Application of Advanced Failure Analysis Results for Reliability and Availability Estimations

S. Rudov-Clark, J. Stecki, and C. Stecki
PHM Technology Pty Ltd, Melbourne, Victoria, 3001, Australia
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srudov-clark@phmtechnology.com

Abstract— A software tool was developed to simulate the system-wide effects of all part or component level failures that can be enumerated at the design or later stage in the life-cycle of a complex system.[1,2] The basic analysis output is a propagation table which lends itself to a number of different uses, including the estimation of system reliability and availability. This paper outlines the methodology developed to apply the failure analysis results to system reliability and availability analysis using a functional-dependency based approach. The case study provided illustrates how the analysis can be refined and updated through the system life-cycle to support design optimisation, configuration management and mission planning.

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1. THE MADE APPROACH TO FAILURE ANALYSIS

Conceptual design analysis can be conducted on a system model which consists of no more than functional 'black boxes' which represent the functional requirements of the system. Figure 1 provides the example of a simple hydraulic actuator system in which only the top-level functions have been defined. The black and red lines connecting the in-ports and out-ports of each element represent the flow of functional outputs between them, thus providing a functional dependency mapping of the system. The system consists of a source of flowrate (a pump), fluid lines, a flow control valve and an actuator.

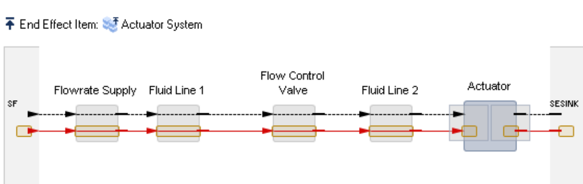

Figure 1 – Functional model of Actuator System

At the conceptual stage of design, the potential failure modes are hypothesised by 'disturbing' the functional outputs of each system element.[1] These qualitative disturbances are applied using the 'fault injection' setting in which the user may select an upwards or downwards change in the output flow (or dynamic parameters) of the element. Fig. 2 presents the fault injection settings of the relief valve in terms of the parameter 'flow resistance', whereby failure of the relief valve can be injected as an increase or decrease to its flow resistance.

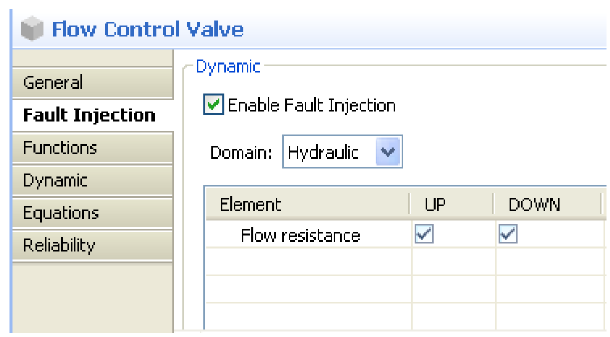

Figure 2 – Fault injection settings for relief valve

The responses to component level failures are simulated using either Fuzzy Cognitive Map (FCM) analysis or Dynamic Analysis (DA), depending on the modeling approach adopted by the user. In this paper we present the results of DA, which employs the qualitative bond graph approach. The dynamic method of analysis requires the additional input of the dynamic properties of each component. Fig 3 displays the properties of the relief valve, which include the dynamic group (according to bond graph theory), type and dynamic variable, resistance factor. These properties, together with the system functional topography, are used to automatically construct a bond graph of the system. Provided the user has complied with the rules for constructing a causally correct model, the automated analysis will calculate both upstream and downstream system responses to every injected component failure. The software provides assistance to the user to ensure that the model is causally correct. The software constructs the state equations for the system and solves them using the Bond Graph method.

