Development of a Mechanical Component Failure Database

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SUMMARY & CONCLUSIONS

In this paper, we present a methodology to derive component failure rate and failure mode data for mechanical components used in automation systems based on warranty and field failure data as well as expert opinion. We describe a process for incorporating new component information into the database as it becomes available. The method emphasizes random mechanical component failures of importance in the world of safety analysis as opposed to the wear-out and aging mechanical failures that have dominated mechanical reliability analysis. The method provides a level of accuracy significantly better than warranty failure data analysis alone. The derived database has the same form as that for electrical/electronics databases used in FMEDA analyses used to show compliance with international performance-based safety standards. Thus, the mechanical database can be used in conjunction with existing electrical/electronics databases to perform required probabilistic safety analysis on automation systems comprised of both electrical and mechanical components.

1 INTRODUCTION

Safety instrumented systems (SIS) are automatic systems designed for the purpose of taking action to avoid danger or to reduce the consequences of a potentially dangerous event. International performance-based standards [1,2] require that designers of these systems use probabilistic analysis for equipment failures classified as “dangerous” to determine if any given design meets risk reduction goals. The analysis must incorporate all equipment needed for the automation system to protect against pre-identified hazards. Typical equipment includes mechanical/electronic sensors, electronic signal conditioning modules, microcomputer controllers, relays, solenoids, pneumatic actuators and valves. The probability of failure analysis requires, at a minimum, the failure rates and failure modes data for all subsystems.

SIS typically consists of one or more safety instrumented functions (SIF). Each SIF has three subsystems. Each subsystem consists of one or more instrumentation products. A sensor is used to detect the potentially dangerous condition. A “logic solver” is used to perform filtering, timing, comparisons and other functions required to generate a trip signal. A “final element” is used to actually execute the required action. An example typical of the petro-chemical industries is shown in Figure 1. This SIF measures pressure in a vessel and closes feed valves to prevent rupture if pressure becomes too high.

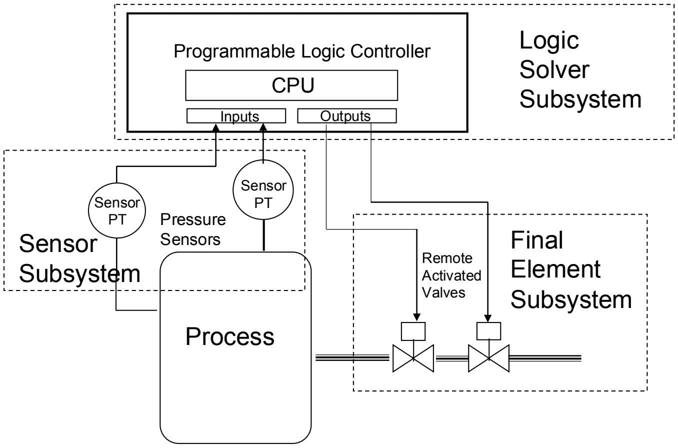

Figure 1 - Safety Instrumented Function Example – High Pressure Protection

To perform the safety analysis for the SIF, the designer needs to estimate or predict (in the case of a design not yet constructed and/or fielded) the failure rates and failure modes of each of the products used in each subsystem.

For the electrical/electronics equipment, Failure Modes, Effects and Diagnostic Analysis (FMEDA) techniques [3,4,5] have been used to provide failure rates, failure mode distributions, and diagnostic self-test capability measures for products based on extensive component failure rate and failure mode databases [6,7,8]. In essence, these techniques compute a product failure rate based on the failure rates and failure modes of the components which comprise the product. These techniques rely on the existence of, and regulatory authorities' acceptance of, these component-level databases of failure rate and failure mode data that have been collected (over many years) from field failure data for a wide variety of electrical/ electronics components.

For products that contain only electrical/electronic components these techniques provide the required subsystem failure rates and failure mode information. However, when the subsystem contains mechanical components (either alone or in conjunction with electrical/electronics components) these techniques cannot be applied because of a lack of mechanical component failure data. No database, similar to the electronics component failure database, yet exists for mechanical components. If such a database of failure rate and failure mode information for mechanical components existed, it could readily be used in conjunction with FMEDA techniques to generate the information required at the product level to comply with the new standards [1,2].

While it could be argued that a variety of mechanical failure models to predict failure rates exist, it is also true that most work on mechanical component failure models is focused on mechanical failure due to aging or wear-out. However, in the highly-maintained safety systems of relevance to IEC 61508 [1], mechanical failures due to aging and wear-out should be infrequent occurrences due to preventive maintenance. The failures that are principally of concern are random failures during the useful life of the equipment. Thus, there is a need for techniques to estimate the rates of random mechanical component failures in order to perform the probabilistic failure analysis required.

