Analysing the Fault Behavior of a Complex Mechanical System for Diagnosis: A Bond Graph-Based Approach

Jinxin Wang, Shenglei Zhao, Xiuzhen Ma, and Fengshou Gu

Abstract Multiple faults diagnosis is a critical problem in mechanical fault diagnosis. Fault behavior analysis aims to find out the response characteristics of operating parameters under different faults and is the most primitive task for multiple faults diagnosis. This paper proposes a bond graph-based approach to analyse the mechanical fault behavior for diagnosis. The analytical model of an engineering system is firstly established via bond graph. The temporal causal graph is derived from the bond graph model to depict the analytic relationships system variables. The operating parameters response characteristics under different faults are then derived by representing the faults with abnormal change of system variables. The approach is illustrated via an engine lubrication system. The presented approach avoids time-consuming formula transformation which is necessary in mathematical model-based approach, and therefore provides an efficient for fault behavior analysis.

Keywords Multiple faults diagnosis · Fault behavior analysis · Bond graph · Temporal causal graph · Engine lubrication system

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1 Introduction

A complex mechanical system will inevitably suffer from various failures during its service cycle. Condition monitoring and fault diagnosis (CMFD) technique aims to pinpoint the origin of an abnormality timely if it presents, which provides an effective means to ensure the safe and high-efficient operation of a complex mechanical system.

The diagnosis of multiple faults diagnosis is a crucial task in CMFD [1–4]. It can be divided into 4 different steps: fault behavior analysis, fault description and feature selection, fault detection, and fault isolation. Fault behavior analysis aims to find out the fault propagation path and the response characteristics of operating parameters under different faults, which is the most primitive task among the 4 tasks.

Correlation analysis and fault tree are two primary approaches for fault behavior analysis. Correlation analysis takes advantage of mathematical statistics theory to deal with the sample data of two state variables, and investigates the correlation of variables according to the data distribution regularities. This approach has been successfully used to study the causal relationships of mechanical faults and symptoms for some equipment [5, 6]. However, a large number of typical fault sample data is the prerequisite for this method. In practice, high-quality data is not always available for different machines, which limits this method to being widely used in real-world.

Fault tree is another method for fault behavior analysis [7–9]. Different from correlation analysis, this method takes the most undesired fault as Top Event, and then describes the propagation path of the target fault via an inverted tree structure. The causal relationships of faults and symptoms are therefore derived by exploring this tree. Fault tree gets rid of the dependency on sample data, however, the fault propagation path are actually modeled according to experts' subjective experience. Thus, different experts may give different diagnostic results. Besides, a fault tree for multiple fault diagnosis often requires a very complete expert knowledge base, which is usually difficult to obtain in practice.

Some researchers also use the commercial software to investigate the mechanical fault behavior [10], e.g. AMESim for hydraulic valve leakage, GT-Power for engine misfire. Although this approach provides an efficient way for fault behavior analysis, the fault type that commercial software can deal with limited by the component libraries the software can provide. Thus, commercial software-based approach is found limited in some cases.

Mathematical model-based approach is an alternative way to pursue the causal relationships of faults and symptoms for diagnosis. This approach firstly describes the working process of a mechanical system via a series of analytical redundancy relations (ARRs), and then introduces the interested fault by changing the state variable, the operating parameters response characteristics under different faults can be got accordingly. Despite this approach gets rid of the dependency on sample data, and avoids the influence of experts' subjective experience at the same time, mathematical model-based approach suffers severely from the enormous cost of modeling and calculation. Take a diesel engine as an example, up to 1640 ARRs can be generated from the 39 differential equations and algebraic equations (required to model the dynamic behaviors of the engine) to depict the dependency among the variables [11–13].

