To improve the reliability of any system, many tools have been introduced which will increase its possibility to satisfy the application requirements. In this work, an attempt has been made to carry out the Fault Tree Analysis (FTA) of Magneto-Rheological (MR) brake to ensure its effectiveness. The Fault Tree analysis is a logical, graphical diagram that describes failure modes and causes. The FTA diagram graphically shows all failures for a system, subsystem, assembly, Printed Circuit Board (PCB), or module. The output from the FTA provides a better understanding of the causes that can lead to a failure mode.

Keywords: Magneto-Rheological (MR) Brake, Reliability, Fault Tree Analysis (FTA), Failure modes and causes, Recommendations

INTRODUCTION
Magneto rheological (MR) brake is type of brake, which works on the principle of properties of MR fluid (Olabi and Grunwald (2007; and Kerem Karakoc et al., 2008). When magnetic field is applied viscosity of fluid suddenly increases which resists the motion of rotary disc and hence the wheel (Sukhwani and Hirani, 2008). Reliability is the probability of a device performing its purpose adequately for the period intended under the given operating conditions. Fault tree analysis is useful tool in performing a system analysis (Srinath, 2002; and Mark Levin and Ted Kalal, 2003).

Fault Tree Analysis (FTA) is a graphical design technique that is an alternative to reliability block diagrams (Elmer and Lewis, 1987). It is broader in scope than a reliability block diagram and differs from reliability block diagrams in several respects.

All failures are faults, but not all faults may be considered failures. The qualitative analysis consists of identifying the various combinations of events that will cause the top event to occur. This may be followed by a quantitative analysis.
to estimate the probability of occurrence of the top event (Charles Ebeling, 1997).

**FAULT TREE ANALYSES (FTA)**

**Steps to FTA**
There are four major steps to a fault tree analysis:

- Define the system, its boundaries, and the top event.
- Construct the fault tree, which symbolically represents the system and its relevant events.
- Perform a qualitative evaluation by identifying those combinations of events that will cause the top event.
- Perform a quantitative evaluation by assigning failure probabilities or unavailabilities to the basic events and computing the probability of the top event (Charles Ebeling, 1997).

**Fault Tree Construction**
The FTA is done by brainstorming process. In brainstorming, it is agreed that there are no bad ideas. This way everyone feels comfortable in submitting his or her thoughts. Begin by having everyone write his or her two to three ideas on Post-its. When the team is satisfied that everyone has recorded his or her ideas on Post-its, then FTA process is started.

Place the top-level (system-level) failure mode on top of the fault tree. Next, begin identifying failure causes associated with the above failure mode. You can go down several levels associating a second-, third-, and possibly fourth-level failure cause that is associated with the above failure mode. Place each subsequent failure cause beneath the previous failure cause using the Post-its statements. To get the next lower level of failure cause, ask the question, what event would have to occur to cause the higher-level failure? Usually, two to three levels of extraction in failure causes are adequate. The goal is not to drive to the root cause, but to bring to the surface failure causes in the design cycle that cannot be tolerated. Leave enough room between the levels for interconnecting lines and logic gates. Continue to the process till the desired level of abstraction has been reached.

In building the FTA, you eventually reach a point where a decision needs to be made. The decision is that you have reached a sufficient level of failure cause description to evaluate its effect on the design. These failure causes are circled. However, you may reach a point where you cannot go further because the team lacks the expertise, knowledge or understanding of the failure cause. All the lower level failure causes on FTA should be either circles or diamonds. At this point, you are done with the fault tree analysis (Mark Levin and Ted Kalal, 2003).

The FTA uses standard logic symbols shown in Table 1, commonly found in flowcharting for process control, quality control, safety engineering, and so on, to tie together the sequence of event.