In this paper we describe the methods we used to obtain failure rates and frequency of failure modes for a variety of mechanical components. These components include springs, plungers, seats, o-rings, diaphragms, bearings, structural members and many others. These are components used to build solenoid valves, pneumatic actuators, hydraulic actuators, many different types of valves and other mechanical control products.

2 *NOTATION*

FMEDA	Failure Moe, Effect, and Diagnostic Analysis
SIF	safety instrumented function(s)
SIS	safety instrumented system(s)
λ_i	initial product failure rate in failures/hr
λ_{prod}	product failure rate in failures/hr

3 *INITIAL DATABASE*

3.1 *Overview of Creation of Initial Database*

FMEDA analysis techniques use electrical/electronic *component* failure rate and failure mode data to calculate *product* failure rate and failure mode data. In order to create a relevant mechanical *component* failure rate and failure mode database, we essentially "reverse engineered" existing product level mechanical failure data to estimate component level information.

First we estimated the total product failure rate, λ_{prod}, and estimated the relative frequency of failure attributable to each component. Individual component failure rates were then estimated by multiplying λ_{prod} by the relative frequency of failure attributable to that component. Finally, expert opinion was used to estimate the relative frequency of each of the failure modes for each component.

The overall process used to produce the initial mechanical component database is shown in Figure 2. Below we provide a detailed description of the process. Note that due to the proprietary nature of the manufacturer's data, the actual numbers used in the example are purely hypothetical. They are intended to illustrate the process incorporating expert opinion and are not to be taken as actual data for the product.

3.2 *Estimating λ_{prod} and Relative Frequency of Component Failures*

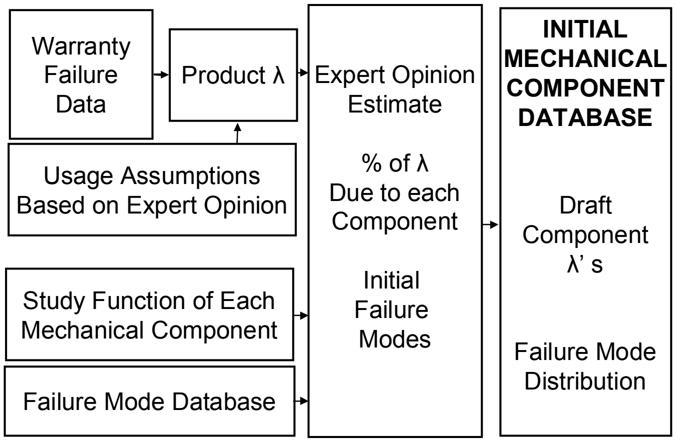

Figure 2 - Initial database creation process

The initial database of mechanical component failure rates was created during the analysis of a valve positioner, an electro-mechanical product that implements microprocessor-based control of a pneumatic subsystem. The product has been in production for several years and the company has a good database of warranty failures including failure analysis to identify the specific component failure which caused the product failure. Warranty failures are a subset of all field failures. They include only the failures reported during the warranty period. Generally a warranty failure database will contain no information about actual operating hours prior to failure.

To create the initial database for component failure rates and failure mode distributions, we first estimated an initial product failure rate, λ_i, as…

λ_i = estimated total # of warranty failures / total operational hours during warranty period (1)

The warranty data clearly contained the total number of *reported* failures. However, not all failures are reported by users even during the warranty period. Based on the expert opinion of the service and reliability group of the product manufacturer, we believe about 70% of all warranty failures were reported while the remaining 30% were unreported. Consequently, we estimated the actual total number of failures as…

estimated total # of warranty failures = total # of reported failures during warranty period / 0.7 (2)

The estimated total operational hours during the warranty period were computed based on the operating hours during warranty of all fielded product units (whether or not a failure occurred in a given unit) assuming that the product unit operates 24 hours a day and was put in service 3 months after its shipping date. The 3 month figure is typical of the average delay between shipment, and installation and startup.

Next, the relative frequency of failure was computed for each component as…

relative frequency of failure of a component = # of times a particular component failed/total # reported failures (3)

This resulted in the fraction (or percentage) of product failures attributable to a given component. At this point, a group of three experienced (20+ years each) mechanical, service and reliability engineers from the product manufacturer were asked to review the relative component failure rates. Based on their expertise, adjustments were made.

Say a particular component contributed to 25% of the reported product failures, but the experts felt that the 25% figure was too high. Their reasoning was that the 25% figure included a number of component failures due to a manufacturing problem which had since been corrected. Based on their expert opinion, the 25% relative failure rate was reduced to 20%, and the 5% removed from that component's relative failure rate was apportioned (again using expert opinion) over the remaining components with reported failures. Thus, the relative component failure rates summed to 100%.