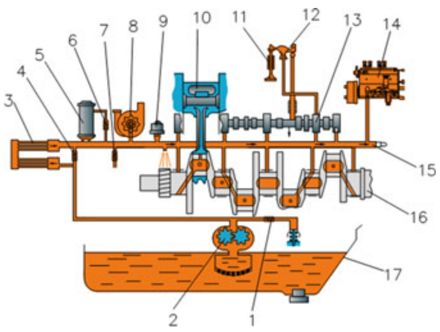
Bond graph is a graphical modeling methodology. It models an engineering system by considering the energy flows between the components. Different bond elements are used to describe the storage, release, transfer and conversion of the energy. A complete model of an engineering system is constructed via combining the various bond elements according to the connection of components. Bond graph is a domain-independent modeling method (it can describe the system from different domains, e.g. electrical, mechanical, hydraulic, in the same way), therefore it is a powerful tool for modeling engineering systems when different physical domains are involved. Besides, not constructing the ARRs directly, bond graph firstly takes use of graphical elements to represent the interaction of system components and then derives the mathematical analytical equation from the graphical model. Compare with the conventional mathematical model-based approach, bond graph simplifies the construction of ARRs and therefore provides an effective way for fault behavior analysis.

This paper presents a bond graph-based approach to analyse the mechanical fault behavior for diagnosis. The analytical model of an engineering system is firstly established via bond graph. The temporal causal graph is derived from the bond graph model to depict the analytic relationships system variables. The operating parameters response characteristics under different faults are then derived by representing the faults with abnormal change of system variables. The approach is illustrated via an engine lubrication system. The rest of this paper is organized as follows. Section 2 introduces the structure and working principle of engine lubrication system. Section 3 describes the presented approach and illustrated using an engine lubrication system. The model and the presented approach are verified in Sect. 4. Finally, Sect. 11 summaries the paper.

2 Example: Engine Lubrication System

Lubrication system is one of the most crucial systems in diesel engine, which supplies enough oil to the engine friction pair to guarantee the safe and reliable operation of a diesel engine. Fault diagnosis is a vital task to guarantee the safe operation of engine lubrication system.

A schematic diagram of a typical marine diesel engine lubrication system is shown as Fig. 1. The gear pump is driven by crankshaft through a transmission gear or a belt. A relief valve is usually installed after the oil pump to prevent the damage caused by excessive oil pressure. The lubricating oil then enters the oil cooler to keep a certain temperature. The oil cooler is usually connected in parallel with a thermostatic valve to control the oil temperature. The cooled lubricating oil enters the filter. Each filter is connected in parallel with a bypass valve to prevent the engine lubrication failure caused by filter clogging. The main oil gallery is usually installed with a pressure relief valve to adjust the pressure of the lubricating oil. Besides lubricating the friction



1-relief valve of gear pump, 2-gear pump, 3-oil cooler, 4- thermostatic valve, 5-oil filter, 6-bypass valve, 7-pressure regulating valve, 8-supercharger, 9-oil pressure gauge, 10-piston, 11-air valve, 12-rocker arm, 13-camshaft, 14-fuel injection pump, 15-main oil gallery, 16-crankshaft, 17- oil sump

Fig. 1 A typical marine diesel engine lubrication system

pair, the lubricating oil can also take heat away from the engine body to make the pistons, crankshafts and other components working at a certain temperature.

3 Fault Behavior Analysis Using Bond Graph-Based Approach

3.1 Modeling the System Dynamic Behavior Based on Bond Graph

3.1.1 Bond Graph Theory

In bond graph, four generalized variables: effort $e(t)$, flow $f(t)$, momentum $p(t)$ and displacement $q(t)$ are defined to represent the energy flow in any systems. The effort $e(t)$, flow $f(t)$ are two basic variables, where the power of the instantaneous energy flow is product of these two variables, see Eq. (1).

$$Power(t) = e(t) \cdot f(t) \tag{1}$$

Momentum $p(t)$ and displacement $q(t)$ are defined as

$$\begin{cases} \frac{\mathrm{dp(t)}}{\mathrm{dt}} = e(t) \\ \frac{\mathrm{dq(t)}}{\mathrm{dt}} = f(t) \end{cases} \tag{2}$$