**Fault Classification**
The faults can be classified into following types:

- **Primary Fault:** Primary faults are caused by defective design, manufacture, or construction and are therefore most closely correlated to wear-in failure.
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><img src="image" alt="Rectangle" /></td>
<td>Rectangle</td>
<td>Fault event; it is usually result of the logical combination of other event</td>
</tr>
<tr>
<td>2.</td>
<td><img src="image" alt="Circle" /></td>
<td>Circle</td>
<td>Independent primary fault event</td>
</tr>
<tr>
<td>3.</td>
<td><img src="image" alt="Diamond" /></td>
<td>Diamond</td>
<td>Fault event not fully developed, for its causes are not known; it is only as assumed primary fault event.</td>
</tr>
<tr>
<td>4.</td>
<td><img src="image" alt="House" /></td>
<td>House</td>
<td>Normally occurring basic event; It is not a fault event.</td>
</tr>
<tr>
<td>5.</td>
<td><img src="image" alt="OR Gate" /></td>
<td>OR Gate</td>
<td>The union operations of events; i.e. the output event occurs if one or more of the inputs occur.</td>
</tr>
<tr>
<td>6.</td>
<td><img src="image" alt="AND Gate" /></td>
<td>AND Gate</td>
<td>The intersection operation of events; i.e., the output event occurs if and only if all the inputs occur.</td>
</tr>
<tr>
<td>7.</td>
<td><img src="image" alt="INHIBIT Gate" /></td>
<td>INHIBIT Gate</td>
<td>Output exists when X exists and condition A is present; this gate functions somewhat like an AND gate and is used for a secondary fault event X.</td>
</tr>
<tr>
<td>8.</td>
<td><img src="image" alt="Triangle-in" /></td>
<td>Triangle-in</td>
<td>Triangle symbols provide a tool to avoid repeating sections of a fault tree or to transfer the tree construction from one sheet to the next. The triangle-in appears at the bottom of a tree and represents the branch of the tree shown someplace else.</td>
</tr>
<tr>
<td>9.</td>
<td><img src="image" alt="Triangle-out" /></td>
<td>Triangle-out</td>
<td>The triangle-out appears at the top of a tree and denotes that the tree A is sub-tree to one shown someplace else.</td>
</tr>
</tbody>
</table>

*Source: Struss and Fraracci (2010)*
Secondary Fault: Secondary faults occur in an environment or under loading for which the component is not qualified.

Command Fault: Command faults must look beyond the component failure to find the source of the erroneous command.

Passive Faults: Passive faults may usually be thought of as a mechanism for transmitting the output of one active component to the input of another.

Active Fault: Active faults contribute to the system function in a dynamic manner, altering in some way the system's behavior (Struss and Fraracci, 2010).

Fault Tree Evaluation by Cut-Set

The direct evaluation procedure helps us to assess fault trees with relatively few branches and basic events. When larger trees are considered, both evaluation and interpretation of the results become more difficult and digital computer codes are invariably employed. Such codes are usually formulated in terms of the minimum cut-set methodology (Struss and Fraracci, 2010). Basically fault tree evaluation cut-set is commonly divided into qualitative and quantitative analysis. In qualitative analysis information about the logical structure of the tree is used to locate weak points and evaluate and improve system design. In quantitative analysis the same objectives are taken further by studying the probabilities of component failures in relation to system design (Struss and Fraracci, 2010).

Qualitative Analysis

There are three steps to calculating the qualitative analysis. These steps are as follows:

Minimum Cut-Set Formulation: A minimum cut-set is defined as the smallest combination of primary failures which, if they all occur, will cause the top event to occur. It is a combination (i.e., intersection) of primary failures sufficient to cause the top event. It is the smallest combination in that all the failures must take place for the top event to occur. If even one of the failures in the minimum cut-set does not happen, the top event will not take place (Struss and Fraracci, 2010).

Cut-Set Determination: In order to utilize the cut-set formulations, it must express the top event as the union of minimum cut sets. For larger trees, containing perhaps 20 or more primary failures, this procedure becomes intractable, and must resort to digital computer evaluation. Even then the task may be prodigious, for a larger tree with a great deal of redundancy may have a million or more minimum cut-sets (Struss and Fraracci, 2010).

Cut-Set Interpretation: Knowing the minimum cut sets for a particular fault tree can provide valuable insight concerning weak points of complex systems, even when it is not possible to calculate the probability that either a particular cut set or the top event will occur. Three qualitative considerations, in particular, may be very useful: the ranking of the minimum cut sets by the number of primary failures required the importance of particular component failures to the occurrence of the minimum cut sets, and the susceptibility of particular cut sets to common-mode failures (Struss and Fraracci, 2010; and Tang Tingl et al., 2011).

