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GOING BACK IN TIME TO IMPROVE DESIGN: THE ELEMENTAL FUNCTION-FAILURE DESIGN METHOD

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ABSTRACT

In today's world it is more important than ever to quickly and accurately satisfy customer needs when launching a new product. It is equally important to design products that adequately accomplish their desired functions with a minimum amount of failures. When failure analysis and prevention are coupled with a product design from its conception, shorter design times and fewer redesigns are necessary to arrive at a final product design. In this article, we explore the potential of a novel design methodology to guide designers toward new designs or redesigns that avoid failures. The Elemental Function-Failure Design Method (EFDM) is based on functional similarity of the product being designed to failed products within a knowledge base. The idea of using component functionality to explore the failure space in design was first introduced as a function-failure analysis approach by Tumer and Stone (2003). The overall approach offers potential improvement over current failure analysis methods (FMEA, etc.), because it can be implemented hand in hand with other conceptual design steps and carried throughout a product's design cycle. In this paper, this idea is formalized into a systematic methodology that is specifically tailored for use at the conceptual design stage before any physical design choices have been made, hence moving failure analysis earlier in the design cycle. In the following, formalized guidelines for using the EFDM will be outlined for use in new designs and for redesign in existing products. A function-failure knowledge base, derived from actual failure occurrences for Bell 206 rotorcraft will be introduced and used to derive potential failure modes in a comparison of the EFDM and traditional FMEA for two design examples. This comparison will demonstrate the EFDM's potential in conceptual design failure analysis.

1. INTRODUCTION

A company specializing in electric power transformers rolls out a new high capacity transformer. Knowing that the high electricity handling capabilities of this new transformer will necessitate increased heat transferring capacity, the designers add large horizontal cooling fins to the sides of the transformer case. However, shortly after installation, the transformers begin to fail due to overheating after the oil used to cool them leaks out of the casings through cracks that develop at the welded connection points of the cooling fins. It is determined that the cracks developed due to fatigue stresses induced during shipping. (DeGarmo et al., 1997)

If the designers of these transformers had been more aware of the common failures that befall large heat transferring components, is it likely that these failures could have been avoided? In this paper we report on a method and its potential in preventing costly problems like the one discussed above.

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The research presented here is motivated by two engineering maxims: 1) The faster a product design can be taken from concept to finalization, the less expensive the design costs will be; 2) The less likely that a failure will occur within a product's life cycle, the more the consumer will appreciate it. The methodology presented here seeks to capitalize on these two maxims by keeping the designer(s) of a new product constantly cognizant of failure modes that have a tendency to occur for the same functionality as that of the new product.

The Elemental Function-Failure Design Method (EFDM) offers a new approach to coupling failure analysis with product design from the conceptual stage. The research builds upon the function-failure method developed by Tumer and Stone (2003), which allows for historical failure data to be collected and related to the failed artifact's functionality. These relations are used to build knowledge bases of past failures that will be used by designers to avoid these failures in future designs. The function-failure analysis method was developed and tested using household products in Arunajadai et al. (2002) and using NTSB rotorcraft accident data in Roberts et al. (2002). Research using spacecraft historical problem and failure data is also currently underway to develop a comprehensive function-failure knowledge base for NASA missions (Tumer et al., 2003). In this paper, the function-failure analysis approach is formalized specifically for use in conceptual design, and extended to combine with a concept generator approach (Strawbridge et al., 2002) to develop new designs with fewer failures.

In this light, the paper first reviews related research and background of the function-failure analysis and the function-failure knowledge base required for the analysis in Section 2. In Section 3, an example function-failure knowledge base and its development are shown. Then, a formalized methodology and general guidelines for using the methodology in conjunction with a concept generator method are presented in Section 4. Comparisons of the EFDM to traditional FMEA methods for a new product design and for an existing product redesign are reported to evaluate and demonstrate the merit of the new approach in Section 5. Conclusions about the advantages and disadvantages of EFDM over FMEA followed by recommendations and future work round out this paper.

2. BACKGROUND AND RELATED RESEARCH

2.1 Background: Traditional Failure Analysis in Design

Failure Modes and Effects Analysis (FMEA) has been the industry standard failure analysis method for many years. Originally developed from the US military standard MIL-P-1629A (1980), FMEA has been rigorously tested and enhanced by many organizations, most notably the United States' auto manufacturers. In a joint undertaking by Chrysler, Ford, General Motors and the Automotive Industry Action Group a reference manual for conducting FMEA was published in 1993 (AIAG, 1993). This manual was intended to guide the FMEA activities of these companies and their suppliers. Despite this effort to formalize a single FMEA procedure, there are still many different methods for undertaking an FMEA analysis. Another shortcoming of FMEA methods is that they are not well suited for the conceptual design of a product, since details of the physical design are rarely known (Hari and Weiss, 1999). This often leads to time-consuming redesigns that must also be evaluated with FMEA methods, leading to even longer total design times. Also, the FMEA procedure requires the input of a concurrent engineering team of five to nine cross-functional and multi-disciplinary individuals (Stamatis, 1995), thus making it not only time consuming, but also quite expensive. In industry, "engineers consider FMEA to be laborious and time-consuming (and thus expensive) to carry out" (Wirth et al., 1996).

Wirth et al. (1996) state that FMEA has two fundamental weaknesses: the lack of methodological guideline and the use of natural language. The AIAG manual (1993) has addressed the lack of a methodological guideline for conducting FMEA, but it is still common for FMEA practices to vary between different fields, companies and even FMEA teams. The criticism of FMEA using natural language originates from the description of functions and failure modes within their analysis. Wirth et al. expand their criticism to declare that the descriptions of systems and functions are often incomplete. The problems associated with the use of natural language often lead to ambiguity, or uncertainty when conducting FMEA. This problem is amplified when the FMEA results are viewed by outside parties or after time has passed. This deficiency has greatly slowed any attempt to reuse information from FMEA in new design cases. The descriptions of failure modes are frequently the most ambiguous. In particular, the description of the same failure can differ greatly between two FMEA practitioners. It is common for failures to not even be recorded at the same level; sometimes they will be recorded at the molecular level and other times they will be recorded at a much more abstract level. It is necessary that a common and accepted vocabulary be used in order for all failures to be classified accordingly.

Another drawback of FMEA is its reliance on the FMEA team to develop a list of failure modes that "could" or "might" occur for any given component. This necessitates that members of the FMEA team have a vast knowledge of potential failures in order to enumerate every possible failure that could occur. Within an FMEA these potential failures are then subjectively ranked for severity, occurrence and detectability based upon the users' judgment. The rankings generated by this subjective system can greatly fluctuate when assigned by different engineers.

