Hybrid Prognostic Approach for Micro-Electro-Mechanical Systems

Haithem Skima
Kamal Medjaher
Christophe Varnier
AS2M Department, FEMTO-ST Institute
24 Rue Alain Savary
25000 Besançon, France
haithem.skima@femto-st.fr
kamal.medjaher@ens2m.fr
christophe.varnier@ens2m.fr

Eugen Dedu
Julien Bourgeois
DISC Department, FEMTO-ST Institute
1 Cours Leprince-Ringuet
25200 Montbéliard, France
eugen.dedu@univ-fcomte.fr
julien.bourgeois@femto-st.fr

Abstract— **This paper presents a hybrid prognostic approach which is applied on electro-thermally actuated MEMS valve. The method can be applied on different categories of MEMS to assess their health state, calculate the remaining useful life (RUL) and take appropriate decisions to anticipate the failures. In this paper a detailed description of the proposed method is presented. It consists of combining both degradation and nominal behavior models in order to estimate the current and future MEMS health states. A test bed for several MEMS is designed to acquire data in relation with the health state of the MEMS. The data processing obtained with this platform aims at deriving degradation models. Physical modeling is used to build the nominal behavior model of the valve. To show the effectiveness of the proposed method and in order to validate the implementation of Prognostics and Health Management (PHM) models on MEMS, two simulated degradations of the valve MEMS are considered.**

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1. INTRODUCTION

PHM is a process that monitors systems, assesses their health state, detects and diagnoses their faults, anticipates the time to failures by calculating the remaining useful life (RUL) and takes appropriate decisions accordingly. Prognostic approaches can be categorized into three classes, namely model based (also called physics-based approach), data-driven and hybrid prognostic approaches [1]. The first approach deals with the prediction of the RUL of components by using mathematical or physical models to describe the degradation phenomena. The second approach aims at transforming sensory data into relevant models of the degradation behavior [2]. Finally, the hybrid approach combines both data-driven and model-based approaches and benefits from both categories to overcome their drawbacks. Prognostic results obtained from this approach are claimed to be more reliable and accurate [1].

PHM approaches are widely applied on industrial systems ranging from small components [2] (bearings, batteries, etc.) to complete machines [3] (wind turbines, electrical motors, etc.) and they can be applied to MEMS to improve the reliability and availability of systems in which they are utilized, to avoid failures and to reduce maintenance costs. However, the miniature scale of these microsystems introduces some challenges which should be taken into account while developing a PHM system for MEMS.

This paper presents a hybrid prognostic method applied on electro-thermally actuated MEMS valve. Firstly, in section 2, a brief literature review related to MEMS is presented. In section 3, the proposed method is introduced. The experimental platform and the system description are provided in section 4. In section 5, a detailed modeling of the electro-thermal actuator used in the MEMS valve is presented. Section 6 shows the simulation results of two degradation models. Finally, section 7 concludes the paper.

2. STATE OF THE ART

A Micro-Electro-Mechanical System (MEMS) is a microsystem that integrates mechanical components using electricity as souce of energy in order to perform measurement functions and / or operating in structure having micrometric dimensions. MEMS are used in different applications such as aerospace, automotive, biomedical, and communication technologies to achieve different functions in sensing, actuating and controlling. They can be classified into several categories: bio MEMS, micro sensors, micro actuators, RF MEMS, optical MEMS, microfluidics MEMS and power MEMS. Most of these microsystems are designed with some basic parts such as cantilever beams, membranes, springs, hinges, etc. [4]. These parts are subject to degradation and failure mechanisms due to several influence factors (temperature, humidity, vibration, noise, etc.). Common failure mechanisms identified and known until now concern stiction, wear, fracture, creep, delamination, contamination, adhesion, fatigue, degradation of dielectrics, and electrostatic discharge. Some of these failure mechanisms are described below.

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Stiction

Stiction is one of the most important and almost unavoidable problems in MEMS. It is the most difficult to model and detect. Stiction is the adhesion of contacting surfaces due to surface forces, which mainly contain capillary forces, van der Waals molecular forces, casimir forces, hydrogen bridging and electrostatic forces [5]. It can also occur when microstructures are exposed to a humid environment. This failure mechanism is very common for MEMS electrostatically actuated as micro-mirrors and RF MEMS.