[1] 978-1-4244-7351-9/11/$26.00 ©2011 IEEE
[2] IEEEAC paper #1215, Version 4, Updated Jan 13, 2011

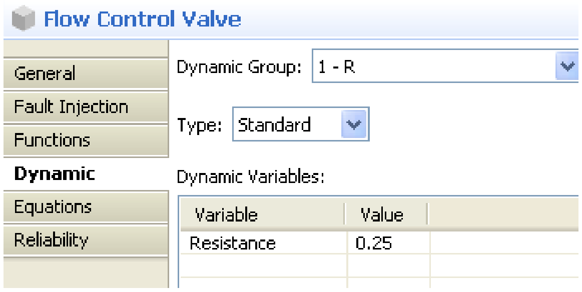

Figure 3 –Dynamic properties of the Flow Control Valve

2. Reliability Analysis

RBD Analysis

The MADe software can convert the functional diagram into an RBD by converting the flow connections between components into reliability connections. Where the multiple flow connections exist between two items, they are represented by a single reliability connection. All components are assumed to have exponential failure distributions and are connected in series. [2] The model was converted to an RBD (Fig. 4) and the analysis results, using series/parallel decomposition method as shown in Figure 4. The actuator system is a simple grouping of elements in series, therefore the probability of failure is the probability of each element failing as independent, non-exclusive events. This is a simple summation of the P(f) of each component less the product of P(f) for each possible combination of these failure events.

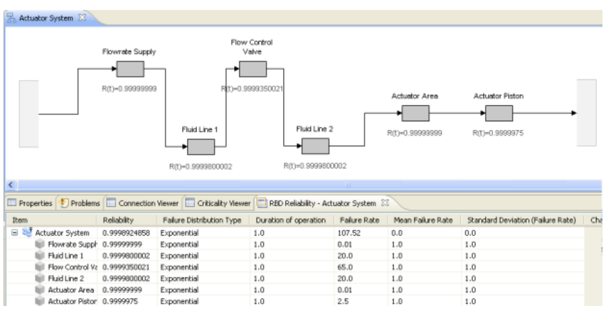

Figure 4 – Reliability Block Diagram of the system

Functional Failure Analysis

During failure analysis, the failure of every component was propagated through the system to determine the end-effects (usually the system failure modes). The result is a list of 'failure paths' which describe the series of events that lead to system failure. The results of failure analysis can be viewed in Fault Tree format [3] for convenience, as shown in Fig. 5.

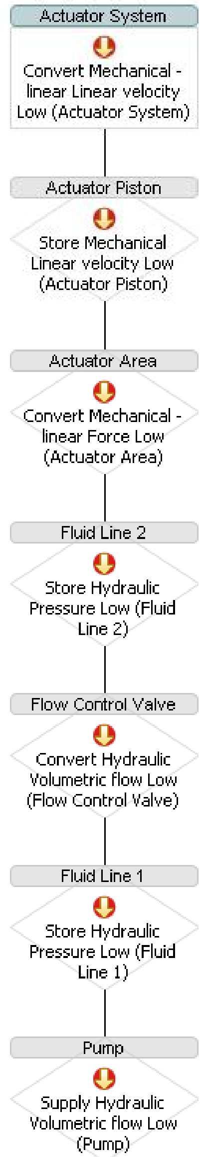

Figure 5 – Fault Tree display of a cut set for actuator system failure.

Functional Reliability Analysis

Functional reliability analysis of a system traces backwards from each system failure mode to each possible source, via the failure paths which, for conceptual designs, begin at component failure modes.

The functional reliability of each component is calculated based on the failure rate and duration of operation of the item, or of each part within the component. The process is outlined in the flowchart in Figure 7.