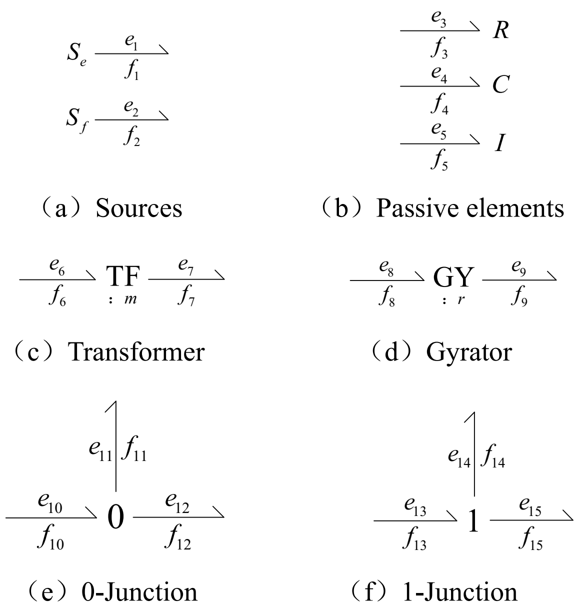
Six basic elements are defined to model the components in real systems, see Fig. 2. Figure 2a shows the effort source S_e and flow source S_f, which often used to describe the energy source with a specific effort/flow level. Figure 2b shows the three passive elements: R-element, C-element and I-element. R-element is used to describe the components which dissipate energy, e.g. dampers, frictions and electric resistors in real-life systems. C-element and I-element are used to represent the components which store all kinds of energy. Specifically, in C-element, the energy is stored by accumulating the net flow, and in I-element, the energy is stored by accumulating the net effort.

Figure 2c, d show the two-port elements: transformer and gyrator respectively, which are usually used to represent the energy conversion both in same energy form and different energy form. Variables m and r are called transformer module and gyrator ratio respectively.

Figure 2e, f are two junctions, which are used to represent the conservation of energy. The 0-junction is also named common effort junction, which is used to connect the elements with equal efforts. The 1-junction is also named common flow junction, which is used to connect the elements with equal flows.

Although bond graph had been successfully applied in electrical, mechanical, hydraulic domains, it was found limited in thermodynamics domain. To solve this

Fig. 2 Basic elements of bond graph



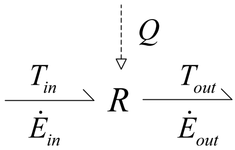


Fig. 3 The 2-port R-element representing convection in pseudo bond graphs

problem, Karnopp proposed pseudo bond graphs [14]. Different from classical bond graph (or power bond graph), temperature T and heat flow rate $\dot{E}$ are chosen as effort source S_e and flow source S_f in pseudo bond graphs ($\dot{E}$ is already a power term). The convection of heat is therefore represented via a two-port R-element, see Fig. 3. The variables T_{in} and $\dot{E}_{in}$ represent the inlet temperature and heat flow rate, while T_{out} and $\dot{E}_{out}$ represent the outlet temperature and heat flow rate. The differential equation can be written as Eq. (3). The thermodynamic equations derived by this way match the Euler method very well, which makes pseudo bond graphs being widely used in thermodynamics domain.

$$\begin{aligned} &\text{if } Q > 0, \quad \dot{E}_{in} = \dot{E}_{out} = \rho c Q T_{in} \\ &\text{if } Q < 0, \quad \dot{E}_{in} = \dot{E}_{out} = \rho c Q T_{out} \end{aligned} \tag{3}$$

3.1.2 Mechanical Domain

We model the dynamic behavior of engine lubrication system based on bond graph theory. The working of engine lubrication system involves three domains: mechanical, hydraulic and thermodynamic. We model the mechanical domains first. The crankshaft is modeled by a flow source S_f. The gear pump is connected with crankshaft via a set of transmission gear or a belt. The transmission is modeled via a transformer TE where the transformer module i represents the transmission ratio. Parameter R_{effic} describes the energy loss while transmission. Since the pump has a certain mass, it will consume some energy while working. We describe this process via I_{pump}. The bond graph model of mechanical domains can be seen as Fig. 4.

3.1.3 Hydraulic Domain

The pump converts the mechanical energy into hydraulic energy, which can be modeled via a transformer TE. R_{pleak} represents the leakage of oil pump. The oil flow through the cooler is governed by the parameters R_{cooler} and C_{cooler}, which represent the fluidic resistor and hydraulic volume respectively. The thermostatic valve presents a narrow opening and is modeled via a resistance R_{thermo}, which is also connect in parallel with cooler. The filter and bypass valve has similar physical effect with cooler and thermostatic valve, so that they have Similar model structure.