Fracture

Mechanical fracture is the local separation of an object or material into two or more pieces under the action of stress. Fracture is most likely to occur in structural beams with long thin pieces of material that often serves as the supporting basis for a structure, which are a basic building block of most MEMS devices, for example, accelerometers, micro-mirrors, etc. This type of failure has various causes: mechanical shock and overload, corrosion, vibrations and cracks due to fatigue.

Contamination

Several MEMS rely on the movement of mechanical components to perform their functions. However the penetration of unwanted materials, which is called contamination, can affect the mechanical aspect of a MEMS by blocking the moving parts and then causing its failure. Contamination can be introduced during fabrication processes such as surface cleaning and metal deposition or in-use operation where foreign particles penetrate inside the MEMS [6].

Fatigue and creep

Fatigue begins with cracks in the area of âĂŃâĂŃhigh stress concentration and propagates through the material until failure occurs slowly. This phenomenon can occur in metallic and silicon MEMS. The plastic deformation or creep is the slow movement of atoms typically caused by the temperature and the applied stress. It generally occurs in MEMS with metal films (TI DM mirrors).

Figure 1 illustrates some examples of these failure mechanisms.

In the literature, several research works dealing with MEMS have been reported [4,6,10–16]. Most of the published works deal with:

- design and fabrication of MEMS;
- testability and characterization of MEMS;
- identification and understanding of failure mechanisms;
- design, fabrication and packaging optimization;
- accelerated life tests to develop reliability models;
- statistical studies of failures on a significant number of samples.

In fact, these works deal with reliability, and no contributions are targeted toward implementing PHM for MEMS. Unfortunately, reliability has several limitations. According to its definition, it is valid only for given conditions and period of time. Also, the predictive reliability models are obtained from statistical data on a significant number of samples which is difficult to achieve in laboratory. These models are not personalized for each MEMS and therefore there is no update of the model parameters during their utilization.

PHM is a way to adress the above limitations. It assesses the

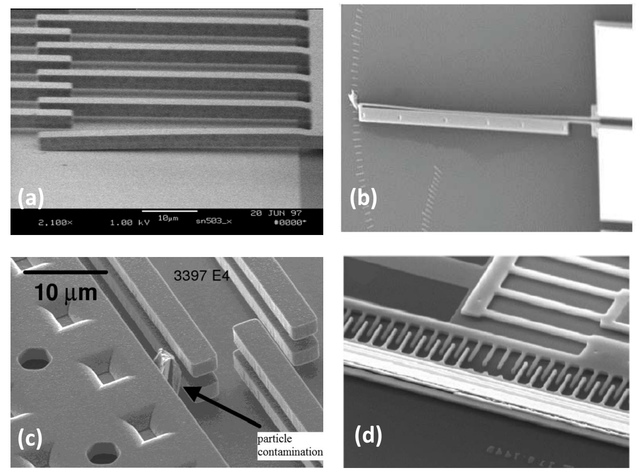

Figure 1. Failure mechanisms illustration: (a) stiction of the finger on the substrate, (b) stiction in electrothermal actuator, (c) contamination in a comb-drive, and (d) finger fracture [7–9].

health state of the MEMS at any time, predicts the RUL by taking into account the current and future conditions, updates the degradation models parameters based on monitoring data, anticipates failures in a system based on MEMS and optimizes decision making.

3. Proposed method

The main steps of the proposed method are summarized in Figure 2 and explained below. It contains four main steps.

- Nominal behavior models: obtained by writing the corresponding physical equations of the targeted MEMS. The parameters of the model are identified by exciting the MEMS and getting its time response. In other cases, these parameters can be obtained from the manufacturer's specifications.
- Degradation models: obtained experimentally through accelerated life tests. The aquired data are analyzed by using appropriate modeling tools.

The operating conditions, such as temperature and humidity variations, affect the degradation models and the nominal behavior models.

- Health assessment and prediction: this task is performed by combining both nominal behavior and degradation models of the targeted MEMS. The globel model is then used to predict the state of the MEMS. The state is then compared to the failure threshold beyond which the MEMS is considered faulty or out of sevice.
- RUL estimation and decision making: the RUL is calculated as the difference between the failing time and the current time. RUL values allow appropriate decision making.