Attempts have been made to modify FMEA for use in conceptual design. Hari and Weiss (1999) have developed a failure analysis method known as CFMA that uses an FMEA-style analysis on a functional representation of a design. CFMA is a step in the right direction, but continues to use the natural language and subjectivity of traditional FMEA methods. A thorough investigation of the CFMA reveals that it also includes some amount of form-dependence for the new design being analyzed. For a failure analysis to be truly applicable to conceptual design it must not assume any form for the design, it should simply rely on a functional representation in order to perform its failure analysis. The Advanced FMEA (AFMEA) method of Kmenta et al. (1999) is a system design failure analysis method that is based upon the desired functions of the system. This functional dependence allows AFMEA to be performed in the early stages of system design.

In electrical design, there have been attempts to undertake

FMEA-like failure analysis at the conceptual design stage. The FLAME System (Hunt et al., 1995; Price, 1996) even links its failure analysis to a functional model derived during conceptual design. In FLAME, the functional models are embodied by components from an extensive library. The embodied representations are then subjected to a computer simulation in order to see the effect of a list of possible failures within the new design. This list of possible failure modes exists for all components within the library, and has been assigned based on historical failure occurrences. This type of system can be adopted in electrical design since the systems, and their possible failures, can be easily simulated by computer analyses. However, for mechanical design, subjecting all components of a design to an entire list of possible failure modes, even within a computer simulation, would prove extremely time-consuming and impractical.

WIFA (the German acronym for "knowledge-based FMEA") (Wirth et al., 1996) is a failure analysis tool that seeks to populate knowledge bases with information from past FMEAs and use them when conducting current FMEAs. This methodology strives to use historical information from past failure analyses to guide new designs by storing the past FMEA results in a knowledge base. But, by archiving past FMEAs, WIFA is not populating its knowledge bases with actual occurrence data. It is relying on the analysis of past FMEA teams to be widely applicable to new designs.

Knowledge base-driven failure analysis tools, like some of those reviewed above, can trace their roots to the efforts of Collins et al. (1976) and Barbour (1977) to introduce matrix techniques into FMEA logistical archiving. The failure-experience matrix of Collins et al. shows a great advance in archiving historical failure information for use in future designs. Coincidentally, related work of Collins (1981) formed the basis for the failure mode vocabulary used in this article. The Advanced Matrix FMEA Technique of Goddard and Dussault (1984) added to the work of Barbour. This was an early drive for standardizing the format for FMEAs into matrices to allow for ease of information storage and reuse. More currently, Henning and Paasch (2000) reuse past FMEA data to develop matrices that aid in investigating the diagnosability of failure occurrence. Their method seeks to evaluate designs based on life-cycle costs of fault (failure) isolation. All of these researchers have lessened the logistical problems of reusing past FMEAs and archiving actual failure data.

2.2 Related Research: The Function-Failure Analysis and Knowledge Base

A critical part of the EFDM method is the required knowledge base of previous products. In particular, the designer needs an elemental function-component (**EC**) and a component-failure (**CF**) matrix. The function-failure knowledge base, also known as the elemental function-failure (**EF**) matrix, exists as a computed result of these first two matrices and is developed through the process detailed by Roberts et al. (2002). Within **EF**, the rows are representative of function and flow pairings (i.e., a functional description) and the columns represent failure modes. Entries in the matrix, ef_{ij}, indicate the number of distinct components solving function i that have failed by failure mode j. The process of populating a function-failure knowledge base begins by obtaining actual failure information from an engineered product. The failure information is scrutinized to determine the failed component and the failure mode. A functional model for the failed component is then developed (Stone and Wood, 2000; Hirtz et al., 2002) at a detailed level. The sub-functions from the detailed functional model are then entered into the **EC** matrix and through the above calculation are correlated to their respective failure mode and added to the function-failure knowledge base. As more failed components are added to the knowledge base, the distribution of failure mode occurrences across functions can be used to determine which failure modes will occur more often than others for each function. A suitable knowledge base for the EFDM should contain failure information for many sub-functions so that it can be used for new designs that span a wide range of functionality.

In order to build a suitable knowledge base that can be applied across a wide range of new product designs, it is necessary that a standard vocabulary be used for not only the product functionality, but also for the identification of failure modes. This standardization of vocabulary is achieved by determining and recording a product's functionality within the functional basis formalized by Hirtz et al. (2002). Similarly, to standardize the language used in describing failure modes, the vocabulary of Arunajadai et al. (2002) is utilized in this research. These vocabularies provide exhaustive nomenclatures to describe product functionality and mechanical failures.

In previous work by Roberts et al. (2002), National Transportation Safety Board (NTSB) accident reports concerning Bell 206 rotorcraft accidents were reviewed to allow for an initial test of the function-failure theory of Tumer an Stone (2003). The NTSB reports offered the first opportunity to populate a knowledge base with an abundance of actual component failures. The work of Roberts et al. sought to investigate the failures in four systems of the Bell 206 rotorcraft. They examined 33 components from the compressor, engine, powertrain, and turbine systems. Of these 33 components, 18 of them exhibited 10 unique failure modes. In their research, functional descriptions of these components were only examined at the highest (most vague) level of description, resulting in one to five function and flow terms for each component. Roberts et al. did succeed in using a common functional vocabulary to populate a knowledge base, but their natural language descriptions of failure modes leads to problems when trying to relate this knowledge base across a wide range of products. We have extended this work and derived a more representative function-failure knowledge base by using a more standardized vocabulary to describe the failure modes and by examining the components' functional models at a more detailed level. This extended knowledge base will be used in this paper for our case studies.

