Automated design and optimisation of sensor sets for Condition-Based Monitoring

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Abstract

A software tool was developed for automating the design, optimisation and performance assessment of sensor sets to support the Prognostics and Health Management (PHM) of the Joint Strike Fighter. The software (MADe) is based on a model-based simulation of failure propagation through the various subsystems of the aircraft to generate a system-level failure modes and effects database. The failure database generated by this analysis is used to identify the monitoring requirements of the system to achieve a specified level of failure coverage. This paper outlines the analysis approach and provides a case study to demonstrate the application of automated sensor design and optimisation.

Keywords: PHM, FMEA, system health monitoring, failure database

Introduction

The traditional system design process is primarily concerned with meeting performance specification and therefore maintainability is usually not included explicitly in the design process. As a result, Useful Life, Fallback analysis, Hazard analysis, Failure analysis and Maintenance analysis tasks are typically carried out only after the system design has been completed. When carried out post-design or post-manufacturing, the results of these studies have only a limited impact on design of the system which by then is already completed and the system may already exist. Thus, if the results of these analyses show that there will be unfavourable impact on maintainability of the system the corrective actions have to be carried out by modifying existing hardware, adding sensors, revamping maintenance procedures. The PHM paradigm aims to achieve improved reliability and maintainability of systems by applying failure analysis, model based monitoring and artificial intelligence technology to predict when a machine will need to be serviced or replaced. Successful application of PHM requires the integration of system reliability and safety into the design process, in order to identify PHM requirements and optimise system design to fulfil them.

The concept of a Maintenance Aware Design environment (MADe) is considered to be an enhancement to, and front end methodology for, Prognostics and Health Management (PHM). The MADe approach is based on the application of *functional analysis*, *failure analysis*, *sensor selection algorithms* as well as *prognostic and health monitoring* tools in the early design stages i.e. during development of specification, concept formulation (synthesis) and hardware implementation. It provides a framework within which PHM related software tools can work together to provide design support for two major tasks. The first is to identify potential operational and diagnostic problems in the conceptual stages of system design and provide aids to making the necessary capability and requirements trade-offs to optimise design of the final system. The second task is concerned with what-if analysis of new design concepts as well as pre-existing hardware systems from the point of system's PHM and health management capabilities.

The basic tool in MADe is automated FMEA/FMECA which identifies functional faults by qualitative modelling and/or simulation of generalised information (energy, information or mass) flow in a system [1]. The effects of failure modes, identified by FMEA, are considered to be 'symptoms' from a health monitoring point of view. The results of FMEA are used to determine diagnostics requirements, (i.e.: the location and types of sensors) and also to formulate models for use in diagnostic and prognostic work. In this paper the sensor selection and minimisation methodology is outlined using a simple hydraulic actuator system to demonstrate the method and verification of analysis results.

Sensors analysis technique

To demonstrate the capabilities of the MADe sensor module, an actuator system was modelled using the MADe system modelling interface. The model, shown in Fig.1, consists of functional blocks representing system elements connected by black lines which represent the interactions between them in terms of energy flow. For the energy-based model of the actuator system, the functions are defined using a standardised functional taxonomy [2] and by assigning dynamic properties to the component in accordance with the bond graph methodology, for example, the fluid line pictured in Fig. 1 transports fluid from the flowrate supply to the relief valve. In terms of energy, the ideal fluid line acts as a capacitor for hydraulic energy - the input to the fluid line being volumetric flow, and its output hydraulic pressure - thus the bond-type of the fluid line is 0-C [3].

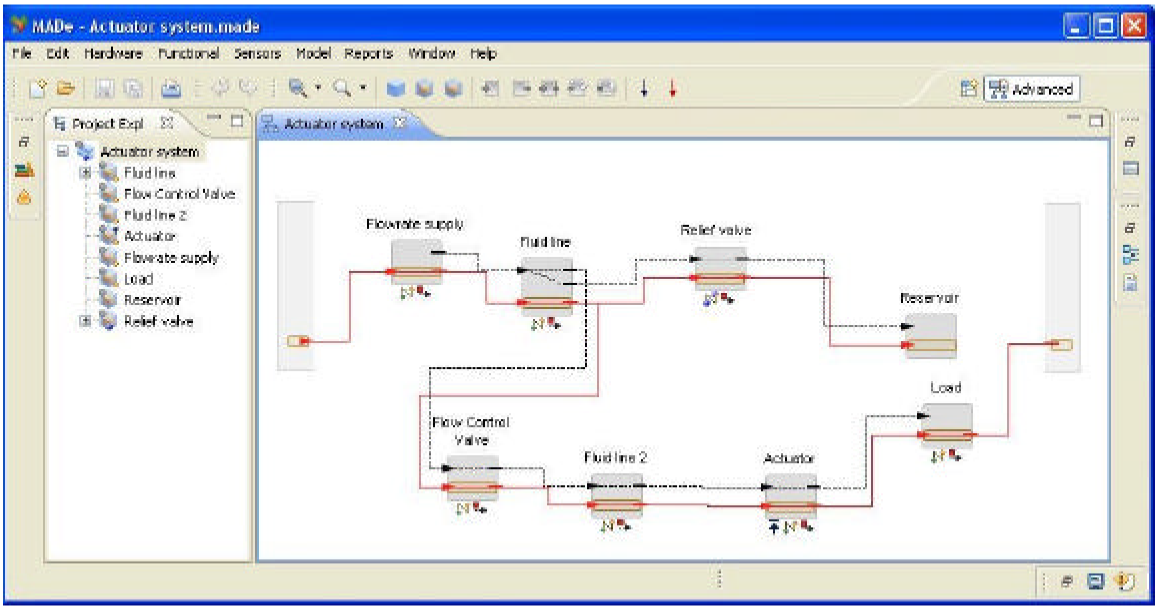


Fig. 1: Actuator System model

Having defined the functions and flows between components, their failure modes are identified in physical terms using a 'failure diagram'. The diagram enables the engineer to map the sequence of events that result in a failure mode, and forms the starting point for automated processing of the Failure Concept Map for functional FMEA. The failure diagram is also used to calculate the criticality of each causal path from initial failure cause to final end-effect of the failure mode. The failure diagram for the fluid line is presented in Fig. 2. Using the MADe terms for failure cause (triangular icon), failure mechanism (diamond icon) and fault (circular icon) of each part of the line (tube and fitting), the physical process of failure is mapped and causal connections assigned. The polarity, progression rate and causal strength of each connection are used in subsequent criticality analysis. The octagonal icons represent losses and other symptoms associated with the failure process that may be used for monitoring and failure identification purposes.