To develop the models, experimental data are required and that is why the experimental platform is designed.

4. Experimental platform and system description

The experimental platform used to test the proposed method is shown in Figure 3. It is composed of an ARDUINO device, a voltage supplier, supports for the camera and the MEMS, a light source for the camera allowing to see the movement

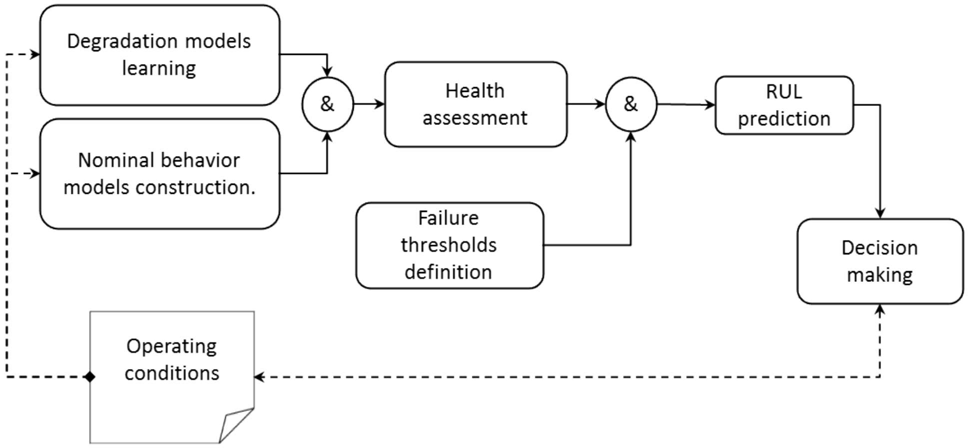

Figure 2. Main steps of the proposed method.

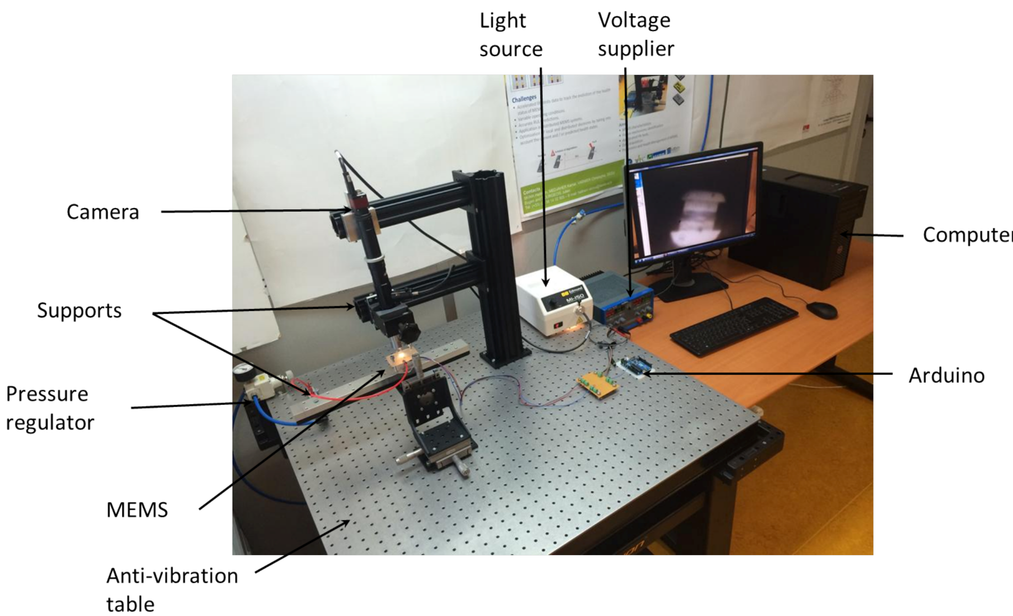

Figure 3. Overview of the experimental platform.