However, a significant number of product components (about 30) had no failures in the warranty data. Yet clearly they *could* fail. This implies that λ_i underestimated the actual product failure rate, λ_{prod}. Rather than assign these components a relative failure rate of zero, initially each was assigned a modest relative failure rate of 0.1% adding an additional 3% to the relative failure frequency. Thus the total relative failure frequency summed to 1.03 instead of 1. λ_{prod} was estimated as…

$$\lambda_{prod} = \lambda_i * 1.03 \qquad (4)$$

This final estimate of product failure rate, λ_{prod}, was compared with product failure rate data from other databases [9,10,11] in order to check for reasonability. We then estimated individual component failure rates as λ_{prod} times the relative failure frequency for each component.

3.3 *Estimating Relative Frequency of Component Failure Modes*

Our warranty data did not include any failure mode information. To obtain estimates for relative frequency of failure modes, our expert group then studied the function of each mechanical component and created an initial list of failure modes for each component. Using their expert opinion, they assigned a relative frequency to each of the failure modes. This completed our initial component failure database that consisted of a list of components, the failure rate of each component, the failure modes of each component and the relative frequencies of each failure mode. The FMEDA analysis technique was then applied using the data in the initial mechanical component database [12] and the accepted electrical/electronics databases to estimate the product failure rate as a function of product failure mode. These results were checked for reasonability by the expert team.

4 DATABASE UPDATES AND VERIFICATION

4.1 *Database Augmentation Based on Another Product*

Analysis was required for a second mechanical product. This product was of similar functionality to the product used to create the initial component database but was produced by a different manufacturer. When we tried to use the initial component database to perform a FMEDA on this new product, we discovered that some different design principles were used in the new product and components existed in this product that did not appear in the initial database.

In this case there was no good field failure data to use to estimate the component failure rates for the new components. However, the mechanical designers and service experts for this product were available so the initial database was augmented with expert estimates of component failure rates and relative frequency of component failure modes for the new parts. Using this new, augmented component database, a FMEDA analysis was performed to estimate product failure rate. The results were reviewed by the second set of experts for reasonability and adjusted by changing the new component failure data based on their experience.

4.2 *Verification of Mechanical Component Database*

Clearly, to verify the correctness of the above described techniques for building the database of mechanical component failure rates and frequencies of failure modes, we should ideally perform a FMEDA analysis to estimate product failure rates for a product (not used to build the database) with good field failure data. We then could compare the FMEDA estimate of product failure rates to the product failure rates computed from the field failure data.

Detailed end-user field failure data, based on periodic inspection and testing, became available for a third mechanical instrumentation product. Such end-user field failure data is considered to be of the best kind because it inherently incorporates field application conditions. Unfortunately, it contained some components not currently in the database. Therefore, the database was once again augmented with new component information based on expert opinion. Then a FMEDA analysis using the newest mechanical component database was performed for this product and the results were compared to the field data. The FMEDA-estimated product failure rate was about 50% larger than that computed from the field data. This was considered quite acceptable. The database *should* produce conservative estimates because it is difficult to know or predict field application conditions when performing a FMEDA analysis.

4.*3 Review, Feedback, Update*

The steps described above for augmenting the mechanical component failure database amount to a continuous review, feedback, and update process which is illustrated in Figure 3.

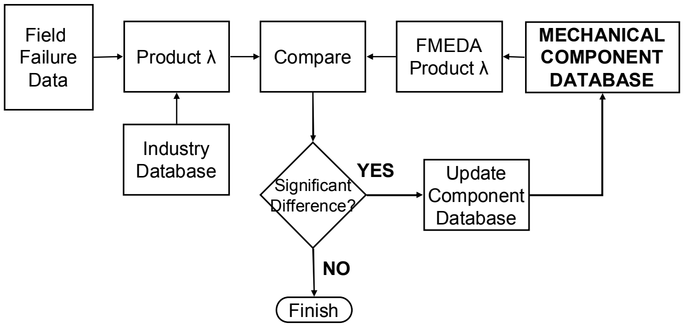

Figure 3 - Mechanical component database update process

The feedback loop has been performed many times now over a wide variety of mechanical instrumentation products including:

a. Floating Ball Valve (2)
b. Trunion Mount Ball Valve (3)
c. Spool Solenoid Valve (3)
d. Pilot Operated Spool Solenoid Valve (2)
e. Hydraulic Solenoid Valve
f. Quick Exhaust Valve
g. Pneumatic Booster Relay
h. Poppet Solenoid Valve
i. Pilot Operated Poppet Solenoid Valve
j. Pressure Relief Valve
k. Gate Valve
l. Butterfly Valve
m. Triple Offset Butterfly Valve
n. Globe Valve
o. Valve Positioner (4)
p. Piston Pneumatic Actuator
q. Rack and Pinion Pneumatic Actuator (3)
r. Diaphram Pneumatic Actuator

Each of these product types has different design characteristics and each review has added knowledge to the database. The component descriptions and application conditions have been refined with each review.