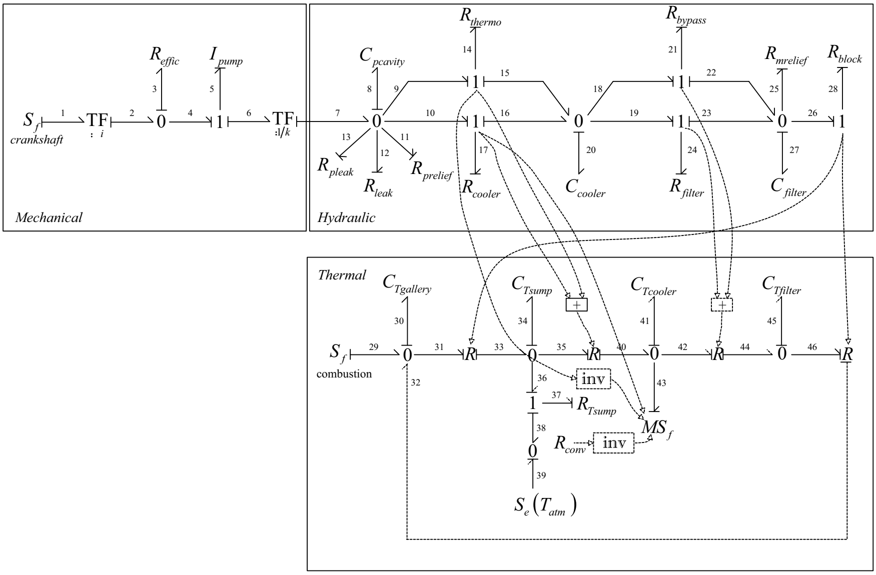


Fig. 4 The bond graph model of engine lubrication system

We regard the engine body as a resistor for oil flow, therefore it is represented via R_{block}. $R_{mrelief}$ describes the fluidic resistor of pressure regulating valve.

3.1.4 Thermal Domain

The working engine can be seen as a heat source which is therefore represented as S_f. The components of engine is modeled as $C_{Tgallery}$. C_{Tsump} is the heat of oil sump. The oil in sump will dissipation to air, we model the heat dissipation via R_{Tsump}. The temperature of environment is thought as constant, so it is modeled as S_e. The oil flows into cooler under the working of pump. We model the heat capacity of cooler as $C_{Tcooler}$. The dissipated heat is represented by MS_f. The model of oil filter is similar with cooler. The transmitted heat is not only related to temperature, but also to mass flow. So the thermodynamic model is connected with hydraulic part via two-port R-element.

The bond graph model of engine lubrication system is shown as Fig. 4. R_{leak} represents the leak oil through oil pipe, and it is quantize by Q_{leak}.

3.2 Analysing the Parameters Response Characteristics Using Temporal Causal Graph

Although we can derive the analytical redundancy relations and analyse the fault behavior through the ARRs, this work is thought to be time-consuming and error-prone. Temporal Causal Graph (TCG) is a signal flow diagram, in which the variables are represented as vertices and the relations between the variables as directed edges, and the relations type are described via a set of labels $L = \{1, -1, =, \lambda, 1/\lambda, \lambda dt, \lambda/\lambda dt\}$. Specifically, 1, λ and $1/\lambda$ describe the positive correlation, in which the coefficients of association are 1, λ and $1/\lambda$ respectively; -1 represents the negative correlation; = means two variables are equational in number; λdt and $1/\lambda dt$ represent the integral relationships in which the parent nodes are the time derivatives of child nodes. The TCG can be derived directly from the bond graph model, see [15].

