Accelerated lifetime tests and failure analysis of an electro-thermally actuated MEMS valve

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***Abstract*—This paper presents accelerated lifetime tests for an electro-thermally actuated MEMS valve in order to identify and analyze its failures. To perform the different tests, two experimental setup are specially designed. Tests consist in cycling several MEMS valves by changing at each test the operating condition: with unfiltered air, without air and with filtered air. Results show that different failure mechanisms can be detected depending on the operating conditions of the MEMS valve.**

I. Introduction

A Micro-Electro-Mechanical System (MEMS) is defined as a micro-system that integrates mechanical components using electricity as source of energy in order to perform measurement functions and/or operating in structure having micrometric dimensions. Over the last two decades, MEMS technology has grown from laboratory research projects to global commercialization. Thanks to their miniaturization, low power consumption and tight integration with control and sense electronics, MEMS devices gained wide-spread acceptance in several industrial segments including aerospace, automotive, medical and even military applications to achieve different functions in sensing, actuating and controlling. The most known MEMS are accelerometers for automotive (airbag) applications, gyroscopes for mobiles phones, pressure sensors for engine management and micro-mirror arrays for display applications.

Unfortunately, the reliability of MEMS is considered as a major obstacle for their development [1]. Most of these micro-systems are designed with some basic parts such as cantilever beams, membranes, springs and hinges [2]. These parts are subject to degradation and failure mechanisms which occur during their operation and impact their performances and the availability of systems in which they are utilized. These failures are due to several influence factors [3] such as temperature, humidity, vibration, acoustic 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 [2], [4]–[8].

One of the main challenges in this field is to identify, analyze and understand the failure mechanism to be addressed so that reliability can be developed. To do so, accelerated lifetime test method for evaluating the reliability of MEMS devices can be considered [9].

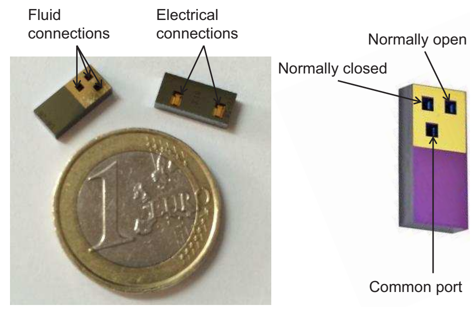


Fig. 1. Electro-thermally acuated MEMS valve designed by DunAn Microstaq company.

In this paper, we present accelerated lifetime tests for an electro-thermally actuated MEMS valve in order to identify and analyze its failure mechanisms. Tests are performed in an experimental platform, and inside the Scanning Electron Microscopy (SEM). They consist in cycling several MEMS valves continuously in different conditions: with unfiltered air, without air and with filtered air.

The paper is structured in five sections. After the introduction, Section II presents the targeted MEMS. Section III introduces the experimental setup. Results are presented and discussed in Section IV. Finally, Section V concludes the paper.

II. System description

The targeted system consists in an electro-thermally actuated MEMS valve of DunAn Microstaq, Inc. (DMQ), company designed to control flow rates or pressure with high precision at ultra-fast time response ($<< 100\ ms$). It is currently being used in a number of applications in air conditioning and refrigeration, hydraulic control and air pressure control. Fig. 1 shows a general scheme of the MEMS valve.

This valve is made by using standard semiconductor processes augmented with standard MEMS processes in etching and wafer bonding. It consists of three silicon layers bonded together by 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 or fluid connection ports: common port, normally closed and normally open. The SEM image (Fig. 2) shows the movable membrane through the normally open fluid port.

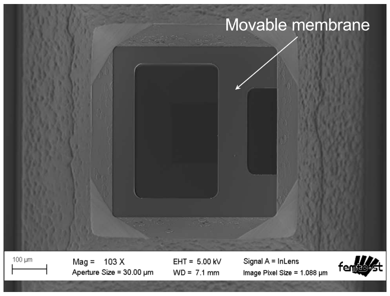


Fig. 2. SEM image of the movable membrane through the normally open fluid port.

