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# Wear rate-state interaction modelling for a multi-component system: **Models and an experimental platform Models and an experimental platform Models and an experimental platform Models and an experimental platform**

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e-mail: phuc.do@univ-lorraine.fr state, and also the state of other components. An experimental platform that aims to provide more insight into the true nature of degradation of multi-component systems is also described. Some preliminary<br>experimental results demonstrate the feasibility and advantages of the proposed deterioration model for experimental results demonstrate the feasibility and advantages of the proposed deterioration model for describing highly stochastic degradation processes in industrial engineering. experiently model results dependance proposed in model of the proposed of deterioration process of a component depends upon the operational conditions, the component's own Abstract: This paper proposes a general deterioration model for a multi-component system. The describing highly stochastic degradation processes in industrial engineering. describing highly stochastic degradation processes in industrial engineering.

 $\odot$  2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.  $\epsilon$  and the  $\sigma$  results demonstrate the feasibility and advantages of the proposed determines of the proposed d  $\heartsuit$  2010, if AU (international rederation of Automatic Control) flosting by Elsev

Keywords: Maintenance, degradation, rate-state interaction, multi-component system

#### 1. INTRODUCTION 1. International and the control of 1. INTRODUCTION

predicting remaining useful inferme is a key element for<br>preventing failure of components, which incurs unexpected preventing failure of components, which means unexpected<br>downtime leading to low plant efficiency and higher maintenance costs. However predicting remaining useful infinitenance costs. However predicting remaining useful<br>lifetime can be very challenging in a real world environment, the time can be very chancinging in a real world environment, have an impact on the components degradation process. A have an impact on the components degradation process. A<br>key to having more accuracy while predicting these components' remaining useful lifetime is to be able to master their deterioration process. Many deterioration models have their deterioration process. Many deterioration models have<br>been proposed and successfully applied for various industrial been proposed and successfully applied for various mudstrian<br>systems, see Wang (2002) and Van Noortwijk (2009) for an bysicilis, see wang  $(2002)$  and van Noortwijk  $(2009)$  for an overview. It is shown in the literature that the deterioration process may depend on the interactive that the determination process may depend on the operational condition (load, temperature, vibration, humidity, maintenance operation, etc), see for instance Deloux et al. (2009), Song et al. (2014) and Do et al.  $(2015)$ . It is also shown that the deterioration process of a system may depend on the current state of the system Si et al. (2012). However, in such works, the system Si et al.  $(2012)$ . However, in such works, the deterioration models can be only applied for single-<br>component systems.  $\text{component systems.}$ Predicting remaining useful lifetime is a key element for  $d_{\text{total}}$  can be very changing in a real world environment,  $t_{\text{sub}}$  determining useful incline is to be able to master systems, see wang  $(2002)$  and van involting  $(2007)$  for an  $\alpha$  det al. (2012). However, in such works, the  $\frac{1}{2}$  ifetime can be very challenging in a real world environment due to the random nature of events that might hannen and components' remaining useful lifetime is to he able to master systems see Wang  $(2002)$  and Van Noortwijk  $(2009)$  for an etc), see for instance Deloux et al. (2009). Song et al. (2014) process of a system  $\frac{1}{2}$  (2012) However in such works the  $\frac{1}{2}$  deterioration models can be only annlied for singlecomponent systems.

containing materials keep becoming more complex, subsystems within a system as a whole. Taking into consideration dependencies between components when modelling the deterioration behaviours of multi-component systems has recently shown an increase in popularity among systems has recently shown an increase in popularity among<br>researchers. Degradation interaction or state dependence, which implies that the state evolution of a component depends on both its state and the state of other components, has been introduced in Bian and Gebrael (2014) for prognostics of system lifetime, and in Do et al.  $(2015)$ , Rasmekomen and Parlikad (2016) for maintenance optimization. However, these works do not consider the operational condition impacts on the deterioration modelling. operational condition impacts on the deterioration modelling. To face this issue, the first objective of this paper is to To face this issue, the first objective of this paper is to To face this issue, the first objective of this paper is to Industrial machines keep becoming more complex,  $r_{\text{rel}}$  multiple interactions for  $r_{\text{rel}}$  interactions for  $r_{\text{rel}}$  interactions for  $r_{\text{rel}}$  $r_{\text{Sys}}$  and  $r_{\text{Sys}}$  is the centry shown an increase in popularity among  $p_{\text{max}}$  been introduced in Dian and Georgen (2014) for To face this issue, the first objective of this paper is to operational condition impacts on the deterioration modelling.  $\frac{1}{2}$  $\frac{1}{2}$  models the deterministic model in the deterministic multi-contract the system of  $\frac{1}{2}$ has been introduced in Bian and Gebraeel  $(2014)$  for prognostics of system lifetime and in Do et al.  $(2015)$  $\frac{p}{q}$  and  $\frac{p}{q}$  system lifetime, and  $\frac{p}{q}$  (2016), for maintenance  $R$  contimization However these works do not consider the