The TCG model of engine lubrication system derived from the bond graph is shown as Fig. 5. Since the TCG describes the functional relationships of variables intuitively, it can conveniently be used to analyse the parameters response characteristics under different faults. Taking filter blocking as an example, the fault behavior can be shown as Fig. 6. The loop in TCG represents the negative feedback, e.g. the filter blocking will decrease the Q_{27}, as for loop $Q_{27} \rightarrow p_{27} \rightarrow p_{25} \rightarrow Q_{25}$, we have $Q_{27} \downarrow\rightarrow p'_{27} \downarrow\rightarrow p'_{25} \downarrow\rightarrow Q'_{25} \downarrow\rightarrow Q'_{27} \uparrow$. The first order derivative of Q_{27} increases, therefore Q_{27} will finally reach a constant value. We investigate 11 faults of engine lubrication system and the response of 8 working parameters, see Tables 1 and 2. The fault behavior is shown as Table 3, in which +1 represents the occurrence of fault would increase the parameter (also marked with red), and -1 is present otherwise (also marked with blue).

4 Experimental Validation

In this section, we introduce some faults (in total 7 faults) shown in Table 1 and the working parameters in Table 2 are detected accordingly. The engine is an in-line 2 cylinders water-cooled marine engine, see Fig. 7. The engine is connected with a reduction gear box. The propeller is installed in a pipe loop which is filled with water. A flow adjusting valve is set at the middle of the pipe loop to give an adjustable load.

The experiments are carried out at 2000 r/min and 25%, 50%, 75% load respectively. The parameters at 75% load are presented as Table 4.

It can be seen from Table 4 that the working parameters present abnormal changes under different faults, and the abnormal changes got from experiment data meet well with Table 3. Take filter blocking as an example, Table 4 shows that lubrication oil pressure after pump and the pressure before filter increase 0.1 bar compared with the one at engine normal condition (+1 in Table 3). On the contrary, the pressure after filter and pressure before engine decrease 1.5 bar (-1 in Table 3). As for the