Fault Tree Analysis of MR Brake

Fault Tree Analysis (FTA) is used for finding top level event like ‘brake is not actuating’ and
Figure 1: FTA 1

Brake is not actuating

OR

Open circuit

Brake switch remains open

Switch spring broken/damaged

High current

Deficiencies in manufacturing process

Thickening of MRF

Prolonged use

Incorrect formulation of MRF

Inappropriate selection of element of MRF

Inappropriate quantity (volume %) of element of MRF

Degradation of MRF

Damaged conductor

Brake terminal connection improper

Faulty clamping

Corroded terminal

Faulty relay

Charging system malfunctioning

Lack of maintenance (failure to top up)

Self discharged

Use of dilute acid

Full discharged battery

Insufficient charge in battery

Insufficient power o/s from battery

Degradation of MRF

This page
Figure 2: FTA 2

Brake Inadequate

OR

Leakage of MR Fluid

OR

Degradation of MR Fluid

OR

Increased Gap Size

OR

Weak magnetic field

OR

Improper Mounting Of seal

OR

Breakage Of seal

OR

Cracked Casing

OR

Dimensional Inaccuracy of mating parts

OR

Less no. of conductor in electromagnet

OR

Use of MRF of low magnetic saturation

OR

Low level current supply

OR

Use of incorrect formulation of MRF

OR

Discharged battery

OR

High resistance conductor

OR

Use of improper material

OR

Heavy (uneven) Load

OR

Poor quality material

OR

Prolonged use

OR

Manufacturing error

OR

Usage of non calibrated measuring instruments

OR

Charging system malfunctioning

OR

Lack of maintenance

OR

Faulty alternator

OR

Sort/open circuit in charging system

OR

Faulty voltage regulator
Figure 2 (Cont.)

Degradation of MR Fluid

OR

Contamination

Thinning of MR Fluid

Incorrect formulation of MR Fluid

Manufacturing/Assembly error

Deflection of disc, stator or casing

OR

Improper heat dissipation

OR

Unwanted reaction with contacting surface

Mixing with foreign particles

OR

Manufacturing error

Use of non calibrated measuring instruments

OR

Inappropriate selection of elements of MR Fluid

Inappropriate quantity (volume %) of elements of MR Fluid

External shock/vibrations

Bearing Failure
Figure 3: FTA 3-Simplified Tree of FTA 1
Figure 4: FTA 4-Simplified Tree of FTA 2

- T2
  - OR
    - A1
    - OR
      - B1
        - C1
        - C2
        - C5
    - B2
    - B3
    - OR
      - B4
      - C7
      - C6
      - D1
    - OR
      - B10
      - C18
      - C19
      - OR
        - D3
      - OR
        - D2
      - E2
    - B11
    - B12
    - C19
    - C20
    - E3
‘brake inadequate’ which may be cause of failure of MR brake. We applied this tool for finding out the faults like primary, secondary, command, active and passive. For that we have found out minimal cut set for MR brake failure.

We carried out FTA by brain storming process. We all group members and our guide sat together and found out and noted down all possible failure causes by discussing within us. The Fault Tree which we have made, i.e., FTA 1 and FTA 2 is shown in Figures 1, 2, 3 and 4.

Faults Classification of MR Brake FTA
The fault of MR Brake is classified into five main faults and tabulated in Table 2.

Minimal Cut Set Evaluation
For the purpose of evaluation, FTA 1 and FTA

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
<th>Command</th>
<th>Passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit</td>
<td>Leakage of MR Fluid</td>
<td>Bearing failure</td>
<td>Breakage of casing</td>
<td>Relay</td>
</tr>
<tr>
<td>No supply or insufficient</td>
<td>Degradation of MR Fluid</td>
<td>Insufficient torque</td>
<td>Bearing failure</td>
<td>Switches</td>
</tr>
<tr>
<td>current</td>
<td>Increased gap size</td>
<td></td>
<td></td>
<td>Electric signals</td>
</tr>
</tbody>
</table>
2 has been simplified into FTA 3 and FTA 4 as follows:

**Boolean Algebra for FTA 3**

The Boolean algebra given below gives the final iterations for FTA 3. It shows the number of minimal cut set present in the FTA 3.

\[ T_1 = C_1 \cup C_2 \cup D_1 \cup D_2 \cup C_4 \cup C_5 \cup C_6 \cup C_7 \cup D_3 \cup D_4 \cup D_5 \cup C_{10} \cup C_{11} \cup C_{12} \cup D_6 \cup D_7 \cup C_{14} \cup C_{15} \cup C_{16} \cup C_{17} \]

The minimal cut set for FTA 3 = 24.