propose a general deterioration model for multi-component<br>systems, which takes into account not only state dependence but also the operational condition effect. The second out also the operational condition effect. The second<br>objective of the paper is to present an experimental platform developed, with the aim of providing the multi-component developed, with the ann of providing the mutu-component<br>degradation model more insight about the true nature of deterioration for components with dependencies. In contrast with previous developed platforms, the experimental platform presented has sensors that are set up and configured in a way presented has sensors that are set up and computed in a way<br>that would best capture wear interdependencies between components, the aim is to estimate the parameters of the components, the aim is to estimate the parameters of the presented degradation model in this paper. propose a general deterioration model for multi-component components, the aim is to estimate the parameters of the<br>presented degradation model in this paper.

propose a general deterioration model for multi-component

appreciated by OEMs and their clients, for logistic reasons appreciated by OEMs and their enems, for logistic reasons among others. The experimental data that the developed allong others. The experimental data that the developed<br>platform will produce will compliment simulation data, and lead to more robust degradation models that in turn lead to more accurate remaining useful lifetime predictions, and thus more accurate remaining useful friedrich predictions, and thus more reliable maintenance scheduling can be done around that. that. that. Highly dynamic maintenance schedules are not well  $\sum_{n=1}^{\infty}$ produce the more robust degradation models that in turn lead to more accurate remaining useful lifetime predictions and thus more reliable maintenance scheduling can be done around  $m<sub>1</sub>$  more reliable maintenance scheduling can be done around that

to provide data for RUL calculations. A bearing accelerated degradation test bed has been developed at femto Nectoux et<br>degradation test bed has been developed at femto Nectoux et al. (2012), the test bed PRONOSTIA was aimed at validating al. (2012), the test bed PRONOS LIA was almod at validating<br>methods related to bearing health assessment, this experimental platform provided 3 test sets for the PHM capermental platform provided 3 lest sets for the TTIM<br>challenge on RUL predictions. A bearing test bed is proposed Yan et al. (2009) Vibration readings were collected using 3 r an et al. (2009) Vibration readings were conected using 5<br>accelerometers for the accelerated degradation test, and a new accelerometers for the accelerated degradation test, and a new<br>vibration signal analysis method was developed to extract wear related features. Similarly a Bearing test bed has been developed by the centre for intelligent maintenance systems, 4 bearings were installed on a single shaft, and 3 experiments The Model of a single shart, and 3 experiments<br>ran to bearing failure, The Morlet wavelet filter-based denan to beaming randice, The Moriet wavelet their-based de-<br>noising method was applied for De-noising and extracting the noising method was applied for De-hoising and extracting the<br>weak signature from the noisy signal, and so perform reliable weak signature from the noisy signal, and so perform reliable prognostics on the bearing data Qiu et al. (2006). prognostics on the bearing data Qiu et al. (2006). prognostics on the bearing data Qiu et al. (2006). Some experimental platforms have been proposed and used some experimental platforms have been proposed and used experimental platform provided 3 test sets for the PHM weak signature from the horsy signal, and so perform reliable.<br>prognostics on the bearing data Oiu et al. (2006).  $\frac{1}{2}$  methods related to bearing health assessment this  $\frac{1}{2}$  acceleration signal analysis method was developed to extract wear related features. Similarly a Bearing test hed has been  $\frac{1}{2}$  bearing failure. The Morlet wavelet filter-based de-

The remainder of this paper is organized as follows: The multi-component degradation model is presented in section 2, section 3 covers the developed experimental platform, some of the experimental data generated by the platform are presented in section 4 along with an analysis on the components' degradation dependence, and finally, section 5 concludes the paper.

## 2. MULTICOMPONENT SYSTEM MODELLING

Let us consider a system with multiple components interacting in series, where if one component fails the system fails. Each component *i* is subject to a continuous accumulation of deterioration in time, that is assumed to be described by a scalar random variable  $X_t^l$ . Component *i* fails if its deterioration level reaches the failure threshold  $L^l$ . When a component is not operating for whatever reason, its deterioration level remains unchanged during the stoppage period if no maintenance is carried out.

### *2.1 Rate-state interaction modelling*

Between two adjacent maintenance activities, we assume that evolution of the deterioration level of component *i* is denoted by

$$
X_{t+1}^i = X_t^i + \Delta X_t^i \tag{1}
$$

Where  $\Delta X_t^i$  is the increment in the degradation level of component *i* during one time unit.