2.3 Related Research: The Concept Generator Method

The research of Strawbridge et al. (2002) is also prominently used in this research. Their concept generator allows functional models to be embodied into a physical form by applying historical physical solutions to new design problems. The concept generator draws these solutions from a repository of information on a wide range of engineered products. This information is archived in matrix form, known as the chi matrix (**X**). It contains column entries for all possible physical concepts and rows for

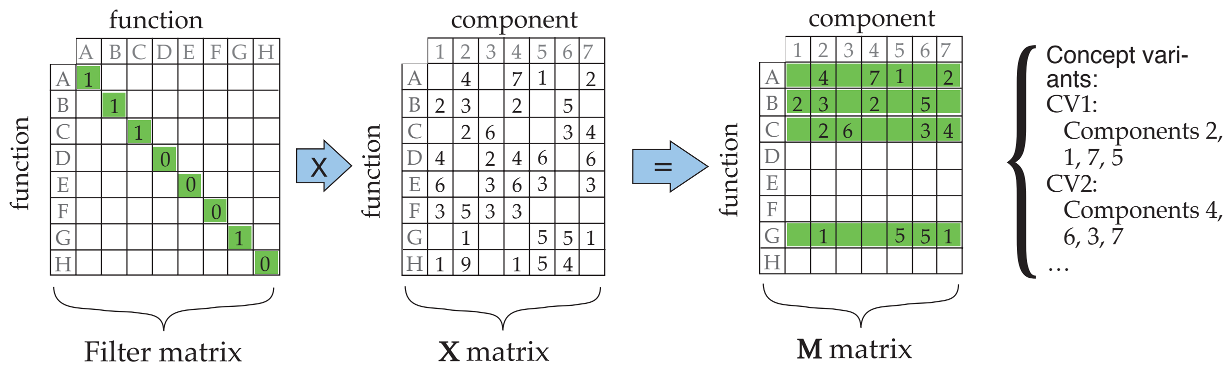


Figure 1. The Concept Generator Method.

each function and flow pairing. To use the concept generator, a filter matrix is formulated from a detailed functional model of the new design. This filter matrix allows the user to "weed out" all physical solutions that hold no meaning within their new design. The filter matrix is then multiplied by **X**, with the resulting matrix listing the possible physical solutions for the functional model. The resulting matrix is known as the morphological matrix (**M**) for the new design. This process can be seen in Figure 1. In this paper, we integrate the concept generator into the EFDM to aid the designer in deriving physical solutions.

3. POPULATING THE FUNCTION-FAILURE KNOWLEDGE BASE

In this research, we use failure information for the Bell 206 rotorcraft to populate our knowledge base. Previous work has utilized the same failure data (Roberts et al., 2002). However, in this research we have reevaluated the failure data in greater detail to derive a more robust knowledge base for use in the EFDM. In particular, the component space has been increased to include the airframe, fuel system and rotor systems, in addition to the four systems investigated by Roberts et al. NTSB accident reports were again used to allow for actual failure occurrence data to populate the component-failure matrix. Various rotorcraft maintenance manuals and engineering judgment where used to derive detailed functional models of each component, therefore attaining the overall rotorcraft function-component (**EC**) matrix. Within these 7 systems, 41 components have been enumerated, with 25 of these components exhibiting a definable failure mode. A total of 63 failures were extracted from the NTSB reports to have occurred in these 25 components. Of these 63 failures, there were 15 unique failure modes within the vocabulary of Arunajadai et al. (2002). These unique failure modes are shown as grey entries in the complete listing of possible failure modes seen in Table 1. The initial high-level exploration of the function space by Roberts et al. (2002) resulted in only 24 unique function-flow representations. By further investigating the function space to a more detailed level, 55 unique function-flow representations have been identified and are listed in Table 2. It is hypothesized that by populating the function-failure knowledge base at this detailed level, it will be better suited for use within the EFDM. This forms the basis for the function-failure knowledge base (shown in Table 3) we will use in determining the potential failure modes with the EFDM in the design examples presented in the following sections.

Table 1. Failure Modes from the NTSB Rotorcraft Accident Study.

Abrasive Wear	Direct Chemical Attack	Intergranular Corrosion
Adhesive Wear	Ductile Rupture	Low Cycle Fatigue
Biological Corrosion	Force/Temperature Induced Deformation	Pitting Corrosion
Brinnelling	Fretting Fatigue	Radiation Damage
Brittle Fracture	Fretting Wear	Selective Leaching
Buckling	Galling and Seizure	Spalling
Cavitation Erosion	Galvanic Corrosion	Stress Corrosion
Corrosion Fatigue	High Cycle Fatigue	Surface Fatigue Wear
Corrosive Wear	Hydrogen Damage	Thermal Fatigue
Creep Buckling	Impact Deformation	Thermal Relaxation
Creep Stress Rupture	Impact Fatigue Wear	Thermal Stress
Crevice Corrosion	Impact Fracture	Yielding
Deformation Wear	Impact Fretting	

Table 2. Functions from the NTSB Rotorcraft Accident Study.

Change Gas	Export HyE	Import Gas	Regulate HyE
Change Liquid	Export Liquid	Import HE	Regulate Liquid
Change PnE	Export ME	Import HyE	Regulate ME
Change RotE	Export PnE	Import Liquid	Secure Solid
Convert HE to RotE	Export RotE	Import ME	Stabilize Solid
Convert PnE to ME	Export Solid	Import PnE	Stop Gas
Convert RotE to ME	Export ThE	Import RotE	Stop HyE
Convert RotE to PnE	Guide Gas	Import Solid	Stop Liquid
Couple Solid	Guide HyE	Import ThE	Stop PnE
Distribute Liquid	Guide Liquid	Inhibit Liquid	Stop Solid
Distribute ME	Guide PnE	Join Solid	Store ME
Distribute ThE	Guide RotE	Link Solid	Supply ME
Export Gas	Guide Solid	Position Solid	Transmit ME
Transmit PnE	Transmit RotE	Transmit ThE	

4. A METHODOLOGY FOR FAILURE ANALYSIS IN CONCEPTUAL DESIGN

Pahl and Beitz (1996) state that the quality of a product has to be built-in from the beginning of the design process and maintained throughout the production process. They go on to state that up to 80% of all faults can be traced back to insufficient planning and design work. Knowing this, it is hypothesized here that be-

Table 3. Function-Failure Knowledge Base from NTSB Rotorcraft Accident Study.