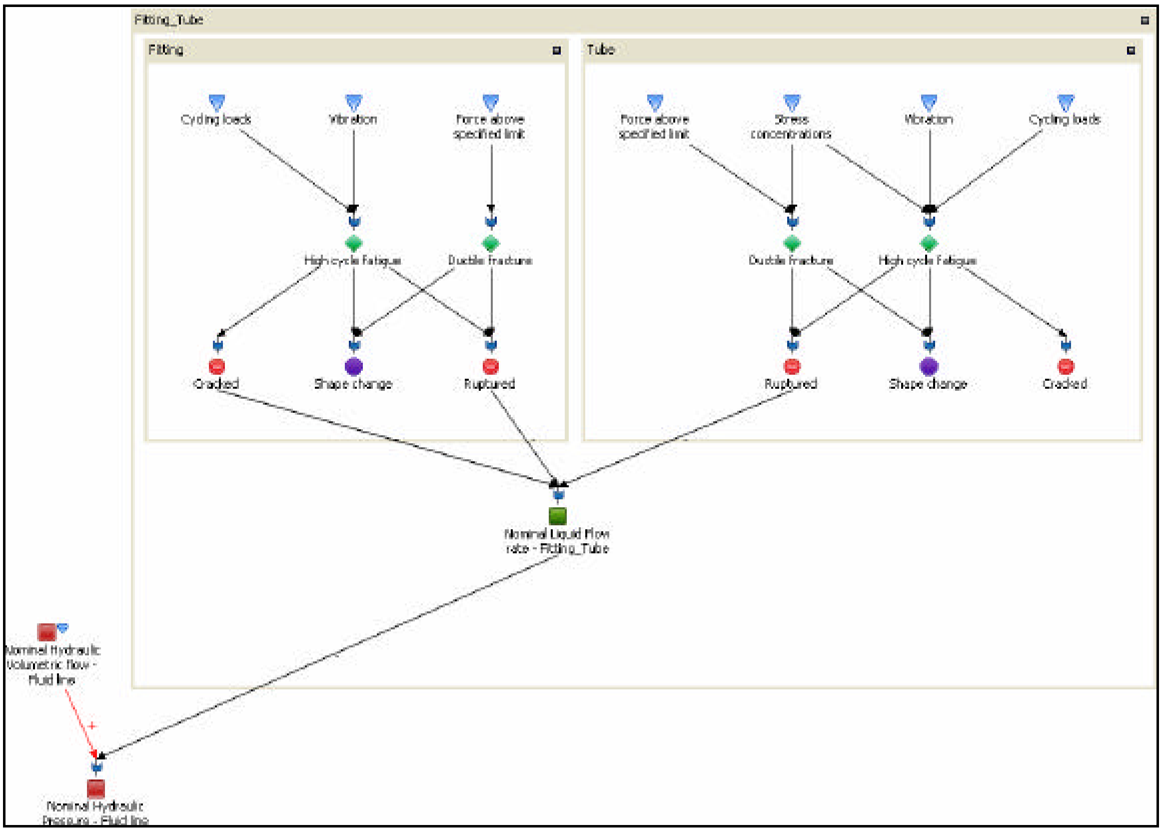


Fig. 2: Failure diagram of the fluid line

Automated Failure Modes and Effects Analysis is initiated by activating the failure modes for each component in the actuator system. For an energy model, failures are activated by increasing and decreasing the input energy flow to the component. For example, the input flow to the fluid line is volumetric flow, and its output flow is hydraulic pressure. Failure modes of the fluid line, as shown in Fig. 2, are: ‘pressure low’, ‘pressure zero’ and ‘pressure high’. Non-dimensional bond graph analysis considers only high and low values of the output flow, hence ‘pressure low’ and ‘pressure zero’ are treated as the same failure mode (in functional modelling a distinction is made between these two modes). The two failure modes ‘pressure low’ and ‘pressure high’ are activated by perturbing the input of the fluid line, in this case volumetric flow, up and then down. The dynamic response of the system is then calculated using the state equations that are automatically generated using the bond graph methodology. The dynamic response at any location within the system can be viewed within MADe, and the results are collated and output in the traditional MIL-STD-1629A FMEA report [5].

The results of automated FMEA are imported to the MADe sensors module in the form of a propagation table. This table provides the system wide responses to every activated failure mode. The responses provide symptoms that can be used to detect and differentiate between failure modes. Once the results have been processed to provide an optimised sensor set, the propagation table is then used to develop diagnostic rules for interpreting sensor set outputs. The level of failure coverage, preferred locations for sensors, and excluded locations for sensor placement are set by the user. The failure coverage can be selected by manually deleting failure modes that are not to be covered, or by applying a 'criticality threshold' which automatically excludes failure modes whose criticality value is below a set threshold value.

The sensors module can also be used to assess the failure coverage of an existing sensor set. The coverage results are returned to the FMECA module and used to revise the detectability rankings of failure modes to provide an updated criticality assessment of the system. The sensor module supports more comprehensive implementation of the risk mitigation methods indicated by FMECA by enabling the designer to examine different 'what-if' system design scenarios in order to achieve a system design with minimum criticality.

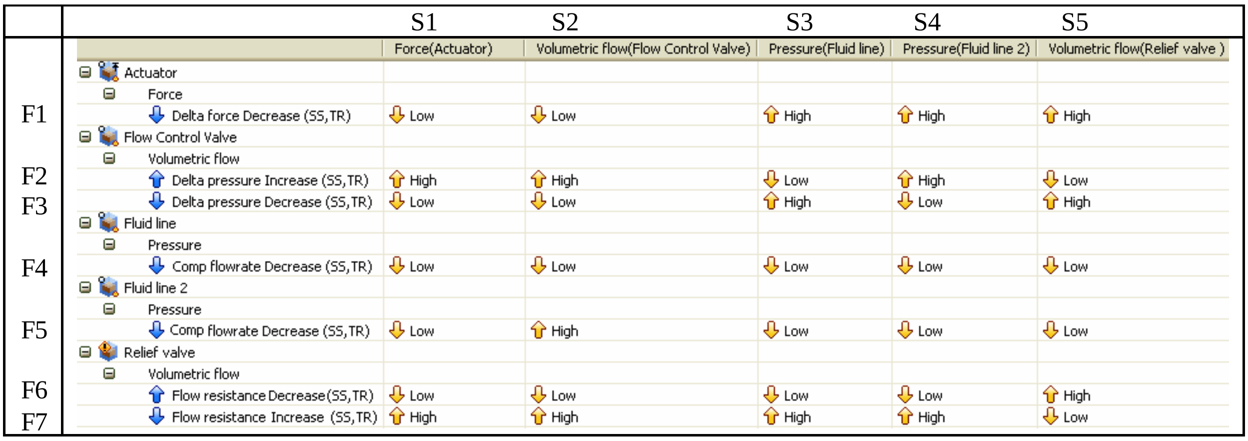
Failure propagation table

Automated FMECA is conducted by activating every failure cause in turn in order to simulate the failure modes of every system element. The response of the system is then analysed using either a dynamic model or by Fuzzy Cognitive Map analysis [2]. The propagation table generated by automated FMECA lists the response of every system element to each activated failure mode in functional terms: that is, as changes to the properties of their output flows. From this table the next and end-effects of a failure mode are identified and presented in a FMECA report. The results are also imported into the sensor analysis module and used to conduct sensor set design. The actuator system model under consideration is dynamic: for this type of model failure modes are activated by 'perturbing' the input energy flows of each system element up or down. Table 1 lists the failure modes for each system element (at the highest indenture level only) and the perturbations applied to activate them.