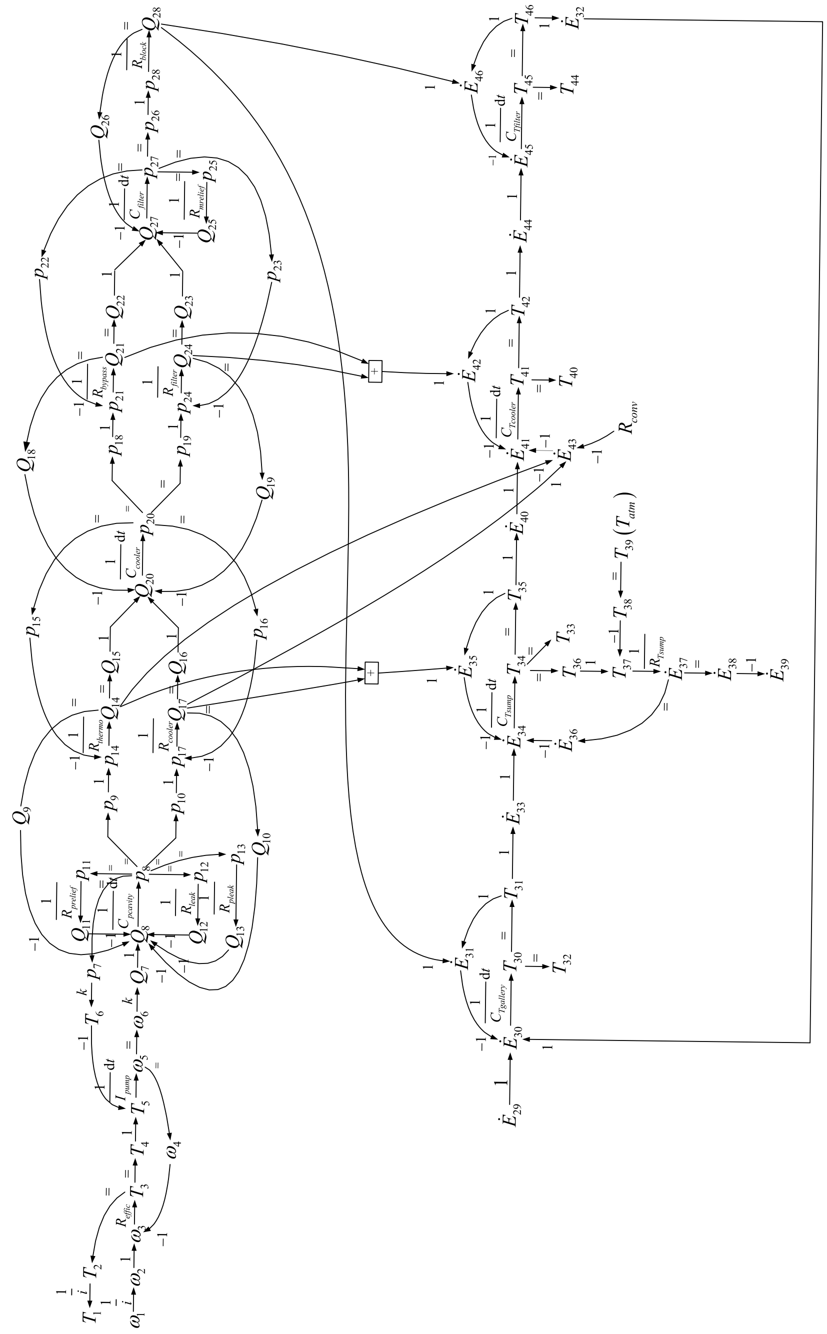


Fig. 5 Temporal causal graph of diesel engine lubrication system

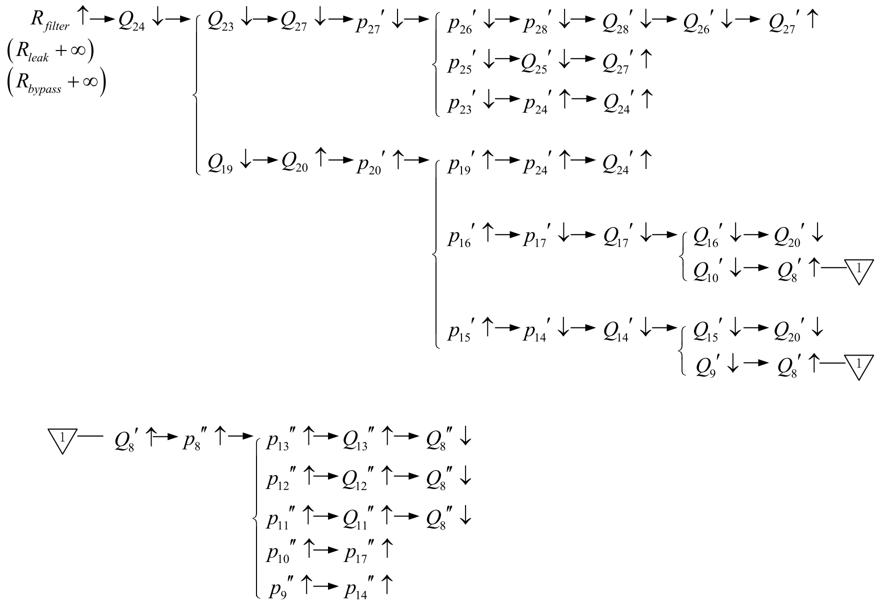


Fig. 6 Failure behavior analysis of filter blocking

Table 1 Common faults of a diesel engine lubrication system

Symbols	Faults	Symbols	Faults
f_1	filter blocking	f_7	Cooler fouling
f_2	Pipe leakage	f_8	Relief valve of pump leakage
f_3	Thermostatic valve stuck	f_9	Relief valve of pump stuck
f_4	Lubrication oil shortage	f_{10}	Main oil gallery blockage
f_5	Bypass valve leakage	f_{11}	Main oil gallery leakage
f_6	Thermostatic valve leakage		

temperature, the temperature at different position all increase compared with normal values (+1 in Table 3). The results show that the fault behavior can be got using bond graph combining with TCG.