Table 3 shows the result for FTA 3. It is characterized in three steps, i.e., singlet, doublet and triplet.

**Table 3: Iteration for FTA 1**

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<th></th>
<th>1</th>
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<tbody>
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<td>B9</td>
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<td>C8</td>
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</tbody>
</table>

**Boolean Algebra for FTA 4**

The Boolean algebra given below gives the final iterations for FTA 4. It shows the number of minimal cut set present in the FTA 4.

\[ T = C_1 \cup C_2 \cup C_3 \cup C_6 \cup C_7 \cup C_9 \cup B_{10} \cup C_{10} \cup C_{11} \cup C_{12} \cup C_{13} \cup C_{14} \cup C_{15} \cup C_{16} \cup C_{17} \cup C_{18} \cup E_1 \cup E_2 \cup E_3 \cup D_2 \cup D_3 \]

The minimal cut set for FTA 4 = 26.

Table 4 shows the result for FTA 4. It is characterized in three steps i.e. singlet, doublet and triplet.

**Table 4: Iteration for FTA 2**

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<th>4</th>
<th>5</th>
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<td>A1</td>
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</table>
Result of Fault Tree Analysis

The Fault Tree Analysis is resulted by using minimal cut set. A cut set is a collection of basic events that will cause the top event. A cut set can be characterized by the number of basic events comprising it. For example Singlet, Doublet, Triplet, etc.

- Singlet—A single event that will cause the top event is singlet.

<table>
<thead>
<tr>
<th>Table 5: Result of Minimal Cut Set for FTA 1</th>
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</thead>
<tbody>
<tr>
<td>Singlet</td>
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</tr>
<tr>
<td>Switch spring broken/damaged</td>
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<tr>
<td>Faulty relay</td>
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<tr>
<td>Prolonged use</td>
</tr>
<tr>
<td>Thickening of MRF</td>
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- Doublet—A two-event minimal cut set is a doublet.
- Triplet—A three-event minimal cut set is a triplet.

Table 5 shows the result of minimal cut set for FTA 1.

RECOMMENDATIONS ON FTA

After successful implementation of FTA on MR Brake in two stages, i.e., ‘Brake is not actuating and brake is inadequate’, it has been found that the top level faults affects the most on the MR Brake system.

There are three areas where the top level faults are found and the recommendations on same are as follows:

- Recommendations for faults related to battery problems:
  - Top up and cleanliness of battery terminals should be done periodically.
  - The charging system should be checked periodically.
  - The conductors used for electrical devices should have good quality.

- Recommendations for faults related to MR Fluid:
  - MR Fluid should be selected as per specified by Lord Corporation.
  - Correct formulation of MR Fluid should be ensured during Design stage.
  - To avoid contamination good quality seals should be selected.
  - Chemical analysis should be mandatory.
• Recommendations for faults related to Design, Manufacturing and assembly:
  – To avoid dimensional inaccuracy $\bar{x}$ and $\bar{R}$ chart should be used.
  – Tolerance fits should be ensured and inspected during Manufacturing and Quality control process.
  – Seals should be mounted properly during assembly of MR Brake.
  – A visual check should be compulsory to ensure proper mounting.
  – For proper heat dissipation, high thermal conductivity material like aluminum and its alloys be recommended.

CONCLUSION

The work has confined the scope to the Qualitative Analysis only which comprises FTA as a Reliability tool.

After performing FTA on MR Brake system, it can be concluded that there is no appearance of AND gate but there are only OR gates. It means that the system is more sensitive for a single fault which leads to top level event. Also we have suggested recommendation for such faults by applying minimal cut-sets theory. These are as follows:

1. Top up and cleanliness of battery terminals should be done periodically OR maintenance free battery is recommended.
2. The charging system should be checked periodically.
3. MR Fluid should be selected based on study of specifications and properties of MR fluids.
4. Chemical analysis of MR fluid should be mandatory.
5. For proper heat dissipation, high thermal conductivity material like aluminum and its alloys is recommended.
6. A visual check should be compulsory to ensure proper mounting.

With the help of these recommendations one can improve the reliability of MR brake system.

REFERENCES

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