∩ C = C
C ∩ D = C
THEN A ∩ D = C

For the system Fig. 1, rules are derived on the basis of above logic and are as:

Rule 1 (simulated rule)

IF

(C₁ (sliding-relation C₃)) and
(F₁₁ (function (C₁))) and
(F₃₁ (function (C₃))) and
(F₁₁ (related F₃₁))

THEN

F₁₁ (cause-function F₃₁)

Rule 2 (inference rule)

IF

(C₁ (sliding-relation C₃)) and
(F₁₁ (function (C₁))) and
(F₃₁ (function (C₃))) and
(F₁₁ (related F₃₁)) and
(C₃ (fixed-relation C₄)) and
(F₄₁ (function (C₄))

THEN

F₁₁ (cause-function F₄₁)

From above it is obvious that the cause-function is obtained on the basis of functional interaction from function-cum-structure graph. This failure is removed either by increasing the capacity of the component or by redesigning the cause-function. It is possible, to identify the critical function and also the parameters for condition monitoring. Critical function is obtained on the basis of role of a function in achieving the desired output/objective. Design parameters of function can help the designer to build-in condition monitoring provisions in the system for failure diagnosis.

3. Steps of Failure Cause Analysis

The above methodology is used for failure analysis of mechanical systems. The step by step procedure is given as:

1. Define the system and identify its functions and components.
2. List characteristics of its components in predicate form. Refer Sec. 2
3. Develop the function-cum-structure graph of the system. This is on the lines of Fig. 1, and analyse the functional interaction of failure function in the immediate neighbourhood to determine the cause-function (Refer Sec. 2.1).
4. Suggest the minimising of the failures either by modifying the failed-function or removing the cause-function. (Refer Sec. 2.1). Carry out also the design modifications based on design specifications of the functions.
5. Identify the critical function of the system as discussed in Sec. 2.1.
6. Suggest also the condition-monitoring provisions for the system.

4. Illustration

The failure analysis methodology is explained with the help of the following example of a Gear pump of a Hydraulic System. The steps are as follows:
Step 1:

An example of a gear pump of a hydraulic system is used to illustrate the procedure. This example is considered to develop the failure cause analysis methodology using function-cum-structure graph. The gear pump consists of two spur gears supported on two shafts enclosed in closely fitted housing. As the gears rotate, fluid is picked by the enmeshing action of the gear teeth from the reservoir through inlet port. The fluid is displaced as the teeth mesh at the outlet side and is forced out of the pump through outlet port into the hydraulic system.

The functions and their relationships for the gear pump are shown in Table 2. In this table, the second, third and fourth columns show components, functions and their parameters respectively. The relationship between functions is shown in the last column.

### Table 2: Gear Pump Functions and their Relationship

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Component</th>
<th>Functions</th>
<th>Parameters</th>
<th>Relationship between functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Driving gear</td>
<td>Displace fluid ($F_{11}$)</td>
<td>Volume, Force and diameter, Speed</td>
<td>$F_{31}$, $F_{21}$, $F_{32}$, $F_{33}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit torque ($F_{12}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Develop rotation ($F_{13}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Driving shaft</td>
<td>Transmit power ($F_{21}$)</td>
<td>Force, diameter and speed, Force</td>
<td>$F_{31}$, $F_{61}$ and $F_{92}$, $F_{33}$ and $F_{62}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support load ($F_{22}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Driven gear</td>
<td>Displace fluid ($F_{31}$)</td>
<td>Volume</td>
<td>$F_{11}$, $F_{41}$ and $F_{12}$, $F_{13}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit torque ($F_{32}$)</td>
<td>Force and diameter, Speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Develop rotation ($F_{33}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Driven shaft</td>
<td>Transmit power ($F_{41}$)</td>
<td>Force, diameter and speed, Force</td>
<td>$F_{21}$, $F_{71}$ and $F_{91}$, $F_{22}$, $F_{62}$ and $F_{102}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support load ($F_{42}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Front Bearing (driving shaft)</td>
<td>Support radial load ($F_{51}$)</td>
<td>Force</td>
<td>$F_{21}$ and $F_{92}$, $F_{22}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support thrust load ($F_{52}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Rear Bearing (driving shaft)</td>
<td>Support radial load ($F_{61}$)</td>
<td>Force</td>
<td>$F_{21}$, $F_{22}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support thrust load ($F_{62}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Front Bearing (driven shaft)</td>
<td>Support radial load ($F_{71}$)</td>
<td>Force</td>
<td>$F_{41}$ and $F_{102}$, $F_{42}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support thrust load ($F_{72}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Rear Bearing (driven shaft)</td>
<td>Support radial load ($F_{81}$)</td>
<td>Force</td>
<td>$F_{41}$, $F_{42}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Support thrust load ($F_{82}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Seal (driving shaft)</td>
<td>Avoid leakage ($F_{91}$)</td>
<td>Volume</td>
<td>- $F_{31}$ and $F_{21}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit force ($F_{92}$)</td>
<td>Force</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Seal (driven shaft)</td>
<td>Avoid leakage ($F_{101}$)</td>
<td>Volume</td>
<td>- $F_{71}$ and $F_{42}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmit force ($F_{102}$)</td>
<td>Force</td>
<td></td>
</tr>
</tbody>
</table>