Table 1: Failure modes and perturbations for actuator system elements (top indenture level)

System element	Perturbation (cause)	ID	Failure Mode
Actuator	Delta force Decrease	F(1)	Actuator - Force Low
Flow Control Valve	Delta pressure Increase	F(2)	Flow Control Valve - Volumetric flow High
Flow Control Valve	Delta pressure Decrease	F(3)	Flow Control Valve - Volumetric flow Low
Fluid line	Compressibility flowrate Decrease	F(4)	Fluid line - Pressure Low
Fluid line	Compressibility flowrate Decrease	F(5)	Fluid line 2 - Pressure Low
Relief valve	Flow resistance Decrease	F(6)	Relief valve - Volumetric flow High
Relief valve	Flow resistance Increase	F(7)	Relief valve - Volumetric flow Low

Fig. 3 shows the propagation table reported in MADe for the system level responses to these perturbations. Every row corresponds to a perturbation used to simulate a failure mode, and the column headers refer to the system response at a location on the system model. For example, perturbing the actuator force down (to simulate failure mode F1) causes an increase in the pressure in the fluid line (location S3 in the system model). The system response numbering system is also used to identify sensor locations for sensor set design and analysis.



		S1	S2	S3	S4	S5
		Force(Actuator)	Volumetric flow(Flow Control Valve)	Pressure(Fluid line)	Pressure(Fluid line 2)	Volumetric flow(Relief valve)
	⊟ Actuator					
	⊟ Force					
F1	⇩ Delta force Decrease (SS,TR)	⇩ Low	⇩ Low	⇧ High	⇧ High	⇧ High
	⊟ Flow Control Valve					
	⊟ Volumetric flow					
F2	⇧ Delta pressure Increase (SS,TR)	⇧ High	⇧ High	⇩ Low	⇧ High	⇩ Low
F3	⇩ Delta pressure Decrease (SS,TR)	⇩ Low	⇩ Low	⇧ High	⇩ Low	⇧ High
	⊟ Fluid line					
	⊟ Pressure					
F4	⇩ Comp flowrate Decrease (SS,TR)	⇩ Low	⇩ Low	⇩ Low	⇩ Low	⇩ Low
	⊟ Fluid line 2					
	⊟ Pressure					
F5	⇩ Comp flowrate Decrease (SS,TR)	⇩ Low	⇧ High	⇩ Low	⇩ Low	⇩ Low
	⊟ Relief valve					
	⊟ Volumetric flow					
F6	⇧ Flow resistance Decrease(SS,TR)	⇩ Low	⇩ Low	⇩ Low	⇩ Low	⇧ High
F7	⇩ Flow resistance Increase (SS,TR)	⇧ High	⇧ High	⇧ High	⇧ High	⇩ Low

Fig. 3: Propagation table for actuator system – system level responses

Sensor discrimination

The propagation table is used to identify system responses that can be used to distinguish between failure modes. The analysis involves a step-wise comparison of the system responses for each failure mode listed in the propagation table to generate MAXTERMS. For 'n' failure modes, the XOR logic rules are applied to each pair of failure modes F(i), F(j), where i=1….n, j=1….n. If the symptoms are different, then G(i,j)=1, if the symptoms are the same then G(i,j)=0. The MAXTERM generated, G(i,j) is therefore a binary text string. If a MAXTERM is a null set, the two failures i and j cannot be discriminated and are identified as an 'ambiguity group' which is reported in the analysis results.

Manual sensor discrimination was conducted by applying the XOR truth table to the propagation table in an excel spreadsheet. The resulting MAXTERMS are presented in table 2 and were found to agree with the MADe auto-generated MAXTERMS. No null sets were found therefore there are no ambiguity groups for system-level failure modes.

Table 2: MAXTERMS for the actuator system (system level of indenture)

ID	MAXTERM	ID	MAXTERM
G12	11101	G34	00101
G13	00010	G35	01101
G14	00111	G36	00100
G15	01111	G37	11011
G16	00110	G45	01000
G17	11001	G46	00001
G23	11111	G47	11110
G24	11010	G56	01001
G25	10010	G57	10110
G26	11011	G67	11111
G27	00100		

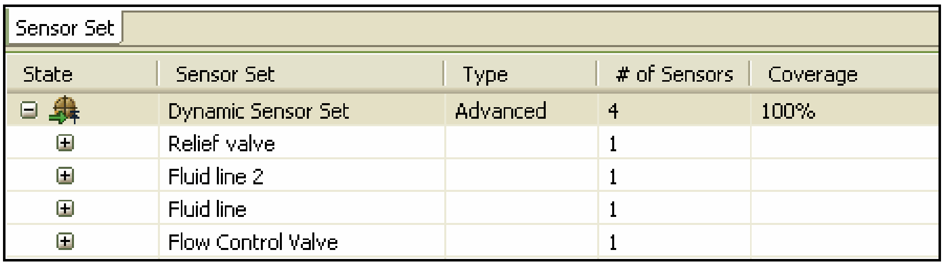
Sensor minimisation

The minimisation process generates MINTERMS: these are sets containing the minimum number of symptoms required to discriminate between failure modes. This is achieved by intersecting the MAXTERMS for each pair of sensor locations until full coverage is achieved.

Appendix 2 presents the MINTERMS that were manually generated for the system level of the actuator model. The results indicate that the minimum number of sensors required to cover all system level failure modes is four sensors. The sensor set that provides 100% coverage is S[2,3,4,5], and this is highlighted in Appendix 2. Referring to the original propagation table (Fig. 3), the sensor set S[2,3,4,5] monitors the following system responses:

- S2: flow control valve, volumetric flow
- S3: fluid line, fluid pressure
- S4: fluid line 2, fluid pressure
- S5: relief valve, volumetric flow

The results for MADe automated sensor minimisation are shown in Fig. 4. It can be seen that a set of four sensors was identified, and that these sensors correspond to those identified by manual analysis and listed above.



