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Fault evolution-test dependency modeling for mechanical systems

Key words: Mechanical systems, Design for testability (DFT), Fault evolution-test dependency model (FETDM)

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Introduction

- Tracking the process of fault growth in mechanical systems using a range of tests is important to avoid catastrophic failures.
- To improve the testability performance of mechanical systems for tracking fault growth, a fault evolution-test dependency model (FETDM) is proposed to implement DFT.
- A testability analysis method that considers fault trackability and predictability is developed to quantify the testability performance of mechanical systems.

Testability modeling strategy in this work

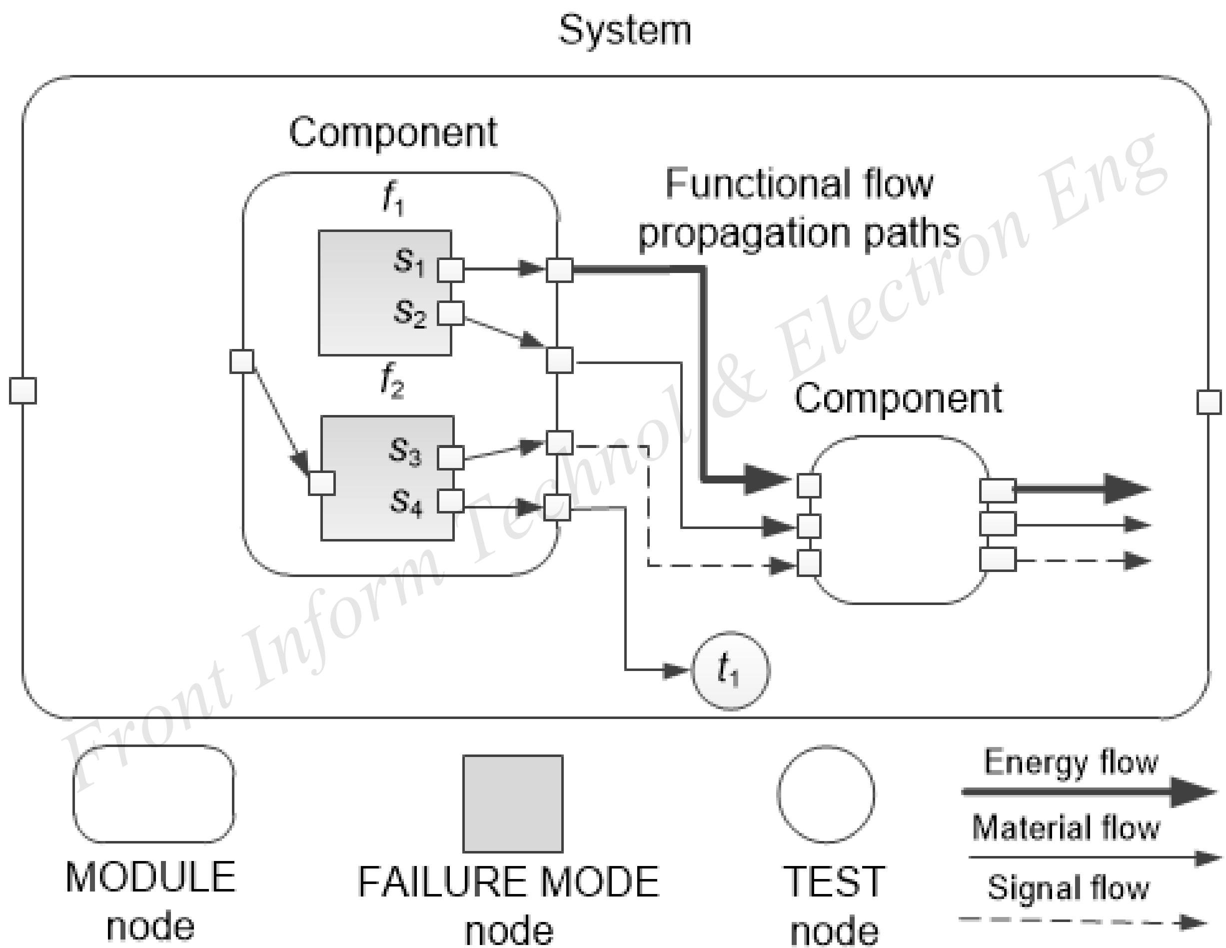

Fig. 1 A schematic of fault evolution-test dependency model

Testability analysis

Fault-symptom matrix

$$\mathbf{FS} = \begin{array}{c} \\ f_1 \\ f_2 \\ \vdots \\ f_M \end{array} \begin{array}{c} \begin{array}{cccc} s_1 & s_2 & \cdots & s_N \end{array} \\ \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ \vdots & \vdots & & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MN} \end{bmatrix} \end{array}.$$