Function/Failure	Abrasive Wear	Adhesive Wear	Buckling	Corrosion Fatigue	Deformation Wear	Direct Chemical Attack	Force Induced Deformation	Fretting Fatigue	Galling and Seizure	High Cycle Fatigue	Low Cycle Fatigue	Stress Corrosion	Thermal Fatigue	Thermal Shock	Yielding
Change Gas	0	0	1	1	0	0	0	1	0	2	0	0	1	1	1
Change Liquid	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0
Change PnE	0	0	0	0	0	0	0	0	0	2	0	0	1	1	1
Change RotE	0	0	0	0	1	0	0	1	2	3	0	0	0	2	0
Convert HE to RotE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Convert PnE to ME	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Convert RotE to ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Convert RotE to PnE	0	0	1	1	0	0	0	1	0	2	0	0	1	1	1
Couple Solid	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Distribute Liquid	0	0	0	0	1	0	0	1	2	3	0	0	0	2	0
Distribute ME	0	2	1	1	1	3	0	2	0	7	1	0	0	1	3
Distribute ThE	2	0	0	0	1	1	0	0	0	4	0	1	2	1	2
Export Gas	2	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Export HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Export Liquid	0	1	1	2	2	3	1	2	2	6	0	0	0	3	3
Export ME	0	0	0	0	0	2	1	0	0	2	0	0	0	0	2
Export PnE	0	0	1	2	0	0	0	2	0	4	1	0	1	1	2
Export RotE	1	0	0	0	0	0	0	0	2	3	0	1	1	1	0
Export Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	8
Export ThE	1	0	0	0	1	1	0	0	0	2	0	1	1	0	1
Guide Gas	1	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Guide HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Guide Liquid	0	1	1	2	1	3	1	1	0	3	0	0	0	1	3
Guide PnE	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Guide RotE	0	0	0	0	1	0	0	1	2	4	0	0	0	2	0
Guide Solid	2	0	1	2	0	0	0	1	0	3	0	1	2	2	1
Import Gas	2	0	1	2	0	0	0	2	0	4	1	1	2	1	2
Import HE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Import HyE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Import Liquid	0	1	1	2	2	3	1	2	2	6	0	0	0	3	3
Import ME	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0
Import PnE	0	0	0	1	0	0	0	1	0	4	1	0	1	1	2
Import RotE	1	0	1	1	0	0	0	1	2	5	0	1	2	2	1
Import Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	8
Import ThE	1	0	0	0	1	1	0	0	0	2	0	1	1	0	1
Inhibit Liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Join Solid	0	2	1	1	2	3	1	3	2	9	1	0	0	3	7
Link Solid	2	1	0	1	1	1	0	1	2	6	0	1	2	3	1
Position Solid	1	2	1	2	2	3	1	2	2	9	0	1	2	4	6
Regulate HyE	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Regulate Liquid	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
Regulate ME	0	1	0	0	0	2	0	0	0	2	0	0	0	1	1
Secure Solid	2	2	1	2	2	4	1	3	2	12	1	1	2	4	7
Stabilize Solid	0	1	0	0	0	2	0	0	0	1	0	0	0	0	1
Stop Gas	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stop HyE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stop Liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stop PnE	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stop Solid	0	0	0	0	0	0	0	0	2	2	0	0	0	1	0
Store ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	3
Supply ME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Transmit ME	0	1	0	1	1	2	1	1	0	5	1	0	0	1	6
Transmit PnE	0	0	0	0	0	0	0	1	0	2	1	0	0	0	1
Transmit RotE	1	1	0	0	1	1	0	1	0	2	0	1	1	1	0
Transmit ThE	2	0	0	0	2	1	0	1	2	7	0	1	2	3	2

ginning failure analysis at conceptual design will have a positive impact on the quality of the product being designed. The major problem with this desire is the difficulty in performing failure analysis on a product that has yet to be designed and only exists as a functional representation. The development of the EFDM has addressed this problem so that failure analysis can be performed at a truly conceptual stage.

The goal of the EFDM is to improve on previous failure analysis tools so that it can be widely applicable, even in conceptual design. The EFDM is conducted under a set procedure, uses no subjective rankings and utilizes standard vocabularies. These traits allow the EFDM to be easy to use and also remove the ambiguity of previous failure analysis tools. The EFDM also offers benefits since it requires fewer people and is based on actual failure occurrence information. The EFDM's reliance on functional models of a design allow it to be used in conceptual design since it requires no physical form of the product being analyzed.

In addition to its failure analysis capabilities, the EFDM is a unique methodology that can be used as a "start-to-finish" design method in conjunction with the concept generator approach or be used with more traditional concept generation approaches as a failure analysis tool. During redesign, the EFDM can be applied when exploring the existing product at the component level. All of these applications of the EFDM require the use of a function-failure knowledge base to convey the relationship between past failures and functionality.

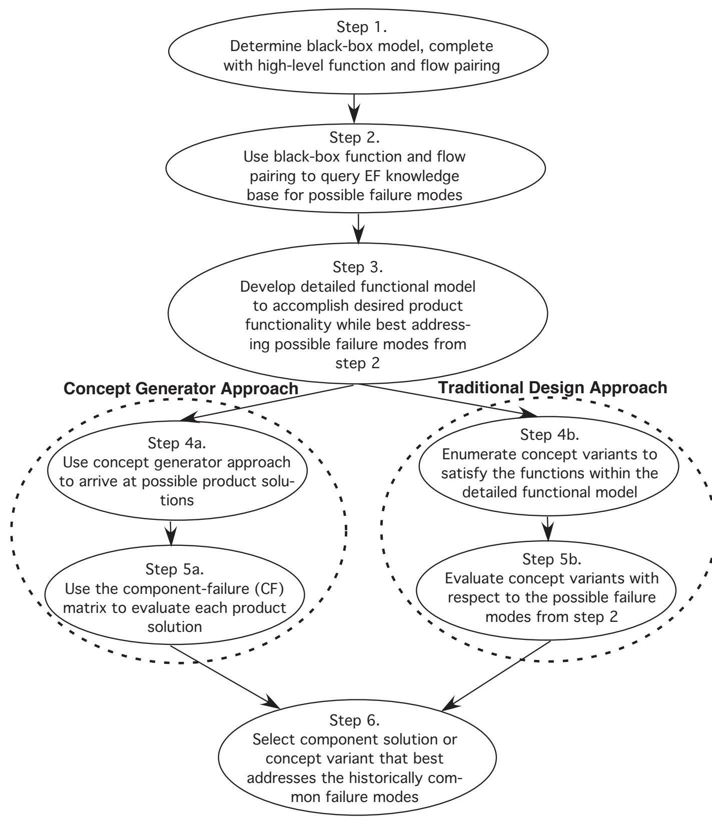


Figure 2. EFDM and Concept Generator Procedure.

4.1 Using EFDM for Design

The EFDM procedure is shown in Figure 2. Specifically, the steps of the method are described below.