Sensor Set

State	Sensor Set	Type	# of Sensors	Coverage
⊟	Dynamic Sensor Set	Advanced	4	100%
⊞	Relief valve		1	
⊞	Fluid line 2		1	
⊞	Fluid line		1	
⊞	Flow Control Valve		1	

Fig. 4: MADe sensor minimisation results for actuator system failure modes (system level)

Lower level analysis: relief valve

Complete sensor set design for the system is achieved by opening each lower level of indenture in turn, and repeating the sensor discrimination and minimisation routines. The lower level model (or ‘sub-model’) of the relief valve component is presented in Fig. 5.

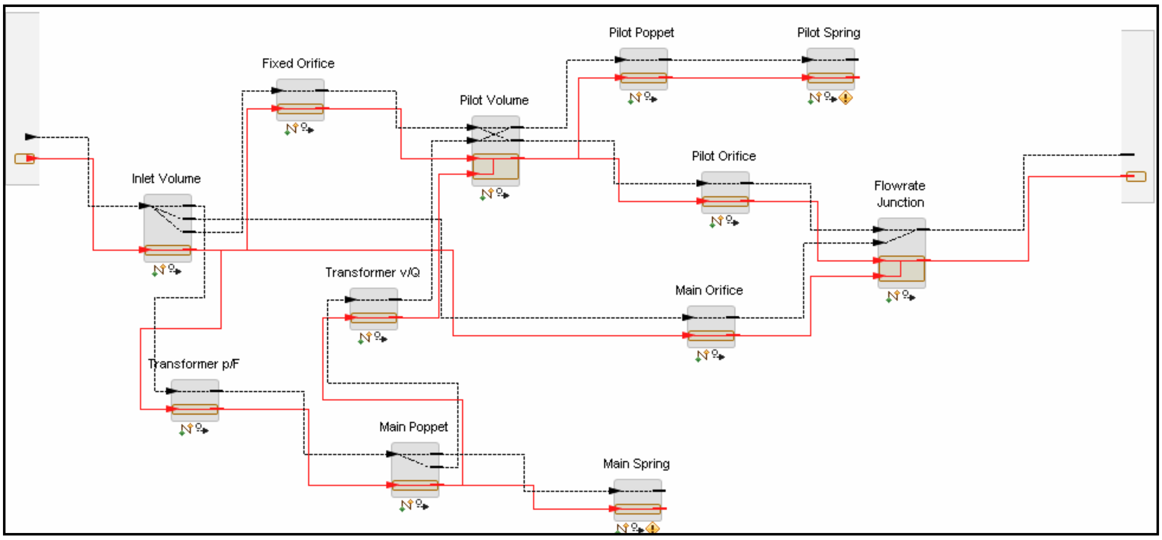


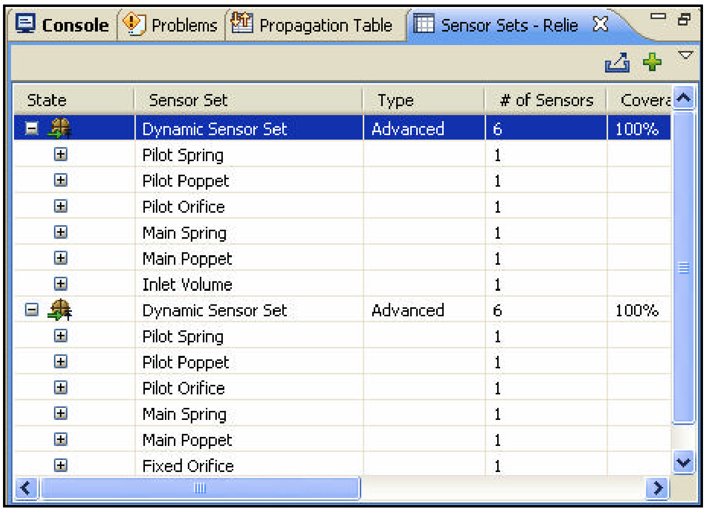
Fig. 5: Subsystem Diagram of the Relief Valve

The failure modes for system elements within the relief valve sub-model are listed in table 3, and the full propagation table is presented in Appendix 3. By repeating the sensor discrimination procedure at the relief valve level of indenture, a total of 376 MAXTERMS were generated, all of which were verified against manual calculations using an excel spreadsheet.

Table 3: Failure modes for the relief valve sub-model

Cause	**Failure Mode**
Flow resistance decrease	High volumetric flow - Fixed Orifice
Flow resistance increase	Low volumetric flow - Fixed Orifice
Flow resistance decrease	High volumetric flow - Main Orifice
Flow resistance increase	Low volumetric flow - Main Orifice
Delta pressure increase	High linear velocity - Main Poppet
Delta pressure decrease	Low linear velocity - Main Poppet
Delta velocity increase	High linear force - Main Spring
Delta velocity decrease	Low linear force - Main Spring
Flow resistance decrease	High volumetric flow - Pilot Orifice
Flow resistance increase	Low volumetric flow - Pilot Orifice
Delta pressure decrease	Low linear velocity - Pilot Poppet
Delta velocity increase	High linear force - Pilot Spring
Delta velocity decrease	Low linear force - Pilot Spring
Compressibility Flowrate decrease	Low hydraulic pressure - Pilot Volume

Two candidate sensor sets afforded 100% coverage of failure modes for the relief valve sub-model, as shown in Fig. 6. Using the sensor location numbering system in Appendix 3, these sensor locations correspond to the sets S(3,5,6,7,8,9) and S(1,5,6,7,8,9) respectively. Due to the large computing requirements for the relief valve sub-model, the results were verified by determining whether the candidate sensor sets provided 100% coverage. Thus the results were shown to be correct, but not necessarily complete, as was determined for the system level model. The failure coverage of each candidate sensor set was verified by trimming the MAXTERMS for the relief valve sub-model such that only symptoms corresponding to the nominated sensor locations remained. The MAXTERMS were then checked for null sets. If no null-sets were found, then 100% coverage is provided by those symptoms. Results showed that the MAXTERMS did not contain any null-sets and thus it could be independently established that the candidate sensor sets provided 100% failure coverage of the relief valve sub-model.