The first function corresponding to each component under column three is the primary function and other functions in the column are secondary functions. It may be mentioned again that the functions of components bolt, pump housing, inlet port and outlet port have not been included as these are assembly functions and do not significantly contribute in reliability of gear pump.

The overall function of the gear pump is to develop flow. The primary and secondary functions which assist in accomplishing this are: displace fluid, develop rotation, transmit power, transmit torque, develop rotation, support load (radial and thrust), transmit force, provide support, attach parts, avoid leakage, facilitate flow and enclose space. The
functions-attach parts, provide support, enclose space and facilitate flow are the functions which do not contribute in geometric motion of components. These are assembly functions and do not contribute significantly in reliability of the gear pump [21]. Therefore, the functions displace fluid, transmit power, transmit torque, support load (radial and thrust), transmit force and avoid leakage performed by gears, shafts, bearings and seals are to be considered in the failure analysis of gear pump.

**Step2:**

The components i.e., gears, bearings shafts and seals and their attributes i.e., connectivity and functions (sliding contact, fixed contact, transmit power, displace fluid, transmit force etc.) form the data of the gear pump system. These are represented by predicates as:

- \( C_1 \) (sliding contact, fixed contact, \( F_{11}, F_{12}, F_{13} \))
- \( C_2 \) (sliding contact, fixed contact, \( F_{21}, F_{22}, F_{23} \))
- \( C_6 \) (sliding contact, \( F_{61}, F_{62} \))
- \( C_9 \) (sliding contact, \( F_{91}, F_{92} \)).

The parameters of transmit power, transmit torque, support load, transmit force and provide rotation are force, gear diameter and speed, force and gear diameter, force and speed. Therefore, the parameters (force and gear diameter) of transmit torque and parameter (force) of support radial load both are related through force and is represented as:

\[
\text{Transmit torque} = \text{force and gear diameter} \times \text{R force (support radial load)}
\]  

These parameters of functions of gear, shaft, bearing and seal form the parametric network based on functional relationships between these functions.