Symptom-test (ST) matrix

$$\mathbf{ST} = \begin{array}{c} \\ s_1 \\ s_2 \\ \vdots \\ s_N \end{array} \begin{array}{c} \begin{array}{cccc} t_1 & t_2 & \cdots & t_K \end{array} \\ \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & & \vdots \\ \beta_{N1} & \beta_{N2} & \cdots & \beta_{NK} \end{bmatrix} \end{array}.$$

Testability analysis

The detectability of test t_k for fault symptom parameter s_j

$$\mathrm{TSD}_{jk} = (1 + \mathrm{e}^{-10(V_{jk} - 0.5)})^{-1} \cdot (1 + \mathrm{e}^{-10(\mathrm{SNR}_k - 0.5)})^{-1},$$

The trackability for fault f_i of test t_k:

$$\mathrm{TFT}_{ik} = \begin{cases} \prod_{j=1}^{|S(f_i)|} \mathrm{TSD}_{jk} \left(1 - \dfrac{\mathrm{TTD}_{jk}}{\mathrm{TTF}_i}\right)^{0.5} \cdot \dfrac{\mathrm{SyD}_{jk}}{\mathrm{TTF}_i}, & \mathrm{TTD}_{jk} \le \mathrm{TTF}_i, \\ 0, & \mathrm{TTD}_{jk} > \mathrm{TTF}_i, \end{cases}$$

The average trackability (AT)

$$\mathrm{AT} = \frac{1}{M} \sum_{i=1}^{M} \frac{1}{|T(f_i)|} \sum_{k=1}^{|T(f_i)|} \mathrm{TFT}_{ik}$$

Case studies

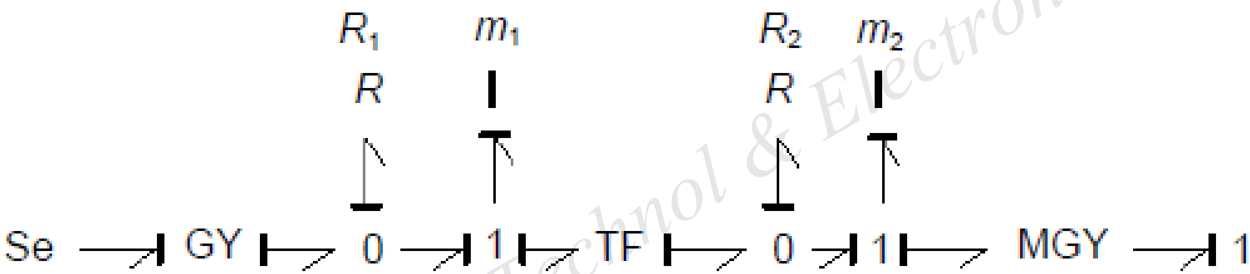

Fig. 2 The system-level bond graph of the centrifugal pump system

Se: effort source; GY: gyrator; TF: transformer; '1': effort junction; '0': flow junction

Case studies (Con'd)