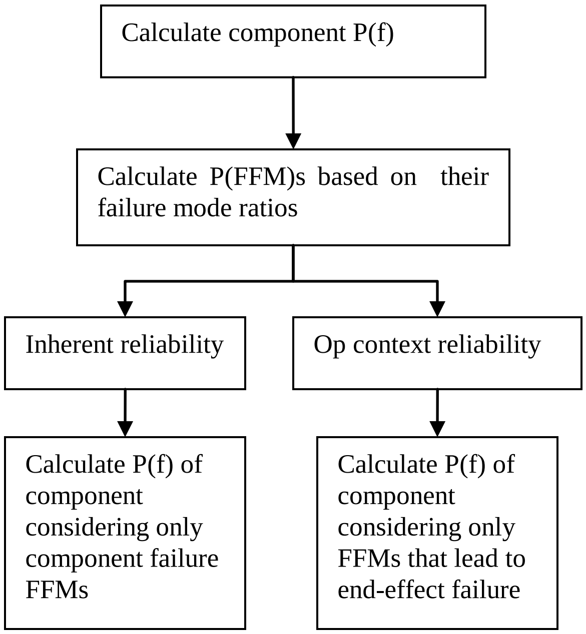

Figure 7 - Flowchart for component reliability calculations

The failure rate for each component failure mode is calculated according to its mode ratio according to equation (1) for exponential failure distributions, or equation (2) for Weibull failure distributions.

$$\lambda_{FFM} = \lambda_{component} \cdot \alpha_{FFM} \quad (1)$$

$$\eta_{FFM} = \eta_{component} / \alpha_{FFM} \quad (2)$$

Where λ denotes a failure rate in failures per million hours, α is the mode ratio and η is the characteristic life of the component (which is a Weibull statistical term).

The probability of failure for each component failure mode is calculated based on the input failure data, which may be a Weibull distribution or an exponential distribution, according to equations (3) and (4).

$$P(FFMi) = 1\text{-}EXP(-t_{op} * \lambda p/1000000) \quad (3)$$

$$P(FFMi)=1\text{-}EXP(-((t_{op}/\eta)\text{^}\beta)) \quad (4)$$

Where t_{op} is the duration of operation for the component, λ_p is the component failure rate (for exponential failure distributions), η is the characteristic life of the component for Weibull failure distributions and β is the slope of the Weibull failure distribution

The overall system probability of failure is then calculated as the sum of each system response to failure (failure mode) that has been nominated by the user as a system failure. The reason why system responses are nominated as failures is because a failed component may generate a system response that is not a failure. That is, the deviation in functional output of the system may still lie within the acceptable limits for nominal operation.

The probability of a system failure mode is the calculated based on the probability of each of the failure paths leading to it (numbered by roman numerals). The calculation includes the union of each failure event (path) which is based on the assumption that the paths are non-exclusive, equation (5) [4].

$$P(SysFFM) = P(FFMi \cup FFMj \ldots \cup FFMn) \quad (5)$$

To conduct Reliability and Availability analysis on the actuator system, an estimate of the failure rate and Mean-Time-To-Repair (MTTR) of each component is required. At conceptual design stage this could be taken from the reliability data of similar components. If the intended operating mode of the system is known, duration of operation can be specified; otherwise a default value of 1 hr is used. The input data required for reliability analysis of a system conceptual design is shown in Table 1. The analysis results for the actuator system are displayed in Table 2.The probability of failure of each failure mode is determined Two types of functional reliability are calculated: inherent reliability and operating context reliability. Inherent reliability is based on the P(f) of the component functional flow responses (high/low) that constitute a functional failure of the component. The operating context reliability of a component considers only those component functional flow responses that will result in a system (end-effect) functional failure, irrespective of whether the responses fulfil the component functional performance parameters.

Table 1. Data required for reliability analysis of a conceptual design

Data type	Description
Functional failure mode inputs	Up/down disturbances to the functional output flow/dynamic properties Failure Mode ratios
Item reliability properties	Failure rate Duration of operation

Table 2. Functional reliability analysis results for actuator system

Component	FFM	λ_{FFM}	$P(f_{FFM})$	End effect
Fluid Line 1	Pressure down	20	1.99998×10^{-5}	Linear velocity low
Fluid Line 2	Pressure down	20	1.99998×10^{-5}	Linear velocity low
Flow Control Valve	Volumetric flow down	45.5	4.5499×10^{-5}	Linear velocity nominal
Flow Control Valve	Volumetric flow up	19.5	1.94998×10^{-5}	Linear velocity nominal
Actuator Piston	Linear velocity down	2.5	2.5×10^{-6}	Linear velocity nominal

Overall probability of system failure is the sum of the P(f) of its failure modes. From Table 2 the P(f) of failure mode 'linear velocity' can determined by summing the P(f) of the component failures that lead to it:

$P(f_{end\ effect})$= 3.99996E-05

Given that linear velocity low is the only system failure mode, the reliability of the system is therefore calculated directly from the P(f).