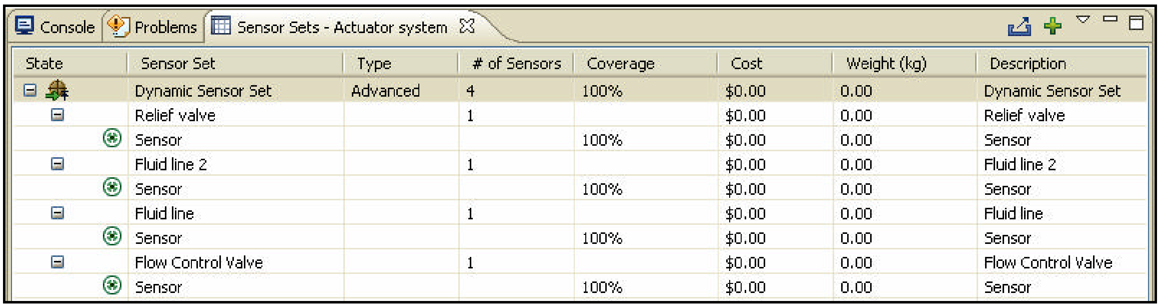


State	Sensor Set	Type	# of Sensors	Covera
⊟	Dynamic Sensor Set	Advanced	6	100%
⊞	Pilot Spring		1	
⊞	Pilot Poppet		1	
⊞	Pilot Orifice		1	
⊞	Main Spring		1	
⊞	Main Poppet		1	
⊞	Inlet Volume		1	
⊟	Dynamic Sensor Set	Advanced	6	100%
⊞	Pilot Spring		1	
⊞	Pilot Poppet		1	
⊞	Pilot Orifice		1	
⊞	Main Spring		1	
⊞	Main Poppet		1	
⊞	Fixed Orifice		1	

Fig. 6: Candidate sensor sets for 100% coverage of relief valve failure modes

Sensor selection and optimisation

The MADe sensor analysis results are automatically output as a ‘tree-list’ of candidate sensor sets in the format shown in Fig. 7. At this stage, the candidate sets are really only a list of locations on the system that require monitoring for the specified failure coverage. The candidate sensor set is only fully defined once actual sensors have been associated with each nominated sensor location. The results for the actuator system indicate that there is one optimal solution for 100% failure coverage at the system level of indenture, and this is a sensor set named ‘dynamic sensor set’. This set has been expanded to list the individual sensor locations for this set.



State	Sensor Set	Type	# of Sensors	Coverage	Cost	Weight (kg)	Description
	Dynamic Sensor Set	Advanced	4	100%	$0.00	0.00	Dynamic Sensor Set
	Relief valve		1		$0.00	0.00	Relief valve
	Sensor			100%	$0.00	0.00	Sensor
	Fluid line 2		1		$0.00	0.00	Fluid line 2
	Sensor			100%	$0.00	0.00	Sensor
	Fluid line		1		$0.00	0.00	Fluid line
	Sensor			100%	$0.00	0.00	Sensor
	Flow Control Valve		1		$0.00	0.00	Flow Control Valve
	Sensor			100%	$0.00	0.00	Sensor

Fig. 7: Candidate sensor sets for 100% failure coverage of actuator system failure modes

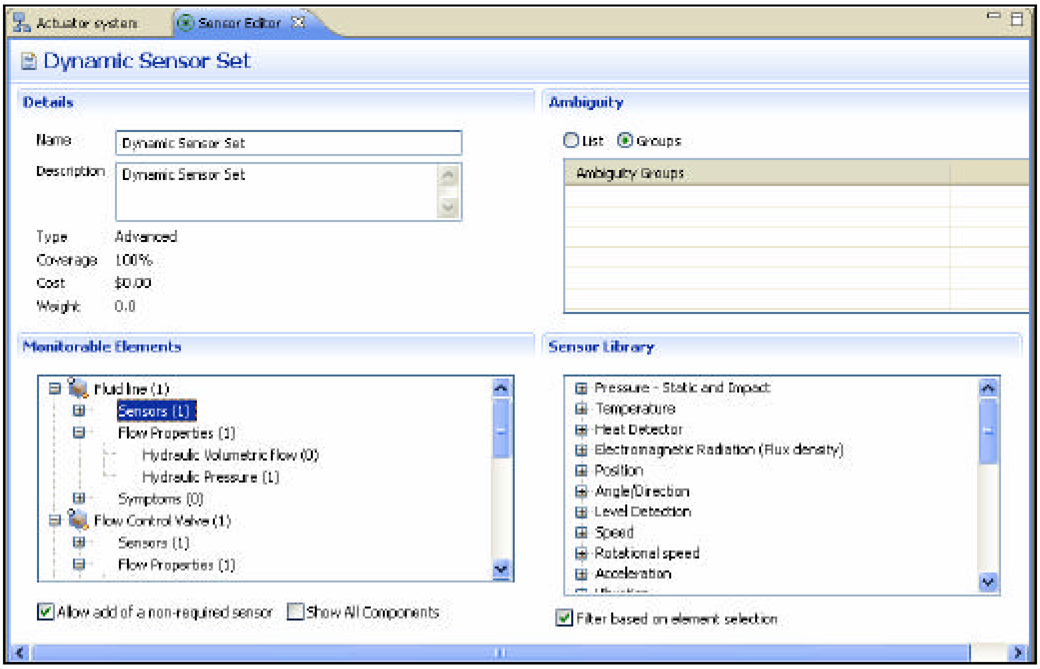
Where multiple candidate sensor sets are available, the user can rank the list of candidate sensor sets according to their total coverage, cost or weight. The cost and weight are generalised values based on the types of sensors required at the specified sensor locations. To obtain a more accurate cost or weight estimate, the user must open the advanced properties window for a candidate sensor set and associate specific sensors with each sensor location.

The advanced properties window is shown in Fig. 8. Information provided includes:

- the type of FMEA analysis that was conducted to generate the propagation table (type: advanced)
- the overall failure coverage that was achieved for the indenture level under investigation
- the total cost and weight of the sensor set (based on sensor details in the library)
- a listing of any ambiguity groups if 100% failure coverage is not achieved
- a list of all monitorable elements at this level of indenture (this identifies the components and their symptoms for every sensor location nominated for the sensor set)
- a sensors library, containing specifics that have been entered for each type of sensor to be used on the system

The sensors library allows the user to enter details of the sensors that have been selected for the system under analysis. Information for each sensor includes:

- cost and weight
- sensitivity, range, response time
- operational/environmental constraints
- type of flow property/loss symptom that is measured



Name: Dynamic Sensor Set
Description: Dynamic Sensor Set
Type: Advanced
Coverage: 100%
Cost: $0.00
Weight: 0.0

○ List ● Groups

Fluid line (1)
- Sensors (1)
- Flow Properties (1)
  - Hydraulic Volumetric Flow (0)
  - Hydraulic Pressure (1)
- Symptoms (0)

Flow Control Valve (1)
- Sensors (1)
- Flow Properties (1)