1. Develop a black-box model for new design or the component being redesigned that best describes its overall functionality. The function and flow pairing should use the secondary level of functions and flows from the functional basis.
2. Use the function-flow representation from the black-box model to query the function-failure knowledge base to determine the most common failure modes exhibited by that function.
3. Derive the detailed functional model for the component. This detailed functional model should show all the de-

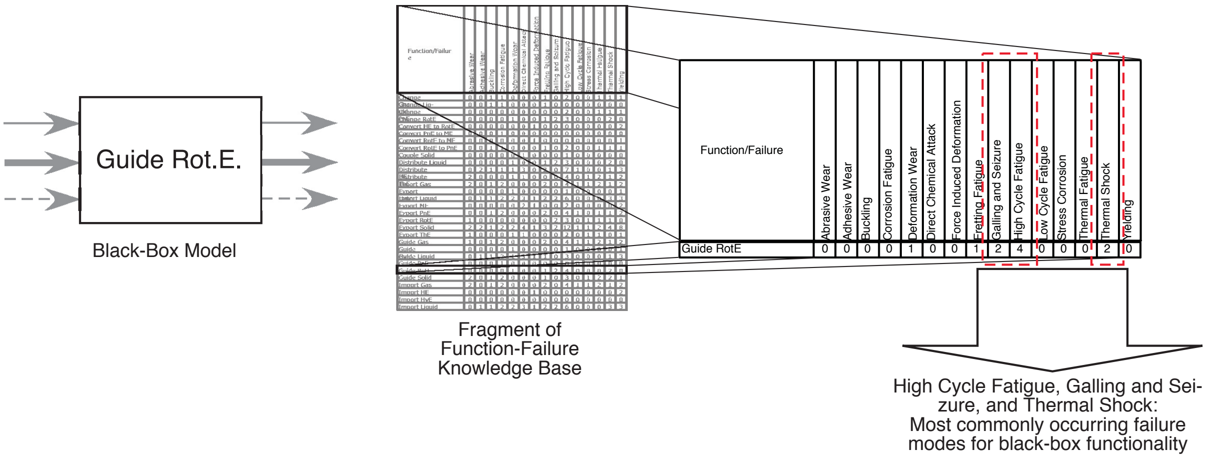


Figure 3. Using the EFDM to Enumerate Failure Modes for a Given Function.

sired functionality of the new design and should also address the failure modes enumerated in step 2.

This generally involves adding functions to those that describe the desired functionality of the new design. For example, if guide rotational energy was a black box function, we see that the three most common failure modes have historically been high-cycle fatigue, galling and seizure and thermal shock. To address thermal shock, the designer adds functionality to the detailed functional model. This functionality will shield the component from external heat and dissipate the heat generated by the component. By doing this, the designer has arrived at a more accurate functional model earlier in the design stage.

It is at this point that the designer could choose from two paths to follow in the design of their component. They could choose to follow a concept generator approach or they could choose to design their component with less archived design knowledge. Steps 4a and 5a show the necessary steps within the concept generator approach, while steps 4b and 5b show the necessary tasks for a design without the use of the concept generator.

4a. Use the detailed functional model from step 3 along with the concept generator to arrive at possible product solutions. To do this, multiply the filter matrix (created based on the detailed functional model) by the function-component (**X**) matrix to generate possible physical solutions.

5a. Evaluate these product solutions with the component-failure matrix. This involves querying the component-failure matrix for each possible physical solution. By doing so, the designer gets a list of failure modes that have historically occurred for each solution.

For a design approach that utilizes more traditional concept generation, use steps 4b through 6b.

4b. Use conventional design methods (brainstorming, etc…) to enumerate concept variants that satisfy the functionality in the detailed functional model derived in Step 3.

5b. Evaluate this list of concept variants with respect to the failure modes from step 2. This involves suggesting suitable analyses for each potential failure mode. For example, if high cycle fatigue is a potential failure mode, then each concept variant should be analyzed for resistance to fatigue. This analysis can also involve exploring materials selection and manufacturing possibilities for each concept variant.

6. Select component physical solution or concept variant with the fewest historically troublesome failure modes or that performed the best during the failure analysis in the previous step. It could be necessary to perform further appropriate analyses to arrive at a final component design that avoids the common historical failure modes. Engineering judgment is required here to ensure that the identified failure modes are viable for the current application and excess analyses are not being performed.

At any point during these design steps, the designer can query the function-failure knowledge base with functions from the detailed functional model in order to better understand failures that are likely to occur the new design. This will often add more functions to the detailed functional model in order to aid components in avoiding common failures. This activity proves helpful in choosing between numerous physical design solutions.

5. COMPARISON OF EFDM TO FMEA

In order to validate the EFDM, two comparisons are undertaken between the EFDM and traditional FMEA methods. The first comparison is conducted using both failure analysis methods on a new design. Similarly, the second comparison conducts both analyses on an existing product and compares the output from each. For these comparisons, independent teams given the same initial problem statement will conduct each analysis.

5.1 Failure Analysis Comparison for a New Design

To test the applicability of the EFDM for a new design, a design problem is formulated that is compatible with the information in the knowledge base of rotorcraft data. This comparison is based on the design of a highly portable, small-scale air compressor that can be attached to a hand-held power drill. This compressor should work with all hand-held power drills and be capable of blowing small debris away in order to clean an area such as a workbench.

Since traditional FMEA methods are not easily applicable to turning functional representations into physical designs, an initial design representation must be given before an FMEA can be performed. The initial physical design of the air compressor, seen in Figure 4 was created using the concept generator approach of the EFDM.[1] For this example, the initial physical representation developed by the concept generator does not include any additional functionality identified by assessing the failure modes of the black-box function (as prescribed in Steps 2 and 3 from above). The functional model used as input to the concept generator is based solely on identifying the chains of sub-functions that satisfy the customer needs.

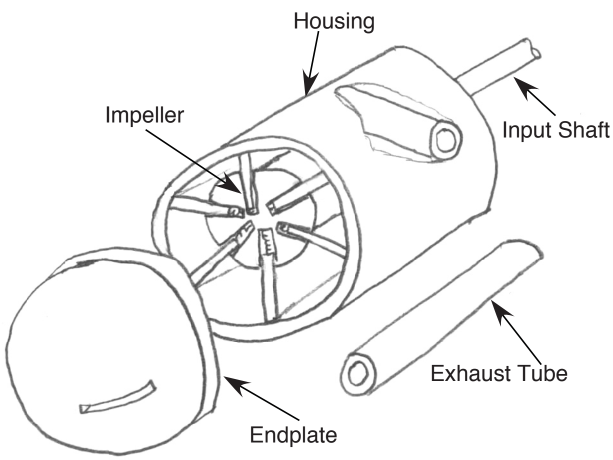


Figure 4. Initial Compressor Physical Design.