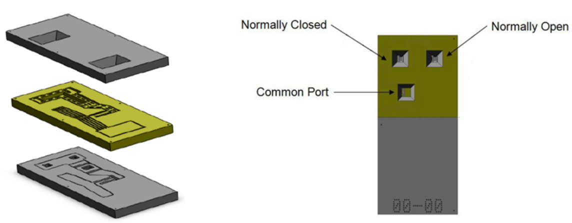

Figure 4. Electro-thermally actuated MEMS valve.

of the membrane inside the MEMS, an air inlet, a pressure regulator and a computer for data acquisition. The central component of the platform consists of an electro-thermally actuated MEMS valve of Microstag company designed to ensure accurate control of fluid in the Modular Silicon Expansion Valve. Figure 4 shows a general scheme of the MEMS valve used in this work. This valve is made using standard semiconductor processes augmented with standard MEMS processes using etching and wafer bonding. It consists of three silicon layers bonded together using silicon fusion bonding. The center layer is a movable membrane. The other two layers of silicon act as interface plates to either electrical connections (top layer), or fluid connection ports (bottom layer): common port, normally closed and normally open. The maximum actuation voltage of the valve is 12 V.

Several MEMS are tested to extract data, used to obtain degradation models that correspond to drifts in the displacement of the membrane, the stiffness, the settling time, the air pressure, the current, etc. The displacement is measured from the response time of the valve obtained using a Matlab image-processing algorithm (Figure 5).

The image acquisition is done using a Guppy Pro F-031 camera with a frame rate of about 70 fps. The air pressure is measured using pressure sensors. The MEMS is supplied with a square signal of 11 V magnitude and frequency equal to 0.8 Hz generated by a voltage supplier and an ARDUINO device. Its current consumption is about 0.62 A.

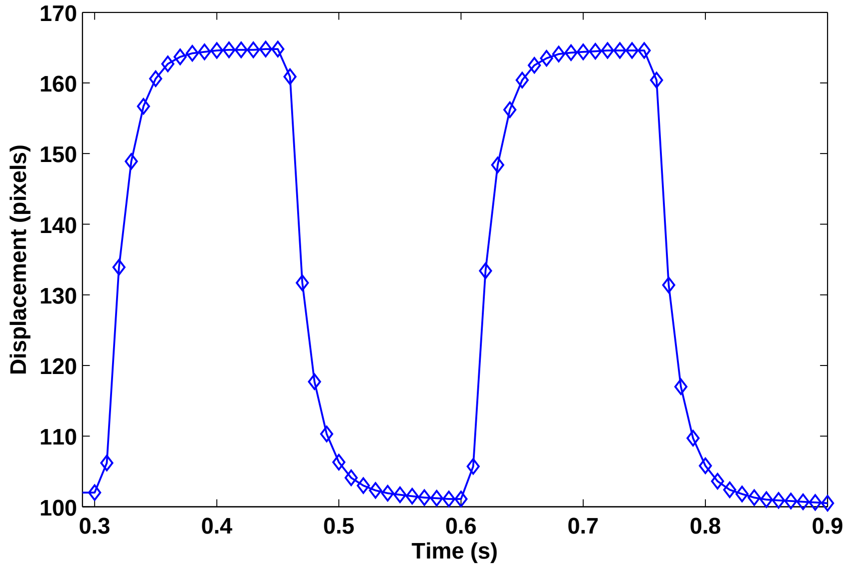

Figure 5. Response time of the valve.

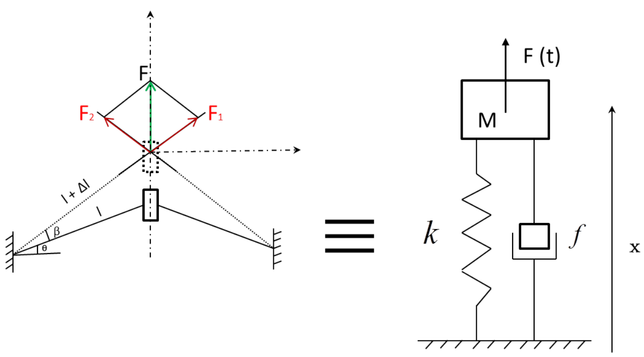

Figure 6. Physical scheme of the electro-thermal actuator.