**Step3:**

Function and structure and their relationships of the gear pump is represented by a functional-cum-structure graph using the above predicates and is shown in Fig.2. The nodes 1 to 10 in the figure, represent the components of the gear pump and the connections between these represent their connectivity. A connection with a dash line shows a sliding contact while a solid line shows a fixed contact. For example, nodes 1 and 2 represent driving gear and shaft and the connection between these nodes represents fixed contact while the dotted connection between the nodes 1 and 3 represents the sliding contact between the two gears. In Fig.8, the sub-nodes represent the functions of these components and the connections between these sub-nodes represent the functional interaction. For example, the sub-nodes \( F_{13} \) and \( F_{21} \) of nodes 1 and 2 represent the function transmit torque and transmit power and the connections between these sub-nodes represent their functional interaction. Similarly, the other sub-nodes represent the functions (\( F_{11} \) to \( F_{102} \)) of components- gears, shafts, bearings and seals i.e., nodes 1 to 10 and the connections between these sub-nodes represent their functional interaction. If the two nodes and their sub-nodes are connected directly, then direct functional interaction exists between the components represented by these nodes. It is evident that direct functional interaction exists between driving and driven gear (i.e., sub-nodes \( F_{11}, F_{12}, F_{13}, F_{31}, F_{32} \) and \( F_{33} \)). Similarly, direct functional interaction exists between driving gear and driving shaft (sub-nodes \( F_{12} \) and \( F_{21} \)); driving shaft, front bearing and seal(sub-nodes \( F_{21}, F_{22}, F_{31}, F_{32}, F_{91} \) and \( F_{92} \)); rear bearing and shaft (sub-nodes \( F_{23}, F_{22}, F_{61} \) and \( F_{62} \)), driven gear and driven shaft
The primary function of driving and driven gear (F_{11} and F_{31}) has no relationship with any of the primary/secondary functions of any other components. This means there is no influence of function displaces fluid upon any other function or vice-versa. The parameters of F_{11} or F_{31} are gear diameter and width of teeth. Hence, the function F_{11} or F_{31} will experience a change through geometric variation of either driving/driven gear. This means gear will not be able to displace fluid fully even if the torque is transmitted by the gear. Also, there is no influence of this function upon any primary or secondary function. However, the influence of F_{21} upon F_{12} may cause only performance degradation of gear, as the function F_{12} is only a secondary function of the gear.

The direct interactions between primary and secondary functions F_{12}, F_{21}, F_{51}, F_{92}, and F_{61} of driving gear and shaft, bearings and seal indicate that these are multi-cause-function failure. This means, if the shaft is malfunctioning, then the cause-functions can be F_{12}, F_{51}, F_{92} and F_{61}. Similarly, if bearing is malfunctioning, the likely cause-functions are F_{21} and F_{92} and if the seal is malfunctioning, the cause-functions are F_{21} and F_{41}. There is also a loop formed between the sub-nodes F_{21}, F_{51} and F_{92} of nodes 2, 5 and 9 and the fault can propagate through F_{21}, F_{51} and F_{92} or through F_{92}, F_{21} and F_{51}. In case, the rear bearing is malfunctioning, the cause-function is F_{21} or F_{22}. The same is true for driven gear and shaft, bearing (front and rear) and seal, represented by the nodes 3, 4, 8, 7 and 10.

**Step 4:**

The functional interaction between the bearing, seal and shaft is between support load (radial and thrust) and transmit torque. This means if the failure is due to torsional vibration, the bearing is incapable of handling the increased radial or thrust load. Therefore, either the bearing is redesigned from strength point of view or the source of shaft vibrations be removed by redesigning. Similarly, the failure function of seals (i.e., nodes 9 and 10), is either due to the overload of bearing or torsional vibrations of shaft, as indicated by functional interaction of F_{92}, F_{51} and F_{21}. This means function failure of seal is also a multi-cause-function.
The sub-nodes 2, 4, 7 and 9 of the nodes 1, 2, 3 and 4 in Fig.2 indicate the functional interaction between gears and shafts (driving/driven). It is obvious that if the gears fail to transmit the torque, the volume displaced by the gear remains unchanged. However, the failure is influenced by force and is indicated by the gear vibration and not in terms of volume of fluid flowing out from the pump. This problem can be minimised by redesigning gear for a higher load and not for the higher volume capacity.

Design specifications are obtained from the physical equations representing relationships between the parameters of the function and structure. For example, the design specifications of the function displace fluid are obtained from volumetric displacement relation i.e.,

\[
V_D = \frac{\Pi (D_o^2 - D_i^2)w_t}{4}
\]

where, \(V_D\) is volumetric displacement, \(D_o\), \(D_i\) and \(w_t\) are outer and inner diameter and width of gear teeth. Therefore, specifications of the function displace fluid are gear diameter and width of tooth profile. A designer is well conversant with the physical equations which are used for analysis at design stage. Similarly, the specification of transmit power, transmit torque, transmit force, support load, develop rotation and avoid leakage are force, gear diameter and gear speed, force and diameter, force, speed and volume.

Step 5:
The most critical function is displace fluid or develop vacuum because if the fluid is not displaced, there will be no flow possible. Two gears- driving and driven of the gear pump, perform this function by the action of gear teeth enmeshing.