The air compressor physical design seen in Figure 4 is subjected to an FMEA and failure analysis within the EFDM. The output from the analyses is the recommended actions for completing the design of the air compressor. The recommended actions from both methods are then compared. The FMEA team is comprised of multiple design engineers while a single design engineer, independent of the FMEA team, performs the EFDM analysis. Table 4 details the results from the FMEA and EFDM failure analyses of the compressor design.

5.1.1 FMEA Results for the Compressor Design

The FMEA team was given the physical design shown in Figure 4 and the design problem statement from above to conduct their analysis. Their analysis led to the recommendations of various material selection criteria and fatigue and stress analyses on components of the compressor design. The FMEA also led to the inclusion of shaft support bearings, an incoming air filter and a grooved surface for connecting the shaft to the drill. Results from FMEA for the compressor design are detailed in Table 4.

5.1.2 EFDM Results for the Compressor Design

To contrast with the results from the FMEA approach, the recommendations from the EFDM approach are also detailed in Table 4. Figure 5 schematically shows how the EFDM is applied to the compressor design. First, a black-box model is developed to show the overall functionality and input and output flows of the new design. The black-box function and flow pairing of "convert rotational energy to pneumatic energy" is then used to query the function-failure knowledge base to compute a list of failure modes likely to occur. This list, also shown in Figure 5, is scrutinized during the derivation of the detailed functional model for the compressor. The inclusion of thermal fatigue and thermal shock in the list of possible failure modes leads the designer to add the functionalities of distribute thermal energy and export thermal energy to the detailed functional model. Similar analysis leads to the inclusion of a "separate gas" function on the incoming airflow to avoid the failure mode of abrasive wear for the "import gas" function.

Table 4. Recommended Actions from Failure Analyses of Compressor.

EFDM			FMEA
Function	**Historical Failures**	**Recommended Actions**	**Recommended Actions**
Stabilize Solid Import Rot.E. Convert Rot.E. to Pn.E. Guide Pn.E. Import Pn.E. Export Pn.E.	Direct Chemical Attack High Cycle Fatigue Abrasive Wear Fretting Fatigue Thermal Shock Thermal Fatigue Yielding	-Choose materials that can properly interact with air and water -Perform fatigue analysis on rotating components and housing -Include a filter screen on air inlet -Include bearings to support shaft -Choose a flexible material for the exhaust tube -Fin the endplate for better heat transfer -Choose a hardened material with clamping flats for input shaft -Perform extensive stress analysis on support feet	-Use hardened and grooved material for input shaft -Add self-aligning bearing to support input shaft -Perform fatigue analysis on housing -Include a cleanable screen for air inlet -Include a precise sealing surface between housing and endplate -Use flexible material for exhaust tube

At this point, functional embodiment with the concept generator leads to concept variants, which were then scrutinized against the list of possible failure modes that occur for their individual functionality. The EFDM analysis directly leads to the inclusion of the incoming air filter, shaft support bearings, finned end cap and flats on the shaft facilitate coupling with the drill in the final design. The EFDM also leads the designer towards various fatigue and stress analyses and aids greatly in material selections throughout the design.

5.1.3 Comparing Results for the Compressor Design

It should be noted that the recommended actions for this new design example from both the FMEA and the EFDM provided insightful directions for component design. The EFDM identified all necessary analyses and suggestions that were made by the FMEA team. For the compressor design, the EFDM did recommend more design and analysis activities than the FMEA. In particular, the thermal consequences of this design were overlooked by the FMEA team, but investigated by the EFDM. Further experimental testing will be necessary to determine if these activities were necessary to improve the design, but it is likely that

[1] Note- This step would normally not occur when performing the EFDM, it is included here to offer a design on which the FMEA can be performed. In the actual EFDM, the first physical model would already exhibit functionality and/or componentry to address possible failure modes. In this case, the initial physical design does not address any possible failure modes.