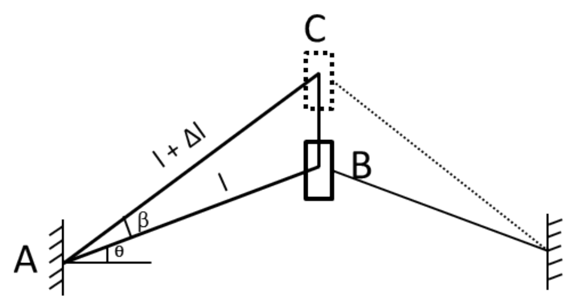

Figure 7. Principal of kinematic closed chain.

5. NOMINAL BEHAVIOR MODEL

The electro-thermal actuator used in the MEMS to move the membrane is assimilated to a second order dynamic system. The actuator is modeled as a mass-spring-damper (MSD) system. Figure 6 shows the physical scheme of the actuator.
The application of the second fundamental law of dynamics leads to the following equation:

$$\Sigma\overrightarrow{F}ext = M\overrightarrow{\gamma} \Leftrightarrow F = M\ddot{x} + f\dot{x} + kx \qquad (1)$$

where f is the friction coefficient, k is the stiffness, M is the mass and $\overrightarrow{F} = \overrightarrow{F_1} + \overrightarrow{F2}$ is the resultant displacement force.

$\overrightarrow{F_1}$ and $\overrightarrow{F2}$ are the forces generated by the thermal displacement which act at the end of the hot arms. They are given by the folowing equation:

$$\|F_1\| = \|F_2\| = EAh\Delta T \qquad (2)$$

where E is the Young's modulus, A is the surface of the arm section, h is the coefficient of linear thermal expansion and ΔT is the temperature variation.

Then, the resultant displacement force can be written as follows:

$$\|F\| = 2EAh\sin(\theta + \beta)\Delta T \qquad (3)$$

The angle θ is always constant, while the angle β is variable. To write the term $\sin(\theta + \beta)$ only as a function of θ, the principal of kinematic closed chain is applied (Figure 7) :

$$\overrightarrow{AB} + \overrightarrow{BC} + \overrightarrow{CA} = \overrightarrow{0} \qquad (4)$$

The Eq. 4 is projected along $(o, \overrightarrow{i})$ and $(o, \overrightarrow{j})$:

$$\begin{cases} AB\overrightarrow{i} + BC\overrightarrow{i} + CA\overrightarrow{i} = \overrightarrow{0} \\ AB\overrightarrow{j} + BC\overrightarrow{j} + CA\overrightarrow{j} = \overrightarrow{0} \end{cases}$$

$$\begin{cases} l\cos(\theta) + 0 + (l + \Delta l)\sin(\theta + \beta) = 0 \\ l\sin(\theta) + x - (l + \Delta l)\cos(\theta + \beta) = 0 \end{cases}$$

Using the above relations, $\sin(\theta + \beta)$ can be expressed as follows:

$$\sin(\theta + \beta) = \frac{l\cos(\theta)}{l + \Delta l} = \frac{\cos(\theta)}{1 + \frac{\Delta l}{l}} = \frac{\cos(\theta)}{1 + h\Delta T}$$

The resultant force can be written as follows:

$$F = 2EAh\cos(\theta) \times \frac{\Delta T}{1 + h\Delta T} \quad (5)$$

Hypothesis: assuming a small temperature variation:

$$U(t) = \frac{\Delta T}{1 + h\Delta T} \approx \Delta T.$$

Eq.1 can be written then as follows:

$$M\ddot{x}(t) + f\dot{x}(t) + kx(t) = 2EAh\cos(\theta)U(t) \quad (6)$$

By applying the Laplace transform on Eq. 6, one gets the canonical transfer function given in Eq. 7:

$$\frac{X(p)}{U(p)} = \frac{K}{\frac{1}{w_0}p^2 + \frac{2\xi}{w_0}p + 1} \quad (7)$$

where $K = \frac{2EAh\cos(\theta)}{k}$ is the static gain, $w_0 = \sqrt{\frac{k}{M}}$ its natural frequency and $\xi = \frac{f}{2\sqrt{kM}}$ its damping coefficient.