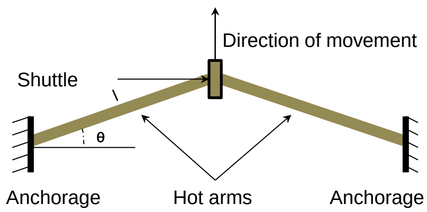


Fig. 3. Schematic view of the Chevron electro-thermal actuator used inside the MEMS valve to move the membrane.

The actuator used in the targeted MEMS to move the membrane, which allows to open or close the fluid ports, is an electro-thermal actuator. This actuator, presented in Fig. 3, is composed of hot arms inclined to the horizontal axis by an angle θ and clamped to the substrate and the freestanding central shuttle. When a voltage difference is applied across the anchor sites, heat is generated along the beams due to ohmic dissipation. The hot arms expand to push ahead symmetrically on the central part of the actuator (the shuttle). This part moves in the direction shown in Fig. 3. The maximum actuation voltage of the MEMS is $12\ V$ and its current can reach $1\ A$. More details concerning the MEMS can be found in [10].

III. Accelerated lifetime tests

Accelerated lifetime test is an aging of a product that induces normal failures in a short amount of time by applying stress levels much higher than normal ones (stress, strain, temperatures, voltage, vibration rate, pressure, etc.). Reliability results can then be obtained by analyzing the product's response to such tests [9].

The difficulty in MEMS failure analysis arises when structures of interest are not readily exposed for direct observation [11]. In some MEMS, structures that provide the stimulus for motion or actuation are obscured from view.

In our case study, the electro-thermal actuator which allows to move the membrane is obscured from view. However, the movable membrane is accessible through the fluid ports. Thus, failures analysis of the targeted MEMS is based on the health state of the movable membrane (surface state, displacement, response time, etc.).

In order to perform accelerated lifetime tests for the MEMS valve, the two following experimental setup are specially designed.

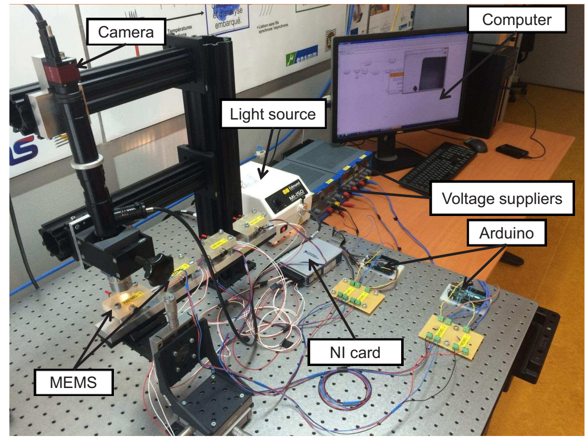


Fig. 4. Overview of the experimental platform.

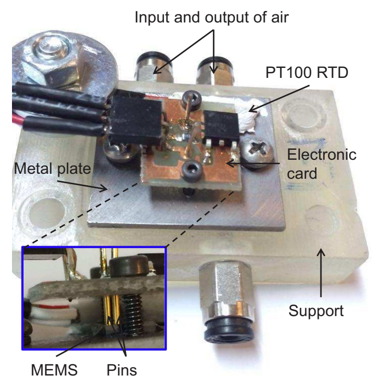


Fig. 5. Support designed to fix the MEMS vlave.

A. Experimental platform

The platform, presented in Fig. 4, is composed of two Arduino cards, two voltage suppliers, supports for the camera and the MEMS, a light source for the camera allowing to see the movement of the membrane inside the MEMS, an air supply, a pressure regulator, an air filter, a National Instrument card (NI 9216) and PT100 RTD for temperature measurement and a computer.

To fix the MEMS valve on the platform, the support presented in Fig. 5 is specially designed. It is composed of a plastic support made by the 3D printer, a metal plate to allow heat dissipation as the MEMS heats a lot, the input-output of air connected to the fluid connection ports and an electronic card for power supply. The MEMS is bonded on the metal plate under the electronic card by using silicone.

To minimize the mechanical noise, the experimental platform is placed on an anti-vibration table except the air filter.