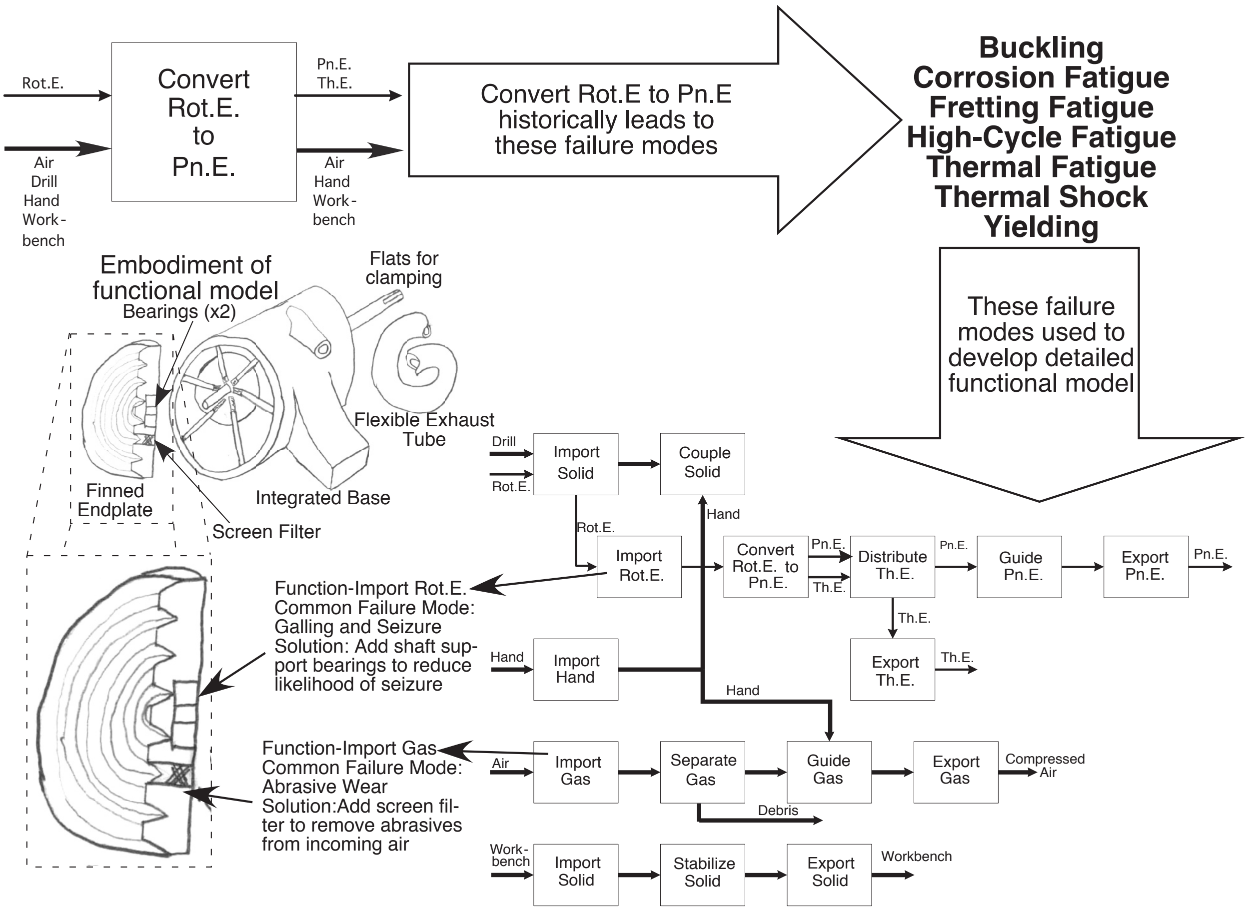


Figure 5. The EFDM Approach for the Compressor Design.

these activities have decreased the need for multiple redesigns. The EFDM was performed by a single designer instead of the multiple designers involved in the FMEA, thus initially showing that the EFDM has the potential of decreasing the cost involved with design failure analysis.

5.2 Failure Analysis Comparison for an Existing Product

For this comparison, three components from a Campbell Hausfeld 1/2" air impact wrench are analyzed using both FMEA and the EFDM. An exploded view of the impact wrench can be seen in Figure 6. The components used within this comparison of failure analysis methods are the anvil, inlet bushing and housing back plate. Recommended actions from each methodology to best eliminate failure mode occurrence will be compared on a component-by-component basis. A team of design engineers is assembled to conduct the FMEA while a single design engineer, independent of the FMEA team, performs the EFDM analysis.

5.2.1 Results for Anvil

The anvil's main functionality is to export both rotational and impact energy from the wrench. Within the casing, the anvil interacts with the hammer, and externally, the anvil attaches to a socket. The socket would then link the impact wrench to the nut or bolt that is being turned. The comparison in Table 5 shows that the recommended actions resulting from both failure analysis methods are quite similar. The EFDM did however identify a somewhat larger list of recommended actions.

5.2.2 Results for Inlet Bushing

The inlet bushing's main functionality is to import compressed air into the impact wrench from an external source. The bushing threads into the wrench housing and is held in place with a thread-locking compound. Either a compressed air hose or "quick-connect" fitting is threaded into the internal diameter of the bushing. A wire screen filter is present within the bushing to filter any solid debris out of the incoming air. The compari-

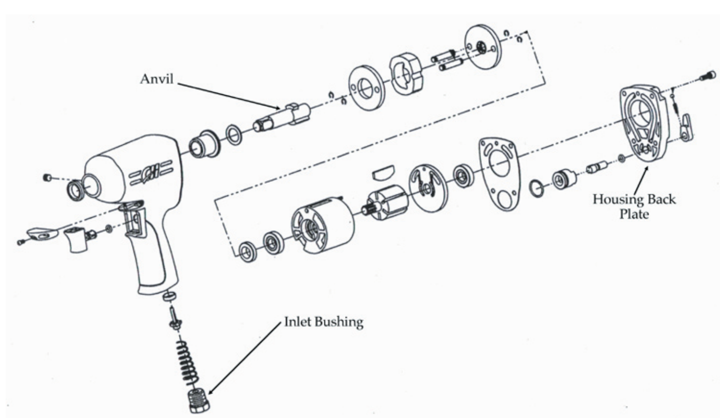


Figure 6. Exploded View of Campbell Hausfeld 1/2" Air Impact Wrench.

son in Table 6 also shows the recommended actions from both methods to be similar. It can be seen that the EFDM does not account for "clogging" of the screen filter. Currently, the failure mode vocabulary does not describe "clogging" accurately, since a "clog" usually indicates the failure of some other component. For example an oil filter might "clog" because it fills with metal chips dislodged from a bearing that is galling. In this case, the bearing would be said to fail via galling and seizure and would be entered into the knowledge base as such.

Table 5. Recommended Actions from Failure Analyses of Impact Wrench Anvil.

EFDM			FMEA
Function	Historical Failures	Recommended Actions	Recommended Actions
Transmit Rotational Energy Transmit Impact Energy Export Rotational Energy	Abrasive Wear Deformation Wear Direct Chemical Attack Yielding Galling and Seizure	-Increase surface hardness -Test completed parts for sufficient surface hardness -Explore surface plating -Perform rotational fatigue analysis -Perform fatigue testing on a sample of completed parts -Perform stress analysis to determine suitable materials and heat treatments -Investigate added lubrication at bushing	-Test completed parts for sufficient surface hardness -Non-destructively test completed parts to assure strength -Lubricate anvil-to-bushing interface

Table 6. Recommended Actions from Failure Analyses of Impact Wrench Inlet Bushing.

EFDM			FMEA
Function	Historical Failures	Recommended Actions	Recommended Actions
Import Pn.E. Transmit Pn.E.	Fretting Fatigue Yielding	-Explore thread-locking solutions -Investigate component hardness to ensure that threads will not yield -Perform hardness testing on completed parts	-Explore thread-locking solutions -Investigate the use of a self-cleaning filter

5.2.3 Results for Housing Back Plate

The housing back plate is bolted to the rear of the impact wrench and supports the internal rotating components while also acting as a manifold to distribute the compressed air. As can be seen in Table 7 the results from the EFDM compare favorably with those from the FMEA.

5.2.4 Comparing Results for the Impact Wrench Redesign

For these three components of the impact wrench, the results from the EFDM suggest performing more analyses than the FMEA does, most likely leading to a more thorough overall failure analysis. It should also be noted that the EFDM recommends all actions that the FMEA team recommended, with the exception of those for the clogged filter. However, it should be noted that clogging is not a recognized failure mode within the vocabulary that has been used for this research. Expansion of the failure mode vocabulary, thus addressing this problem, is a key area for concentrating further research.

6. DISCUSSION AND FURTHER WORK

Revisiting the case of the failed electric transformers from the introduction, the cracks found at the base of the cooling fins originated because of high cycle fatigue. Since transformers operate under static conditions, fatigue had not been considered in the original design selection. But, during their shipment on rail cars, vibrations caused a situation of fatigue to develop at the locations where the fins were welded to the transformer case. As reported, these cracks caused the failure of the transformer coils (DeGarmo et al., 1997).