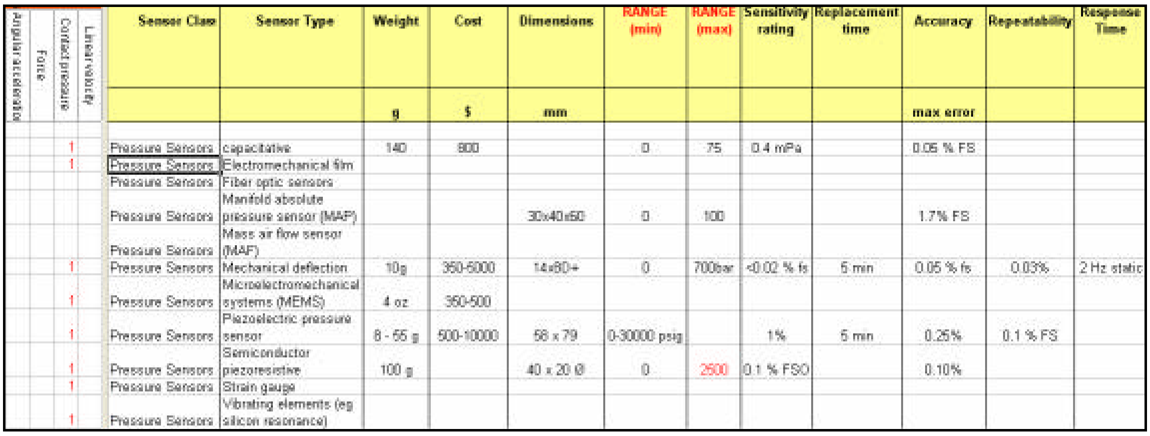
Pressure - Static and Impact
Temperature
Heat Detector
Electromagnetic Radiation (Flux density)
Position
Angle/Direction
Level Detection
Speed
Rotational speed
Acceleration

☑ Allow add of a non-required sensor ☐ Show All Components

☑ Filter based on element selection

Fig. 8: Sensor set details for system level sensor set

The sensor types that are required are automatically selected by identifying sensor types that can measure the relevant flow properties or loss symptoms for each sensor location in the candidate sensor set. A matrix is used by MADe sensors to store sensor details for the library and associate sensors with their measurable flow properties/loss symptoms. An extract of this matrix is shown in Fig. 9. In Fig. 9 four flow properties - angular acceleration, force, contact pressure and linear velocity - are displayed in the left hand columns. The associated sensors are identified by class and type and their details are also listed.



Angular acceleratio	Force	Contact pressure	Linear velocity	Sensor Class	Sensor Type	Weight	Cost	Dimensions	RANGE (min)	RANGE (max)	Sensitivity rating	Replacement time	Accuracy	Repeatability	Response Time
						g	$	mm					max error		
		1		Pressure Sensors	capacitative	140	800		0	75	0.4 mPa		0.05 % FS		
		1		Pressure Sensors	Electromechanical film										
				Pressure Sensors	Fiber optic sensors										
				Pressure Sensors	Manifold absolute pressure sensor (MAP)			30x40x60	0	100			1.7% FS		
				Pressure Sensors	Mass air flow sensor (MAF)										
		1		Pressure Sensors	Mechanical deflection	10g	350-5000	14x80+	0	700bar	<0.02 % fs	5 min	0.05 % fs	0.03%	2 Hz static
		1		Pressure Sensors	Microelectromechanical systems (MEMS)	4 oz	350-500								
		1		Pressure Sensors	Piezoelectric pressure sensor	8 - 55 g	500-10000	58 x 79	0-30000 psig		1%	5 min	0.25%	0.1 % FS	
		1		Pressure Sensors	Semiconductor piezoresistive	100 g		40 x 20 Ø	0	2500	0.1 % FSO		0.10%		
		1		Pressure Sensors	Strain gauge										
		1		Pressure Sensors	Vibrating elements (eg silicon resonance)										

Fig. 9: Matrix of sensor properties and associated flows/symptom losses

Fault detection and Isolation

Diagnostic sets are lists of symptoms that can be used to identify that a particular failure mode has occurred, given that a set of symptoms (system responses) has been detected. They are generated by trimming the propagation table such that only system responses for the selected sensor set are displayed, then constructing either a table or text string of the system responses for each failure mode.

The diagnostic table for the sensor set S(2,3,4,5) is shown in table 4. The results can also be output as a as text strings, for example:

“If (S1=Low, S2=Low, S3=High, S4=High) then F(1)” or:

“If S1= actuator force low, S2=flow control valve volumetric flow low, S3=fluid line pressure high and S4=fluid line 2 pressure high then F(1):actuator force low”

Table 4: Diagnostic sets for S(2,3,4,5)

Diagnostic set	**S1**	**S2**	**S3**	**S4**	**Failure mode**
D(1)	Low	Low	High	High	F(1)
D(2)	High	High	Low	High	F(2)
D(3)	Low	Low	High	Low	F(3)
D(4)	Low	Low	Low	Low	F(4)
D(5)	Low	High	Low	Low	F(5)
D(6)	Low	Low	Low	Low	F(6)
D(7)	High	High	High	High	F(7)

The FMECA analysis provides information as to the origins or causes of the failure mode. These are recorded in the failure diagram of each component. For failure mode F(4) = fluid line pressure low, the failure diagram of the fluid line (Fig. 2) indicates that this failure mode is caused by the fault ‘fluid line bent’. The diagram also shows that there are multiple causes and mechanisms which can lead to this fault, and these are listed in table 5.

Table 5: Causal chains of events for Failure Mode F(4), Fluid Line - Pressure Low

Cause	**Mechanism**	**Fault**
Cycling loads	High cycle fatigue	Cracked fitting
		Cracked tube
		Ruptured fitting
		Ruptured tube
Vibration	High cycle fatigue	Cracked fitting
		Cracked tube
		Ruptured fitting
		Ruptured tube
Force above specified limit	Ductile fracture	Ruptured fitting
		Ruptured tube
Stress concentrations	Ductile fracture	Ruptured fitting
		Ruptured tube

For root cause analysis, the user has access to additional information which can indicate which cause is most likely to have triggered a diagnosed failure mode:

- criticality information that is stored within the concept nodes and causal connections of the failure diagram can be used to compare the relative occurrences, progression rates and causal strengths for each path from cause to failure mechanism
- if any loss symptoms associated with the mechanism or fault are detected, these can be used to distinguish between causes

Fig. 10 provides a conceptual map to illustrate how FMECA and sensor analysis modules work together to support PHM and reliability enhancement of system designs. The application of outputs from the sensor analysis are summarised in the map, in particular, the use of results to support improved criticality assessment and system design optimisation are highlighted as red arrows in the map