Step 6:
The parameters of functions \(F_{12}, F_{21}, F_{51}\) are force and torque, which can cause vibration, noise and misalignment etc. Where as, the parameter of the function \(F_{11}\) and \(F_{31}\) is volume. Volume does not contribute to noise and vibration of the gear pump. This means noise and vibration measurement can be monitoring the behaviour of shaft and bearing, and flow measurement can be used for monitoring the behaviour of gear. Therefore, the designer is able to build-in the provisions of condition monitoring of the system right from the conceptual design stage.

5. Potential of Failure Analysis Methodology

The functional-cum-structure interaction between the components as is discussed above assists a designer or practising engineers in determining the failure cause function of the system and can be implemented at the design stage for development of failure free mechanical systems. Additionally, some of the failure experienced during prototype testing could be reanalysed using the suggested failure cause methodology to minimise the likely failures of the system. Therefore, the suggested methodology is useful in enhancing the reliability of the system through design modifications based on the failure cause-function and is more so in case of adaptive designs.

The relationship between the design specification of the component function is obtained from the equations available in literature (e.g., given in textbooks and handbooks). For the gear pump, the design specifications of the bearing- for the function support load are determined from PV relation:
M. F. Wani and O. P. Gandhi

\[ PV = \frac{F_R}{b \times D_1} \times \frac{\Pi \times D \times N}{60} \]  

(3)

where, PV is heat generated Watt/m², \( F_R \) is the radial load acting on the bearing, \( b \) and \( D_1 \) are the length and diameter of the bearing, \( D_s \) diameter of shaft and \( N \) the speed of shaft. If the failure cause function is support load, the length or diameter of the bearing can be increased to withstand the radial load. Similarly, for the shaft and the seal, the design specifications of failure cause-function can be determined from the appropriate equations of the shaft and seal.

Functional analysis using function-cum-structure graph of the system helps in determining the critical functions of the system at the system conceptual design stage. The functional analysis of the system and components under failure analysis can also assist a designer in incorporating the condition monitoring provisions in the system. This is possible by considering the parameters that are used for monitoring the function. For the gear pump, the volume flow of the gear is more suitable to measure the performance of the gear compared to bearing or shaft, as the volume flow is directly related to primary function of the gear. However, the vibration is more suitable to measure the performance of the shaft and bearing compared to gear in this case. In this way, a designer can select performance-measuring parameters on the basis of the function-cum-structure at design stage.

The propagation of fault will also depend upon the type of connectivity and its cardinality, i.e., denoting the number. Fault propagation is more severe in cases of direct sliding contact as compared to a fixed contact between two components. A sliding contact loop formed between seal, bearing and shaft indicates this. There exist direct sliding between these components i.e., with cardinality equal to one. If cardinality is more than one, e.g., two, the failure propagation is less severe as compared to cardinality equal to one. For example, the failure propagation between node 1 (driving gear) through node 6 (rear bearing of driving shaft) is less severe, as the cardinality is equal to two. In the same path, the failure propagation may be severe from node 1 (driving gear) to node 2 (driving shaft) having cardinality equal to 1.

It is possible to indicate qualitative time period (fast, medium and slow) between the fail function and cause-function. For example, the failure propagation from driving gear to driven gear is fast due to direct functional interaction. This is indicated by the direct sliding edge between the components and with the cardinality of 1. The failure propagation from node 3 (driven gear) to node 6 (rear bearing) is through a medium time period, as the cardinality is 3. The failure propagation from node 6 to node 10 is through slow time period as the cardinality is 6. The developed procedure for failure cause analysis of mechanical systems is applicable to operating system as well.

6. Conclusion

Failure cause analysis methodology of the mechanical systems is suggested based on function-cum-structure graph model of the system. The functional interaction between fail functions and other functions is used to obtain the failure cause-function. This analysis helps a designer to predict the causes of unavoidable failures at conceptual design stage based on functional relationship in case of adaptive designs. This methodology helps in identifying the critical function based on functional analysis from the set of functions. This analysis also helps in incorporating condition monitoring facility in the system at design.
stage. The suggested methodology therefore, leads to the design and development of a reliable, maintainable and safe mechanical system.

References


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