The fundamental dynamic equation (Eq. 1) can be written in the form of a state space representation:

$$\begin{cases} \dot{X} = AX(t) + BU(t) \\ Y(t) = CX(t) + DU(t) \end{cases}$$

Assuming that $\dot{x_1}(t) = \dot{x}(t) = x_2(t)$, Eq. 1 can be written as follows:

$$\ddot{x_1}(t) = \dot{x_2}(t) = -\frac{f}{M}x_2(t) - \frac{k}{M}x_1(t) + \frac{F}{M}$$

$$\begin{pmatrix} \dot{X_1}(t) \\ \dot{X_2}(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\frac{k}{M} & -\frac{f}{M} \end{pmatrix} \begin{pmatrix} X_1(t) \\ X_2(t) \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{M} \end{pmatrix} F$$

$$\begin{pmatrix} \dot{X_1}(t) \\ \dot{X_2}(t) \end{pmatrix} = A \begin{pmatrix} X_1(t) \\ X_2(t) \end{pmatrix} + B * F \,;\, Y(t) = C \begin{pmatrix} X_1(t) \\ X_2(t) \end{pmatrix}$$

where $A = \begin{pmatrix} 0 & 1 \\ -\frac{k}{M} & -\frac{f}{M} \end{pmatrix}$; $B = \begin{pmatrix} 0 \\ \frac{1}{M} \end{pmatrix}$; $C = \begin{pmatrix} 0 & 1 \end{pmatrix}$

This state space representation allows to determine the state of the system at any time. The nominal behavior model of the MEMS is written in two forms: canonical transfer function and state space representation. This model is used in the next section to simulate degradation models.

6. SIMULATION RESULTS

The degradation of the electrothermally actuated valve is related to drifts of its physical parameters. According to the modeling part, the variation of the parameters depend on the variation of the stiffness k which can vary significantly due to cycling. To test this, the experimental platform shown in Figure 3 is designed where MEMS are continuously cycled with a cycling frequency equal to $0.8\ Hz$ and measurements are done each 172 800 cycles, once a day. Measurements are performed for several MEMS in the same conditions to ensure the repeatability of the parameters. The manufacturer guarantees 10 million cycles without performance degradation. To observe significant drift of the performance, one has to wait approximately 50 days. To show the effectiveness of the proposed method, and while waiting to have complete experimental data, two simulated degradation models of the MEMS valve represented by the variation of the stiffness k are considered. The two simulated degradation models, exponential and polynomial, are given respectively by Eqs. 8 and 9.

$$k(t) = \mathrm{e}^{-\mathrm{a*t}} \quad (8)$$

$$k(t) = a * t^2 + b * t + 1 \quad (9)$$

The injection of these degradation models in the nominal behavior model given in Eq. 7 leads to a global model. By analyzing the time response given by this model, the parameters of the system can be estimated at each time and then the health state can be obtained. Furthermore, the RUL of each MEMS can be calculated at each time. The time response obtained experimentally from a new MEMS valve shown in Figure 5 corresponds to a second order dynamic system with $\xi = \frac{f}{2\sqrt{kM}} > 1$.

When the stiffness k decreases with time, exponentially or polynomially, ξ increases, which is explained by the settling time increase. This relation can be verified through the simulation results. Figures 8 and 9 show the two simulation examples related to the proposed degradation models and their impact on the time response of the system.

To calculate the RUL, a failure threshold T_f has to be defined. It is obtained by supposing a limit stiffness value beyond which the MEMS can be considered as out of service. T_f is the time that corresponds to this limit value. The RUL can then be calculated as the difference between T_f and the current time. The RUL values are used to take appropriate decisions such as reconfiguration and maintenance intervention. Figure 10 shows the stochastic estimation of RUL.

7. CONCLUSION

This paper shows the ability to implement PHM on MEMS to assess their health state and calculate their RUL values at any time. A hybrid prognostic method, which is applied on electro-thermally actuated MEMS valve has been proposed. Experimental measurements are performed with several MEMS to collect data and derive the degradation models. A model of the nominal behavior of the MEMS valve has been derived by writing the physical equations. The models are merged to assess the health state of the targeted MEMS, predict its RUL and take appropriate decision. Simulation results showed the effectiveness of the proposed method.