From a practical point of view, the deterioration increment of a component at time *t* may depend on the operational condition (mission profile), its own current state as well as the current of state of other components. In this way, we suggest a general stationary model for the increment  $\Delta X_t^i$ :

$$
\Delta X_t^i = \Delta O_t^i + \Delta X_t^{ii} + \sum_{j \neq i} \Delta X_t^{ji}
$$
 (2)

where:

- $-\Delta O_t^i$  is the increment in the deterioration level of component *i* caused by the operational condition during one time unit, namely the operation effect.  $\Delta O_t^t$  may be specified as deterministic or as a random variable;
- $\Delta X_t^u$  represents the increment in the deterioration level of component *i* induced by itself during one time unit, namely the intrinsic effect. This means that  $\Delta X_t^u$  depends only on the state of component *i* at time *t*. In the same manner,  $\Delta X_t^u$  may be specified as deterministic or as a random variable;
- $-\Delta X_t^{\mu}$  is the increment in the deterioration level of component *i* induced by component *j* during one time unit, called the interaction effect.  $\Delta X_t^{\mu}$  represents the state interaction between the two components *j*, *i* and may be specified as deterministic or as a random variable.

Several variants of the proposed model can be specified:

Case 1:  $\Delta O_t^i > 0$ ,  $\Delta X_t^{ii} = 0$  and  $\Delta X_t^{ji} = 0$  with  $\forall j \neq i$ : neither intrinsic effect nor interaction effect and the proposed model becomes a basic model describing the homogenous

degradation behaviour of independent components, see for instance Van Noortwijk (2009).

Case 2:  $\Delta O_t^i > 0$ ,  $\Delta X_t^{ii} > 0$  and  $\Delta X_t^{ji} = 0$  with  $\forall j \neq i$ : no interaction effect and the proposed model becomes a basic model describing the non-homogenous degradation behaviour, see Si et al. (2012).

Case 3:  $\Delta O_t^i = 0$ ,  $\Delta X_t^{ii} = 0$  and  $\Delta X_t^{i} > 0$  with  $j \neq i$ : here the components *i* and  $j$  ( $j \neq i$ ) are stochastically dependent but the increment in the deterioration level of component *i* depends only on the state of component *j*. For this case, the proposed model corresponds to the model introduced in Rasmekomen and Parlikad (2016) where the interaction effect  $(\Delta X_t^{\prime t})$  is described by a normal distribution whose parameters depend on the deterioration level of component *j.*

Case 4:  $\Delta O_t^i > 0$ ,  $\Delta X_t^{ii} = 0$  and  $\Delta X_t^{ji} > 0$  with  $j \neq i$ : components *i* and *j* ( $j \neq i$ ) are stochastically dependent and the increment in the deterioration level of component *i* does not depends on the state of the component its self, see Do et al. (2015), Bian and Gebraeel (2014)*.*

Case 5:  $\Delta O_t^i > 0$ ,  $\Delta X_t^{ii} > 0$  and  $\Delta X_t^{ji} > 0$  with  $j \neq i$ : the components *i* and *j* ( $j \neq i$ ) are stochastically dependent and the increment in the deterioration level of component *i* depends on the operational condition, the state of component *i* as well as the state of component *j*.

As an example, we consider the case 4 and extend the model proposed for condition-based maintenance of a twocomponent system in Do et al. (2015) to multi-component systems. In that way,

$$
\Delta X_t^i = \Delta O_t^i + \sum_{j \neq i} \mu^{ji} * (X_t^j)^{\sigma^{ji}}
$$
 (3)

where  $\Delta O_t^l$  is described by a gamma law with shape parameter  $\alpha^i$  and scale parameter  $\beta^i$ .  $\mu^j$  and  $\sigma^j$  are nonnegative real numbers that quantify the influence of component *j* on the deterioration rate of component *i*. Fig. 1 illustrates the degradation evolution of a 3-component system with rate-state interaction modelled by eq. (3) with

$$
\alpha = \begin{pmatrix} \alpha^1 \\ \alpha^2 \\ \alpha^3 \end{pmatrix} = \begin{pmatrix} 4.944 \\ 4.350 \\ 5.193 \end{pmatrix}, \beta = \begin{pmatrix} \beta^1 \\ \beta^2 \\ \beta^3 \end{pmatrix} = \begin{pmatrix} 3.919 \\ 1.09 \\ 2.257 \end{pmatrix}
$$

and,

$$
\sigma = [\sigma^{ji}] = \begin{pmatrix} 0 & 0.54 & 0.729 \\ 0.785 & 0 & 0.836 \\ 0.838 & 0.555 & 0 \end{pmatrix},
$$

$$
\mu = [\mu^{ji}] = \begin{pmatrix} 0 & 0.254 & 0.108 \\ 0.384 & 0 & 0.346 \\ 0.242 & 0.118 & 0 \end{pmatrix}
$$

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