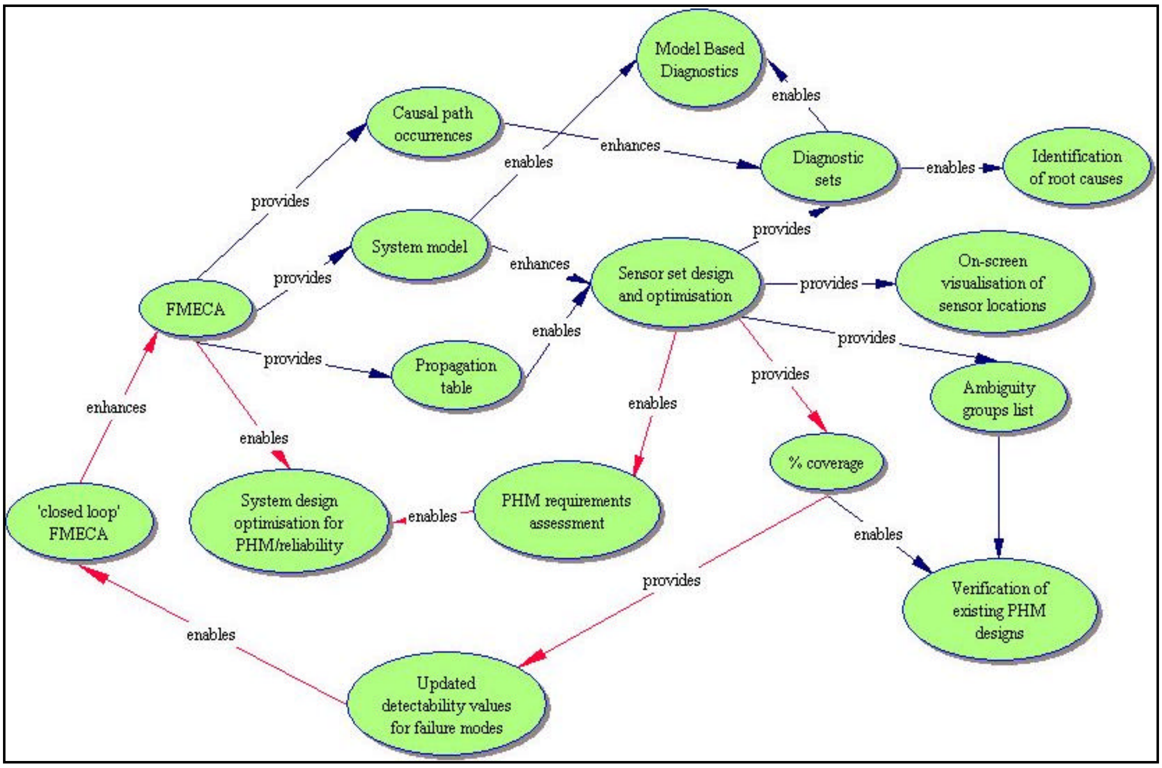


Fig. 10: Conceptual mapping of integrated PHM design and system design optimisation

Conclusion

This paper presents the analysis techniques employed by the MADe sensors analysis and design module. A case study is presented to demonstrate and verify the technique of sensor discrimination using system-wide 'symptoms' of failure, and sensor minimisation by intersecting the MAXTERMS generated by the discrimination routine. The manual calculations showed that the system level minimisation and discrimination results were both correct and complete, and for lower level of indenture analysis the results were found to be correct. The analysis presented also demonstrated the formulation of diagnostic sets for Fault Detection and Isolation and failure coverage assessment of the sensor set. The same method can be employed to assess the failure coverage of a pre-existing sensor set. Results from the sensor set design and assessment module also form the basis for a Model Based Diagnostic module which is under development and will form the final module in the MADe suite of PHM software tools in support of the JSF PHM program.

References

1. Hess, A., Stecki, J. S. and Rudov-Clark, S. D., 'The Maintenance Aware Design environment: Development of an Aerospace PHM Software Tool' In Proc. PHM08, October 6-9, 2008, Denver

2. Rudov-Clark, S. D., Stecki, J. S., 'The language of FMEA: on the effective use and reuse of FMEA data' submitted to HUMS2009, Melbourne, 10 -12 March, 2009

3. Broenink, J. F., 'Introduction to Physical Systems Modelling with Bond Graphs' 1999, in University of Twente Website, url: http://www.ce.utwente.nl/bnk/papers/BondGraphsV2.pdf last accessed 08/01/2009

4. Bouamama, B. O., Medjaher, K., Bayart, M., Samantaray, A.K., Conrard, B., 'Fault detection and isolation of smart actuators using bond graphs and external models' in Control Engineering Practice 13 (2005) 159–175

5. Anon., 'Procedures for performing a failure mode, effects and criticality analysis', MIL-STD-1629A, US Department of Defense, 1980

Appendix 1: Functions of the Actuator System Elements

Item Name			**Element type**	**Function**	**Inputs**	**Outputs**
Level 1	**Level 2**	**Level 3**				
Actuator System			System	Convert angular velocity to linear velocity	Angular velocity	Linear velocity
	Fluid Line		Component	Store hydraulic energy	Volumetric flow	Hydraulic pressure
		Tube/Fitting	Pair	Transport liquid	n/a	Liquid flow rate
	Relief Valve		Subsystem	Regulate hydraulic pressure	Hydraulic pressure	Volumetric flow
		Fixed Orifice	Component	Convert hydraulic energy	Hydraulic pressure	Volumetric flow
		Transformer (p/f)	Component	Convert hydraulic pressure	Hydraulic pressure	Linear force
		Pilot Volume	Component	Store hydraulic energy	Volumetric flow	Hydraulic pressure
		Main Spring	Component	Store mechanical energy	Linear velocity	Linear force
		Pilot Spring	Component	Store mechanical energy	Linear velocity	Linear force
		Transformer (v/q)	Component	Convert mechanical energy	Linear velocity	Volumetric flow
		Flowrate Junction	Component	Connect hydraulic flow	Volumetric flow Volumetric flow	Volumetric flow
		Main Orifice	Component	Convert hydraulic pressure	Hydraulic pressure	Volumetric flow
		Main Poppet	Component	Store mechanical energy	Linear force	Linear velocity
		Pilot Poppet	Component	Store mechanical energy	Hydraulic pressure	Linear velocity
		Pilot Orifice	Component	Convert hydraulic energy	Hydraulic pressure	Volumetric flow
		Inlet Volume	Component	Distribute hydraulic energy	Hydraulic pressure	Hydraulic pressure
	Flow Control Valve		Component	Convert hydraulic energy	Hydraulic pressure	Volumetric flow
	Fluid Line 2		Component	Store hydraulic energy	Volumetric flow	Hydraulic pressure
	Actuator		Component	Convert hydraulic energy	Hydraulic pressure	Linear force
	Flowrate Supply		Component	Translate volumetric flow	Rotational velocity	Volumetric flow
	Load		Component	Convert mechanical energy	Linear force	Linear velocity
	Reservoir		Component	Store hydraulic energy	Hydraulic pressure Volumetric flow	