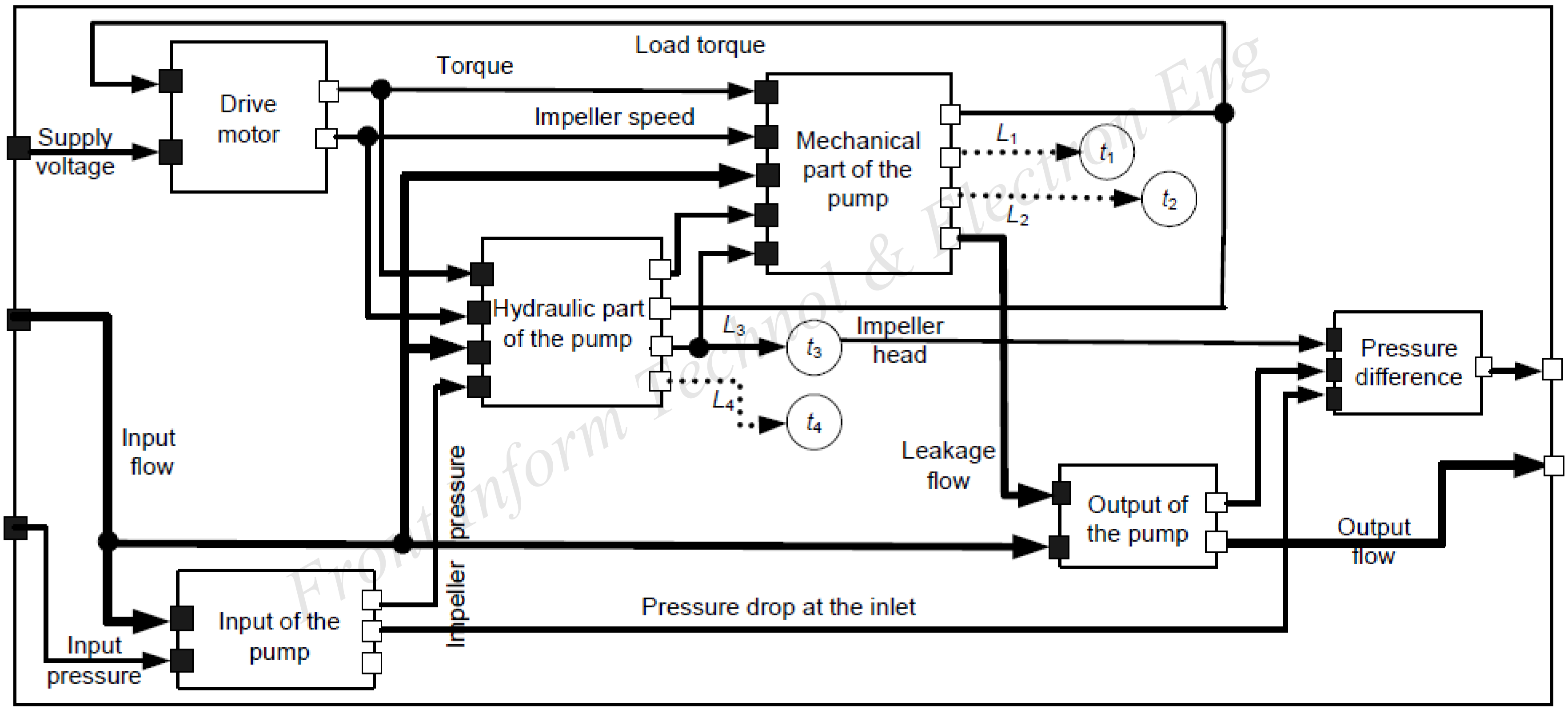

Fig. 3 The FETDM of the centrifugal pump system

Case studies (Con'd)

Table 7 FS matrix

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
f_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
f_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
f_3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
f_4	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
f_5	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
f_6	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
f_7	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
f_8	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
f_9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1

Case studies (Con'd)

Table 8 ST matrix

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}
s_1	0	0	−1	−1	0	0	0	0	0	0	0
s_2	0	0	−1	−1	0	0	0	0	0	0	0
s_3	0	0	−1	0	0	0	0	0	0	0	0
s_4	0	0	0	−1	0	0	0	0	0	0	0
s_5	0	0	0	0	0	0	0	0	0	0	+1
s_6	0	0	0	0	0	0	0	0	0	+1	0
s_7	+1	0	0	0	0	0	0	0	0	0	0
s_8	0	+1	0	0	0	0	0	0	0	0	0
s_9	0	0	0	0	+1	0	0	0	0	0	0
s_{10}	0	0	0	0	0	+1	0	0	0	0	0
s_{11}	0	0	0	0	0	0	+1	0	0	0	0
s_{12}	0	0	0	0	+1	+1	0	0	0	0	0
s_{13}	0	0	0	0	0	0	0	+1	0	0	0
s_{14}	0	0	0	0	0	0	0	0	+1	0	0
s_{15}	0	0	0	0	0	−1	0	+1	+1	0	0

Case studies (Con'd)

Table 9 Results of testability analysis

Analysis content	Value
Number of failure modes	9
Number of tests	11
Number of failure symptom parameters	15
Un-detectable failure (UDF)	$\varnothing$
Un-isolatable failure (UIF)	$\{f_1, f_2\}$
Un-trackable failure (UTF)	$\{f_1, f_2\}$
Un-predictable failure (UPF)	$\{f_1, f_2\}$
RT	$\varnothing$
Average trackability (AT)	0.8868
Fault detection rate (FDR)	100%
Fault isolation rate (FIR)	98.1%
Fault tracking rate (FTR)	98.1%
Fault prediction rate (FPR)	98.1%

Conclusions

- The FETDM and testability analysis methodology are important for improving the ability to monitor the health of PHM systems and system reliability, and to reduce operating costs.
- Future studies will focus on applying FETDM to complex mechanical systems and improving the technique proposed in this paper for use in other engineering systems. A software tool based on FETDM theory is being developed to realize those functions. Moreover, some methods widely used in health assessment and fault prognostics will be considered in developing FETDM to provide better support for condition-based maintenance or PHM.