Experiments are still ongoing in order to derive the degradation models which will allow to estimate the health state of the MEMS and predict their RUL. The results will be used then to optimize the performance and the availability of a distributed system containing numerous MEMS valves.

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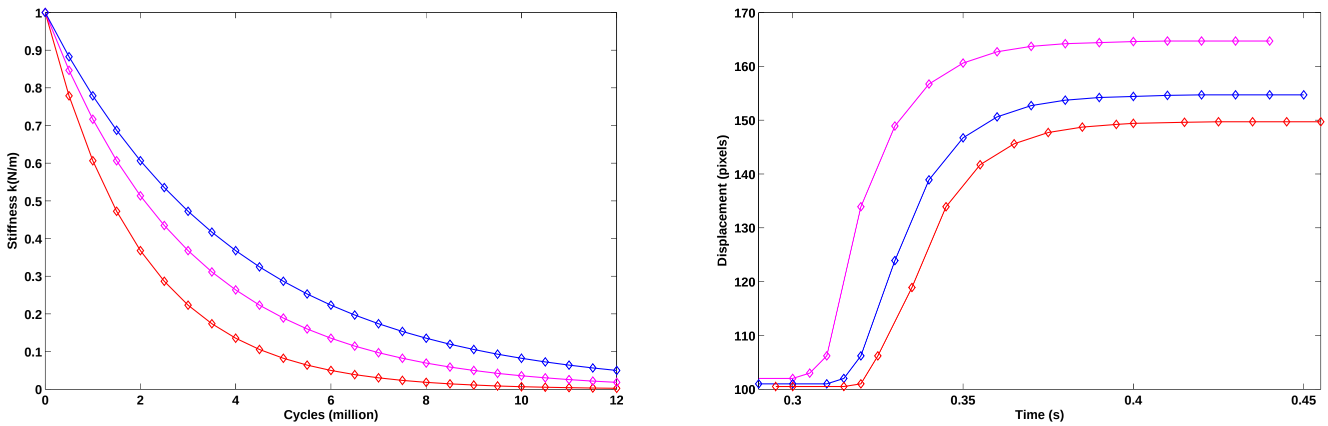

Figure 8. Exponential degradation model and its impact on the time response.

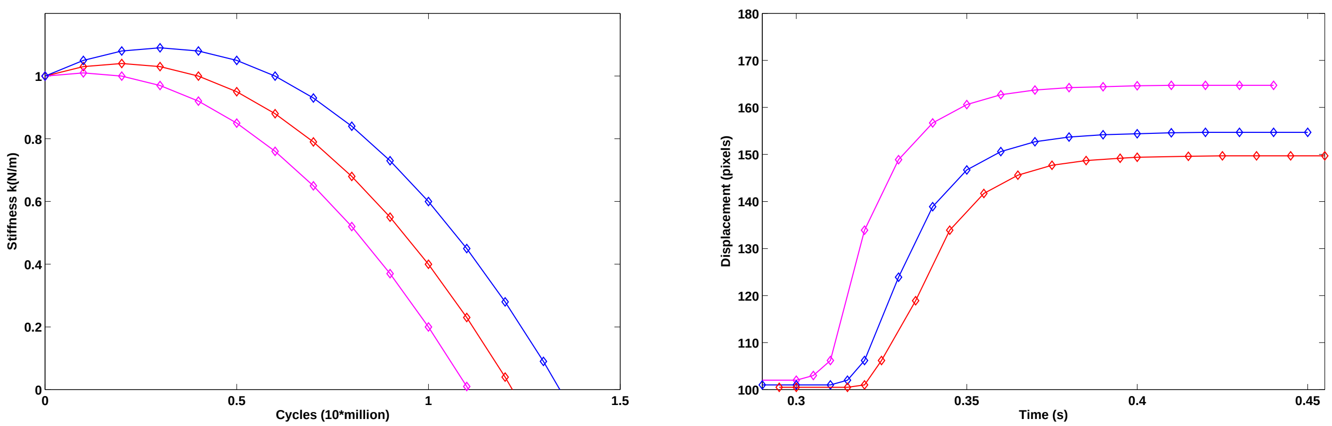

Figure 9. Polynomial degradation model and its impact on the time response.