The acquisition of measurements is the same for all MEMS and for each one of them the following steps are applied: 1) adjust the MEMS below the camera using a 3D positioner until having a very clear image, 2) get the time response by using a Matlab image-processing algorithm, 3) identify the parameters of the system by using the Matlab "system identification toolbox" which leads to the transfer function of

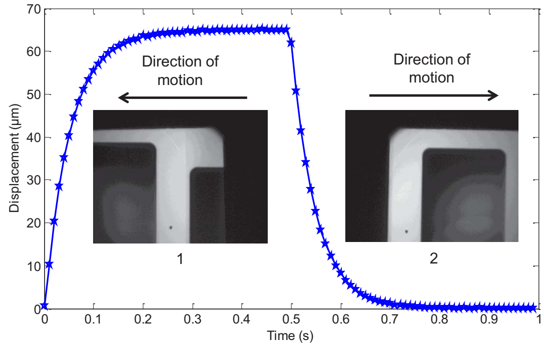


Fig. 6. Time response of the MEMS supplied with a square signal of 8 V magnitude and a frequency equal to 1 Hz. The two images of the membrane, 1 and 2, are taken by the camera through the normally closed port..

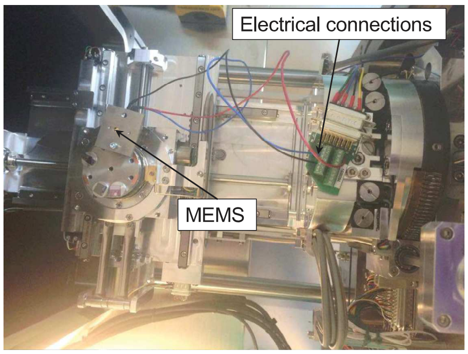


Fig. 7. Setup inside the SEM.

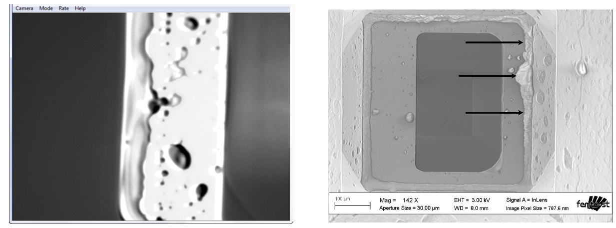
the obtained time response, and 4) store the results in different files in a dedicated computer for later use.

The image acquisition is done by using a Guppy Pro F-031 camera with a frame rate equal to 100 frames per second (fps). MEMS are supplied with a square signal of 8 V magnitude and a frequency equal to 1 Hz generated by a voltage supplier and an Arduino card. This voltage value is not too high to not bring up prematurely degradation and not too low to obtain enough displacement. The current consumption of a new MEMS at 8 V is about 0.55 A and the displacement of its membrane is about 65 μm. Fig. 6 shows an example of an obtained time response of one MEMS.

B. Setup in the SEM

This experiment consists in fixing a MEMS valve inside the SEM using the metal plate (Fig. 7). The valve still cycling continuously inside the SEM and it is supplied with the same signal as in the experimental platform. In this experiment, images for the membrane are taken two times per day. These images are used to monitor its health state during cycling and calculate its displacement.

Note that, tests can last long since the manufacturer of the MEMS valve guaranteed 8 million cycles without performance degradation. For that reason, only results of three tests are presented in this paper.



(a) (b)

Fig. 8. (a) Image taken by the camera showing the damaged membrane of the MEMS caused by the unfiltered air and (b) SEM image showing contamination at the normally closed fluid port.

IV. Results and Discussion

Three accelerated lifetime tests are performed in the two previous experimental setup. They consist in cycling MEMS valves and changing at each test the operating condition: A) using unfiltered air, B) without air and C) using filtered air.

Note that, the first and the third tests were performed with the same air pressure in the experimental platform, and the second test in the SEM. Results of the three tests are presented hereafter.

A. Using unfiltered air

This test consists in cycling four MEMS valves with an unfiltered air. Experiments remained running for more than one month. During this period, measurements were collected every day, after 25000 cycles, and at each measurement the displacement of the membrane is calculated.