5 APPLICATION CONDITIONS

One of the consistent issues highlighted in the feedback process was the need for new components based on different application conditions. When this became apparent, new components were created with a description that included the new application conditions. In order to attempt to make the set of application conditions comprehensive, mechanical design experts from different backgrounds reviewed each part. The key design variables were identified and documented. Then a failure rate for each set of conditions was estimated based on ratios by these experts.

One example is a coil spring. The key variables identified by the mechanical designers for a coil spring included initial spring set, cycle rates in normal operation, cycle stroke length, maximum load versus spring rate, ratio of spring length to coil diameter and wire size.

Each design variable was categorized into several "order of magnitude" type buckets. The relevant combinations were defined and for each combination a new part entry was created in the database with failure rate and failure mode distribution.

In addition to specific design variables, end-user application conditions were considered. It was recognized that the database should include random failures due to:

a. random environmental stress
b. material defects
c. probability that the product designer did not predict all application conditions
d. accidental misapplication and
e. accidental abuse in the end application.

No consideration was made to account for failures due to wear-out (end of useful life) conditions. No attempt was made to create an analytical equation to calculate the component failure rate as a function of the design variables. This was not needed to achieve results sufficient for safety analysis and it was agreed that not enough data existed for this purpose.

An example set of components is shown in Table 1. The first five columns of Table 1 are part descriptor fields. The failure rate is the sixth column of Table 1 (in FITS). The failure modes and the distribution of each mode are presented in subsequent columns in Table 1.

ID	PGroup	PPrimary	PSecondary	Application	Lambda	FModeA	Distributi	FModeB	Distributi
73	spring	coil	tension	any design, formed hook on end of spring	200	settle	0.3	break	0.7
46	spring	coil	compression	low cycle design, full stroke, low cycle	100	settle, loss of force <20%	0.3	break	0.7
60	spring	coil	compression	low cycle design, partial stroke, low cycle	25	settle, loss of force <20%	0.3	break	0.7
59	spring	coil	compression	high cycle design, full stroke, high cycle	60	settle, loss of force <20%	0.3	break	0.7
58	spring	coil	compression	high cycle design, full stroke, low cycle	25	settle, loss of force <20%	0.3	break	0.7
47	spring	wave	compression	high cycle design, partial stroke, low cycle	10	settle	0.8	break	0.2
48	spring	disc, bellville	compression	Fixed load, very restricted stroke and cycle	5	settle	0.1	break	0.9
71	spring	coil	compression	any design, position retention, no significant cycles or stroke	5	settle, loss of force <20%	0.3	break	0.7
56	spring	coil	compression	high cycle design, partial stroke, high cycle	25	settle, loss of force <20%	0.3	break	0.7
49	spring	leaf	flex	high cycle design, partial stroke, high cycle	25	settle	0.8	break	0.2

Table 1 - Spring Failure Data

6 COMPREHENSIVE REVIEW

Once the database included all components from the mechanical instrumentation products listed above, a comprehensive review was conducted. Two independent experts, each with 30 or more years of experience, and two exida engineers, who had participated in the development of the database, re-examined each component entry performing a relative comparison of all database numbers. Some entries in the database were modified to make the database more conservative.

6 RESULTS

The results of the first task (initial database construction) clearly show the feasibility of constructing a database for mechanical component random failure rates and failure modes using existing field failure data.

The "analyze and compare" approach has been used on nearly thirty different applications with comparison results used to update and enhance the original database. The feedback of experienced mechanical designers has been invaluable as good field failure data is rarely available. The result is now a set of mechanical component failure rate and failure mode numbers that produces results comparable to and agreeable with expert opinion as well as some limited field failure data.

We believe that the method provides a higher level of accuracy than limited field failure analysis alone. Not only is field failure data limited in quantity but it is often of questionable quality. One important variable is the number of failures actually recorded. It is generally acknowledged that field failures of less expensive equipment are very likely to be underreported compared to the reporting of field failures for more expensive products.

The mechanical FMEDA method in conjunction with the mechanical component database is now being used for analysis of safety protection functions and has been accepted by regulatory authorities in various parts of the world. The results of the mechanical component database have been published [13].

7 FINAL NOTES

The methods developed represent an ongoing work. We continue to gather data on specific products in different applications. We are expanding the data to include end of life constraints in terms of operating time or cumulative cycles. Additional operating profiles are also being added as new applications, such as automotive, are considered. Additionally, we recently received four additional years of field failure data on the original mechanical product. We plan to perform a new FMEDA analysis on this product and compare the results to the product failure rates estimated from this new field data.

8 ACKNOWLEDGEMENTS

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