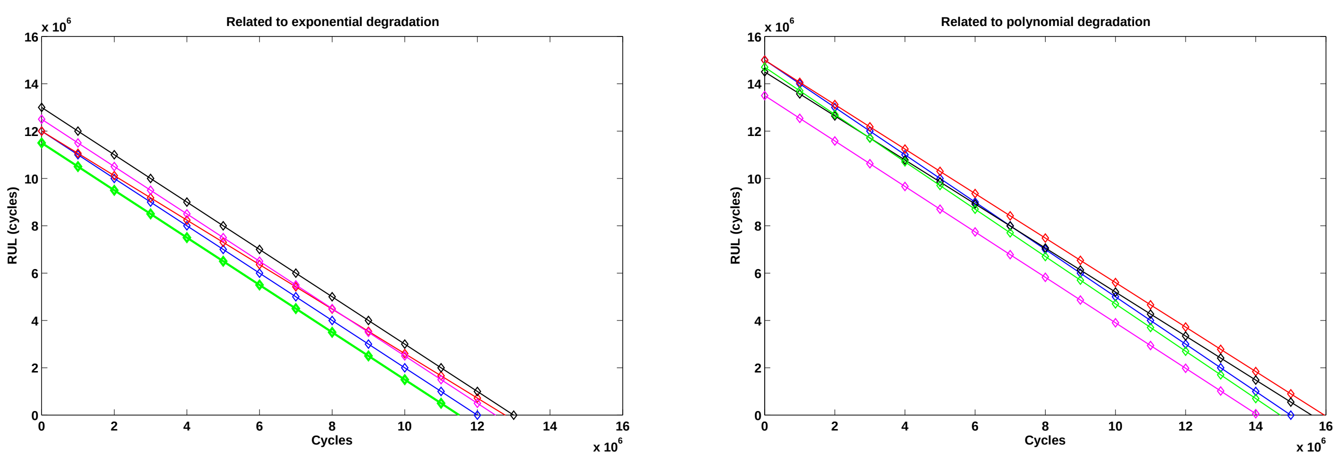

Figure 10. RUL estimation related to exponential and polynomial degradations.

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BIOGRAPHY

Haithem Skima *received his engineering degree in Instrumentation and Industrial Maintenance from National Institute of Applied Science and Technology of Tunis (INSAT) in 2013. Currently he performs his doctoral studies at FEMTO-ST institute in Besançon, France that is funded by "Région Franche-Comté" since 2013. He is with the PHM team in Automatic Control and Micro-Mechatronic Systems departement and complex networks team in Computer Science department. His research activities are concerned with Prognostics and Health Management of Distributed Micro-Electro-Mechanical Systems (MEMS).*

Kamal Medjaher *is an Associate Professor with the National Institute in Mechanics and Microtechnologies (ENSMM), Besançon, France, since 2006. He received his PhD in control and industrial computing from the University of Lille 1, France, in 2005. He is also a researcher at the Automatic Control and Micro-Mechatronic Systems Department of the FEMTO-ST Institute. His current research interests include prognostics and health management with special developments in data processing, feature extraction, health assessment, and remaining useful life prediction.*

Christophe Varnier *is an Associate Professor with the National Institute in Mechanics and Microtechnologies (ENSMM), Besançon, France. He received his PhD in Automation and Computer Science from University of Franche-Comté in 1996. He has been a Lecturer of Computer Science since 1996. He is also a researcher at the Automatic Control and Micro-Mechatronic Systems Department of the FEMTO-ST Institute. His research main fields are operational research and decision support in maintenance engineering. He works particularly on post-prognostics decision.*

Eugen Dedu *is an Assistant Professor at the Computer Science department of FEMTO-ST institute at Montbéliard, France. He received his PhD in Computer Science at the University of Versailles Saint-Quentin-en Yvelines, France, in 2002. His main research interests are in the transport level in computer networks, adaptive video streaming, communication in MEMS sensor/actuators networks and in nanonetworks.*

Julien Bourgeois *is Professor at the Computer Science department of FEMTO-ST institute at Montbéliard, France, where he leads the research team on complex networks. His interests include multimedia streaming, optimization of P2P and MEMS sensor/actuators networks and security management in complex networks.*