At the beginning of experiments, the displacement of the membrane was about 65 μm with a good membrane surface state. After 1 million cycles, the displacement decreased to less than 10 μm with degraded membrane surface state (Fig. 8(a)). Therefore, the MEMS valve can be considered as out of service: a loss of performance leading to a very small displacement with damaged surface of the membrane. In fact, this is due to the penetration of unwanted materials coming from the unfiltered air, called contamination, which blocks the moving parts (the actuator and the membrane) and then causes its failure. The SEM image, presented in Fig. 8(b), shows contamination at the normally closed fluid port of a MEMS tested in this experiment.

B. Without air

In parallel to the previous experiment, a second test is performed and which consists in cycling one MEMS valve inside the SEM without air. In this experiment, the displacement of the membrane is calculated by using the SEM images. After 800000 cycles, the displacement decreased from 65 μm at the beginning of cycling to less than 50 μm. The SEM image taken after the end of cycling shows a good state of the membrane (Fig. 9). Therefore, this can be explained by a degradation at the actuator of the MEMS valve. Unfortunately, this degradation can not be analyzed since the actuator is obscured from view.

TABLE I
SUMMARY OF THE THREE PERFORMED ACCELERATED LIFETIME TESTS.

Test	Initial displacement	Performed cycles	Displacement at the end of the test	Membrane surface state
Using unfiltered air	65 μm	1 $million$	10 μm	$degraded$
Without air	65 μm	800000	50 μm	$good$
Using filtered air	65 μm	12 $million$	15 μm	$good$

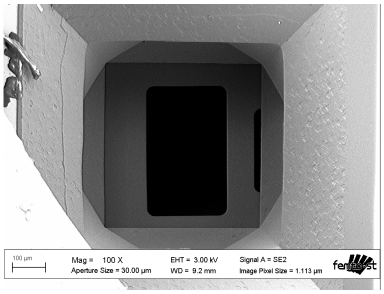


Fig. 9. SEM images of the membrane of the MEMS which cycled inside the SEM without air.

C. Using filtered air

The last experiment consists in cycling four MEMS valves using filtered air. Experiments remained running for more than three months and measurements were collected after approximately 90000 cycles.

All valves tested in this experiment performed 8 million cycles guaranteed by the manufacturer without a significant decrease of the displacement (less than 10% of displacement decrease for some MEMS) or membrane degradation. However, after 12 million cycles, the displacement average for the tested MEMS is about 15 μm (23% of the initial displacement). With a such displacement, the MEMS can be considered as out of service. According to the literature, for the electrothermal actuators, a failure is defined as the point at which the displacement decreases by 20% [12].

Despite the small displacement, membranes of all the tested MEMS still have a good surface state. This can be explained by a degradation at the actuator which is obscured from view.

A summary of the three performed accelerated lifetime tests is given in Table I.

V. CONCLUSION

Accelerated lifetime tests for MEMS valves electro-thermally actuated are presented in this paper. First, a brief description of the targeted MEMS is given. Then, the two experimental setup specially designed to perform accelerated lifetime tests are presented. The obtained results show that operating the MEMS with unfiltered air can cause the contamination at the actuator and the membrane, and then its early failure. Also, we noticed that MEMS operated with filtered air performed 8 million cycles without loss of performance. After that, displacement started decreasing to reach 15 μm at 12 million cycles with a good membrane surface state. This degradation can not be analyzed since the actuator is obscured from view. In a future work, the evolution in time of the different parameters related to the MEMS (temperature, current, stiffness, response time, etc.) which are collected during tests will be analyzed in order to identify and understand failures at the actuator.

The ongoing experiments consist in performing new tests for new MEMS valves by changing different parameters such as the supply voltage and the operating frequency.

This work is only a step towards the implementation of Prognostics and Health Management (PHM) approaches for MEMS devices. Results of all accelerated lifetime tests will be used to apply a PHM approach for the targeted MEMS in order to predict its health state and estimate its time to failure.

ACKNOWLEDGMENT

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