R_{system} = 0.99996

Assuming an exponential failure distribution for the system, the system failure rate can be estimated using the inverse of the expression for P(f) for exponential failures:

λ_{system} = 40 fpmh

Comparing results for the RBD and Functional reliability method, Table 3, it is clear that filtering out the effect of component failures that do not lead to system failure provides a less conservative estimate of overall system reliability. The detail provided in functional reliability analysis however is more useful for system design, when the relative impact of components on system reliability may be used to determine the optimal configuration or the reliability requirements of the components, for example cost/quality trade studies.

Table 3. Comparison of reliability analysis results for RBD and functional reliability methods

Reliability parameter	RBD method	Functional reliability method
P(f) System failure, actuator linear velocity high	n/a	0
P(f) System failure, actuator linear velocity low	n/a	3.99996E-05
System reliability	0.999892	0.99996
System failure rate	107.52	40.0

Figure 7 presents the relative impact that each component has on system reliability. The relative impact is calculated not simply on the component reliability, but on the contributions that each failure mode of the component to the end-effect (system) failure modes. The system failure modes were nominated as 'Low linear velocity' and 'Very Low linear velocity'. Only components whose failure modes will generate a Low or Very Low steady-state system level response will affect the system reliability. Although increased flow resistance in the Flow Control Valve causes a Low transient response at the system level, only the two fluid lines generate a Low steady-state response, therefore the pie-chart presented in Fig. 7 displays a 50/50 split between the two (identical) fluid lines).

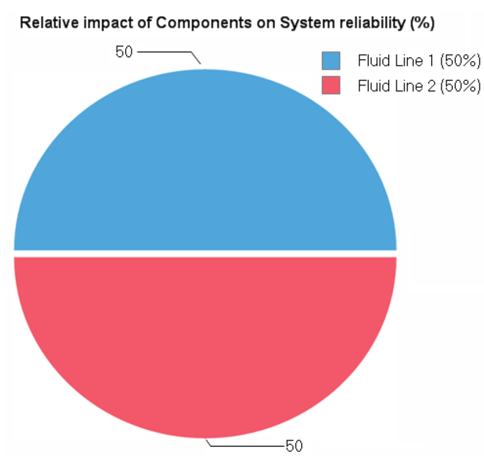

Figure 8 – Relative impact of components on system reliability

3. CONCLUSION

The model and analysis results presented herein are a simple but clear example of how the utility of failure analysis can be extended beyond that of a post-design (sometimes perfunctory) checklist to fulfil contractual and regulatory obligations. By identifying the functional impact of individual component failure modes on the system functional performance, the relative importance of each component with respect to system functional reliability can be assessed. This information is particularly useful in the design phase of a system life-cycle when conducting reliability allocation as part of the component selection process

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BIOGRAPHY

Shoshanna Rudov-Clark (PhD) is an aerospace engineer at PHM Technology. She has conducted research in the area of composite materials for aerospace applications within the Department of Aerospace Engineering at RMIT-University (Melbourne), and has worked in the area of aircraft structural integrity for the Defence Science and Technology Organisation (Melbourne).

Jacek Stecki (PhD) is the Principal Engineer of PHM Technology. He has extensive experience in the fields of offshore engineering, simulation and machine condition monitoring and is a prolific writer on the subjects of maintenance aware design, fluid power, simulation, condition monitoring and offshore engineering

Chris Stecki is CEO of PHM Technology Pty Ltd and has been engaged in the commercialization of the MADe software in the Defence and aerospace sectors since 2006.