Table 7. Recommended Actions from Failure Analyses of Impact Wrench Housing Back Plate.

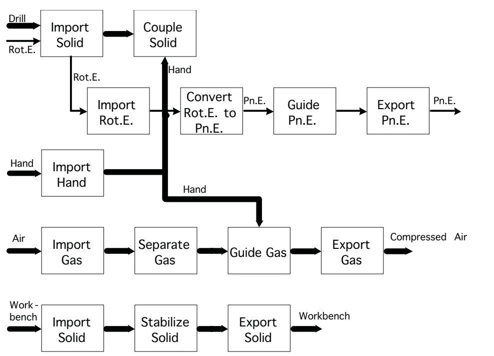
EFDM			FMEA
Function	Historical Failures	Recommended Actions	Recommended Actions
Transmit Pn.E. Guide Pn.E. Stabilize Solid	Yielding Fretting Fatigue Direct Chemical Attack	-Perform x-ray testing on a sample of parts to check for material impurities -Perform testing on a sample of completed parts to check for ability to withstand impact -Choose material with resistance to water, oil, etc… -Ensure good gasket fit with additional sealant -Pressure test assembled wrench to ensure good seal -Explore the implementation of an improved upstream filter	-Non-destructive testing of component under common loading conditions -Explore self cleaning filter for the incoming compressed air -Perform testing to ensure a quality seal between the back plate and the housing

If the EFDM had been used during the design of the transformer case and cooling fins, it is likely that these transformer failures would never have occurred. The cooling fins in this situation perform the function of "transmit thermal energy." When querying the rotorcraft function-failure knowledge base with this function, the most commonly occurring failure mode is high cycle fatigue. This would have brought the possibility of this failure into the sight of the designer and suggested a thorough fatigue analysis or some corrective measures to avoid this failure.

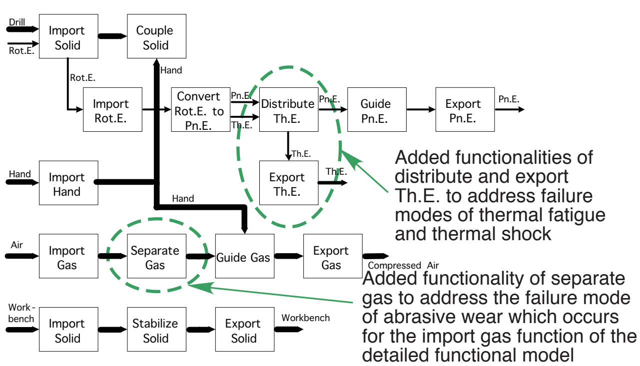
6.1 Advantages and Disadvantages of the Function-Failure Design Method

Many advantages can be gained by beginning the failure analysis of a new design at the conceptual design stage. The main advantages come from arriving at a more reliable product without the need for multiple redesigns in order to eliminate failure modes in advanced stages of the design process, as happens in an FMEA approach. Another advantage over FMEA is that there is no need for a team of engineers with various backgrounds to conduct the analysis. The EFDM allows engineers with novice design experience to use a wealth of historic knowledge to guide their designs toward a goal of being "failure-free." Since a team is not needed in order to conduct the EFDM, the task of failure analysis becomes cheaper and easier to perform.

The use of existing vocabularies to describe failure modes and functionality within the EFDM also shows an improvement over the current failure analysis methods. The common language within the functional basis has been repeatedly verified over a range of engineered products, and is sufficient to describe the functionality of all electromechanical products. Using the functional basis within the function-failure knowledge base ensures that the knowledge base can be used on any new electromechanical design or redesign. The standardized mechanical failure mode vocabulary removes ambiguity in identifying failures and will aid in communication between designers. A more extensive failure mode vocabulary (including polymers, electrical applications, etc.) will allow the EFDM to be applied to a wider range of components and systems, with particular application to spacecraft anomalies,



Compressor Functional Model before applying the EFDM
(a)



Compressor Functional Model after applying the EFDM
(b)

Figure 7. Compressor Functional Models.

and is currently under development (Tumer, Stone, and Roberts, 2003; Tumer, Bell and Stone, 2003).

Another advantage of the EFDM comes from its reliance on actual historical data when conducting a failure analysis. No longer will an FMEA team have to develop a list of failures that they "think" will occur for a component. This removes a great deal of subjectivity from failure analysis.

Using the EFDM also offers designers the advantage of producing more complete and accurate functional models earlier in product design. The EFDM aids designers by finding functions necessary to handle the unintended effects of other functions in a functional model. In the compressor design presented earlier, a functional model derived to simply satisfy the needs of the customer can be seen in Figure 7(a). After applying the EFDM analysis to this design problem, the designer added three functions to avoid common failure modes (shown in Figure 7(b)). By deriving a more accurate functional model earlier in design, designers can possibly avoid the need for multiple redesigns.

However, some drawbacks do exist within the EFDM. The most significant one is due to the necessity to develop large knowledge bases to relate failures to functionality. The development of knowledge bases could prove to be a time-consuming task. However, the time spent developing these knowledge bases and keeping them current is offset by the fact that the EFDM will be more effective if it uses an extensive knowledge base.

Furthermore, the EFDM is currently missing some of the analysis that is present within FMEA. The EFDM does not address the "cause" of failure modes nor does it have any conditions for manufacturability. Archiving historical failure "causes" and manufacturing problems in knowledge bases similar to the function-failure knowledge base could address both of these deficiencies. These knowledge bases could then be integrated into the EFDM, allowing the designer to use this historical data to guide their design as well. The EFDM is also currently devoid of analysis that would be analogous to the severity and detectability rankings that are present within FMEA methods. As the function-failure knowledge base grows and is refined, this information will be added and will then be accessible with the EFDM.

6.2 Future Work

Further research is underway to improve upon the failure mode vocabulary of Arunajadai et al. (2002) to include electrical failures and improve the failure definitions concerning composite materials and polymers (Tumer, Bell, and Stone, 2003). These additions to the failure mode vocabulary will allow the knowledge base to be expanded to include components that exhibit these failures.

At this point, the rotorcraft function-failure knowledge base is the only one that that has been developed and rigorously evaluated. It will be necessary to develop other function-failure knowledge bases or add to the existing one in order archive historical failure occurrence knowledge from other areas such as consumer products and the automotive industry. JPL's space missions are currently under study to derive component functionality and extract failure mode information from the existing Problem and Failure Reporting database (Tumer et al., 2003). The expansion of the function-failure knowledge bases will logically occur after the failure mode vocabulary has been increased.

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