Table 2 Observable parameters of an engine lubrication system

Symbols	Working parameters	Variables in TCG
s_1	Lubrication oil pressure after pump	p_8
s_2	Lubrication oil pressure before filter	p_{20}
s_3	Lubrication oil pressure after filter	p_{27}
s_4	Lubrication oil pressure before engine	p_{28}
s_5	Lubrication oil temperature after pump	T_{34}
s_6	Lubrication oil temperature after cooler	T_{41}
s_7	Lubrication oil temperature after filter	T_{45}
s_8	Lubrication oil temperature before engine	T_{30}

Table 3 Fault-symptom causal relationship of engine lubrication system

Num	Faults	Simulation	Working parameters							
			s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8
1	f_1	$R_{filter} \uparrow$	+1	+1	−1	−1	+1	+1	+1	+1
2	f_2	$R_{leak} : +\infty \rightarrow R$	−1	−1	−1	−1	+1	+1	+1	+1
3	f_3	$R_{thermo} \uparrow$	+1	−1	−1	−1	−1	−1	−1	−1
4	f_4	$Q_7 \downarrow Q_{T_{sumn}} \downarrow$	−1	−1	−1	−1	+1	+1	+1	+1
5	f_5	$R_{by\ pass} : +\infty \rightarrow R$ $R_{filter} \rightarrow +\infty$	−1	−1	+1	+1	−1	−1	−1	−1
6	f_6	$R_{thermo} \downarrow$	−1	+1	+1	+1	+1	+1	+1	+1
7	f_7	$R_{cooler} \uparrow$	+1	−1	−1	−1	+1	+1	+1	+1
8	f_8	$R_{prelief} \downarrow$	−1	−1	−1	−1	+1	+1	+1	+1
9	f_9	$R_{prelief} \uparrow$	+1	+1	+1	+1	−1	−1	−1	−1
10	f_{10}	$R_{block} \uparrow$	+1	+1	+1	+1	+1	+1	+1	+1
11	f_{11}	$R_{block} \downarrow$	−1	−1	−1	−1	−1	−1	−1	−1

5 Conclusions

In this paper, we present a bond graph-based approach to analyse the fault behavior for diagnosis. The approach is demonstrated via an engine lubrication system. Results show that the presented approach can exactly derive the response characteristics of operating parameters under different faults. This approach avoids time-consuming

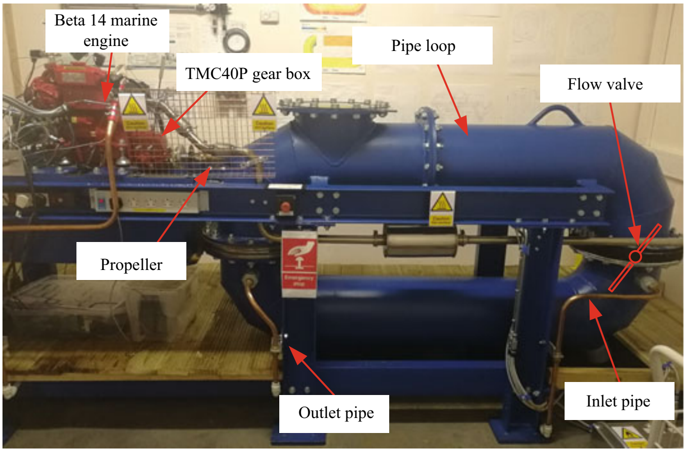


Fig. 7 Test cell of a Beta 14 marine engine

Table 4 Working parameters of a Beta 14 diesel engine lubrication system

Num	Condition	s_1/bar	s_2/bar	s_3/bar	s_4/bar	s_5/°C	s_6/°C	s_7/°C	s_8/°C
1	Normal	4.03	3.86	3.68	3.53	87.40	79.58	81.45	80.26
2	f_1	4.15	4.03	3.17	3.04	90.16	82.59	84.58	83.62
3	f_2	3.62	3.48	3.32	3.18	91.85	83.98	85.98	85.88
4	f_3	4.08	3.80	3.61	3.48	81.91	76.79	78.51	74.88
5	f_4	3.78	3.64	3.47	3.35	94.19	86.63	88.40	86.50
6	f_5	3.88	3.78	3.76	3.61	81.44	73.37	75.76	74.17
7	f_6	3.99	3.93	3.74	3.60	93.06	86.97	88.33	85.89
8	f_7	4.12	3.78	3.62	3.48	89.58	83.19	84.03	82.70

formula transformation which is necessary in mathematical model-based approach, and therefore provides an efficient for fault behavior analysis.

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