Appendix 2: MINTERMS for Actuator System – System Level

S123	**S124**	**S125**	**S234**	**S235**	**S245**	**S345**	**S1234**	**S1235**	**S2345**
L12	L12	L12	L12	L12	L12	L12	L12	L12	L12
	L13		L13		L13	L13	L13		L13
L14	L14	L14	L14	L14	L14	L14	L14	L14	L14
L15	L15	L15	L15	L15	L15	L15	L15	L15	L15
L16	L16		L16	L16	L16	L16	L16	L16	L16
L17	L17	L17	L17	L17	L17	L17	L17	L17	L17
L23	L23	L23	L23	L23	L23	L23	L23	L23	L23
L24	L24	L24	L24	L24	L24	L24	L24	L24	L24
L25	L25	L25	L25		L25	L25	L25	L25	L25
L26	L26	L26	L26	L26	L26	L26	L26	L26	L26
L27			L27	L27		L27	L27	L27	L27
L34		L34	L34	L34	L34	L34	L34	L34	L34
L35	L35	L35	L35	L35	L35	L35	L35	L35	L35
L36			L36	L36		L36	L36	L36	L36
L37	L37	L37	L37	L37	L37	L37	L37	L37	L37
L45	L45	L45	L45	L45	L45		L45	L45	L45
		L46		L46	L46	L46		L46	L46
L47	L47	L47	L47	L47	L47	L47	L47	L47	L47
L56	L56	L56	L56	L56	L56	L56	L56	L56	L56
L57	L57	L57	L57	L57	L57	L57	L57	L57	L57
L67	L67	L67	L67	L67	L67	L67	L67	L67	L67

Appendix 3: Propagation table for Relief Valve sub-model

Abbreviations:

(ss)	steady state response of the system
(tr)	transient response of the system
nom	nominal response
lo	decrease response
hi	increase response

Component	**Cause**	**Failure Mode**	**ID**	**Fixed Orifice**	**Flowrate Junction**	**Inlet Volume**	**Main Orifice**	**Main Poppet**	**Main Spring**	**Pilot Orifice**	**Pilot Poppet**	**Pilot Spring**	**Pilot Volume**
				Vol. flow	**Vol. flow**	**Press.**	**Vol. flow**	**Lin. vel.**	**Force**	**Vol. flow**	**Lin. vel.**	**Force**	**Press.**
Fixed Orifice	Flow resist. inc (ss)	Vol. flow hi	F1	hi	nom	lo	lo	nom	lo	hi	nom	hi	hi
	Flow resist. inc (tr)	Vol. flow hi	F2	hi	nom	lo	lo	lo	lo	hi	hi	hi	hi
	Flow resist. dec (ss)	Vol. flow lo	F3	lo	nom	hi	hi	nom	hi	lo	nom	lo	lo
	Flow resist. dec (tr)	Vol. flow lo	F4	lo	nom	hi	hi	hi	hi	lo	lo	lo	lo
Main Orifice	Flow resist. inc (ss)	Vol. flow hi	F5	lo	nom	lo	hi	nom	lo	lo	nom	lo	lo
	Flow resist. inc (tr)	Vol. flow hi	F6	lo	nom	lo	hi	lo	lo	lo	lo	lo	lo
	Flow resist. dec (ss)	Vol. flow lo	F7	hi	nom	hi	lo	nom	hi	hi	nom	hi	hi
	Flow resist. dec (tr)	Vol. flow lo	F8	hi	nom	hi	lo	hi	hi	hi	hi	hi	hi
Main Poppet	Delta press. inc (ss)	Lin. vel hi	F9	nom	nom	nom	nom	nom	hi	nom	nom	nom	nom
	Delta press. inc (tr)	Lin. vel hi	F10	lo	nom	lo	lo	hi	hi	hi	hi	hi	hi
	Delta press. dec (ss)	Lin. vel lo	F11	nom	nom	nom	nom	nom	lo	nom	nom	nom	nom
	Delta press.	Lin. vel	F12	hi	nom	hi	hi	lo	lo	lo	lo	lo	lo

	dec (tr)	lo											
Main Spring	Delta vel. inc (ss)	Force hi	F13	hi	nom	hi	hi	lo	hi	lo	nom	lo	lo
	Delta vel. inc (tr)	Force hi	F14	hi	nom	hi	hi	lo	hi	lo	lo	lo	lo
	Delta vel. dec (ss)	Force lo	F15	lo	nom	lo	lo	hi	lo	hi	nom	hi	hi
	Delta vel. dec (tr)	Force lo	F16	lo	nom	lo	lo	hi	lo	hi	hi	hi	hi
Pilot Orifice	Flow resist. inc (ss)	Vol. flow hi	F17	hi	nom	lo	lo	nom	hi	hi	nom	lo	lo
	Flow resist. inc (tr)	Vol. flow hi	F18	hi	nom	lo	lo	hi	hi	hi	lo	lo	lo
	Flow resist. dec (ss)	Vol. flow lo	F19	lo	nom	hi	hi	nom	lo	lo	nom	hi	hi
	Flow resist. dec (tr)	Vol. flow lo	F20	lo	nom	hi	hi	lo	lo	lo	hi	hi	hi
Pilot Poppet	Delta press. dec (ss)	Lin. vel lo	F21	nom	nom	nom	nom	nom	nom	nom	nom	lo	nom
	Delta press. dec (tr)	Lin. vel lo	F22	lo	nom	hi	hi	lo	lo	hi	lo	lo	hi
Pilot Spring	Delta vel. inc (ss)	Force hi	F23	lo	nom	hi	hi	nom	lo	hi	lo	hi	hi
	Delta vel. inc (tr)	Force hi	F24	lo	nom	hi	hi	lo	lo	hi	lo	hi	hi
	Delta vel. dec (ss)	Force lo	F25	hi	nom	lo	lo	nom	hi	lo	hi	lo	lo
	Delta vel. dec (tr)	Force lo	F26	hi	nom	lo	lo	hi	hi	lo	hi	lo	lo
Pilot Volume	Flowrate delta dec (ss)	Press. lo	F27	hi	nom	lo	lo	nom	hi	lo	nom	lo	lo
	Flowrate delta dec (tr)	Press. lo	F28	hi	nom	lo	lo	hi	hi	lo	lo	lo	lo