Design procedure against thermomechanical fatigue damage of RF–MEMS switch

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Abstract

The RF–MEMS switch undergoes a complex loading in service, including nonlinear electromechanical excitation, heating and alternate contact between electrodes. Thermomechanical coupling makes aggressive fatigue damage, and requires a suitable strategy to effectively predict the MEMS life. This paper assesses a suitable procedure to predict the microswitch behaviour, to define a suitable range of load and temperature, in operation, against the thermomechanical damages and provides a design criterion looking compatible with set-ups of some commercial products.

Structural mechatronics, RF-MEMS switch, thermomechanical fatigue, buckling, multi-physics

1. Introduction

The operation of RF-MEMS switch typically involves many damage conditions. As Fig.1 shows, a compliant bridge is attracted by the wafer electrode, through an electromechanical action, applied by electric field, to the pull-in, characterized by contact between electrodes [1]. Structure undergoes a severe bending, associated to a progressive heating, induced by the Joule effect, when it is swicthed on [2]. Actuation is periodic, at high frequency, therefore fatigue, thermal loading, wear and sometimes creep are simultaneously applied [3]. Buckling might occur, if compression induced upon bridge by temperature reaches the so-called critical load [4].

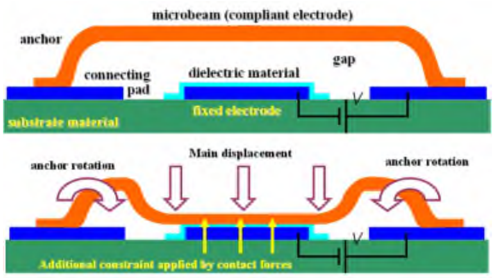

Figure 1. Typical behaviour of the RF-MEMS switch in operation.

Design is aimed at identifying some suitable operational ranges of load, temperature and frequency, for the RF-MEMS operation, by precisely predicting pull-in voltage, fatigue strength, creep damage and buckling conditions. Despite the wide literature about MEMS, a suitable reference to link those phenomena each other is still to be assessed.

2. System and duty cycle characterization

A microswitch configuration is first selected, as in Fig.1, or a cantilevered switch or a bridge with rigid plate suspended by slender arms [5]. System operation is defined. A variable voltage is applied between electrodes to generate an electromechanical action, which bends the flexible bridge, until that a contact between electrodes occurs. If contribution of air is negligible or vacuum is created, microswitch is fully characterized when stress distributed within its material is known, in each step of mission. This includes bending, contact and either heating or cooling effects.

To proceed with design, real dimensions of microswitch are measured, by a profiling system [6]. As a test case, a bridge with nominal length L=540 μm, width b=34 μm, thickness h=3 μm, made of gold material, having Young modulus E=98.5 GPa, Poisson's coefficient ν=0.42, density γ=19.32·10^{-15} kg/μm^3, and thermal expansion coefficient α=14.3·10^{-6} K^{-1}, was analysed.

Microswitch is usually actuated at high frequency, in operation, then a time period of inactivity follows. Its duty cycle can be predicted by a nonlinear coupled structural analysis, as the Finite Element Method (FEM) provides [3]. The bridge starts from an unloaded configuration, at environmental temperature, and is deflected by electric field towards the fixed electrode (Fig.2–1). Residual stress might be present, after the manufacturing process, and is, usually, a tensile effect. It affects the snap-down, occurring when pull-in voltage is reached, for given gap between electrodes and temperature (Fig.2–2).

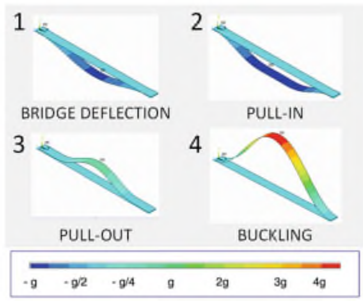

Figure 2. Typical states of the RF-MEMS in operation (from 1 to 4).

Contact activates the current flow through the switch, temperature grows up, until that microswitch remains closed. If required, voltage is inverted to pull it out (Fig.2–3). A suitable temperature is usually stabilized, by either cooling the system or controlling the power. A maximum temperature is defined by design, as 70°C, in test case. Temperature might cause a first buckling of structure, within the operational range. It helps the pull in and out, but requires to analyse the system behaviour in post buckling. At higher temperature, a secondary buckling must be avoided, since it induces an unrecoverable pull-out (Fig.2–4).

3. Thermomechanical buckling

Thermomechanical loading of structure is crucial for design and material damage, respectively. Nevertheless, it was poorly investigated in the literature [1,4,7]. Particularly, temperature of a first buckling should be predicted to analyse the post buckling behaviour, and secondary buckling must be prevented.

Power consumption, P, is defined, by design, as 8 W in test case, and kept constant in operation. This implies a suitable monitoring of bridge resistance, R, and voltage, V. Resistance depends on temperature, since resistivity, ρ, varies:

$$R = \frac{L}{S}\rho_0[1+\alpha(T-T_0)]; \qquad P = V^2/R \tag{1}$$

where pedix zero refers to unloaded condition, at room temperature, S is the contact area, T is the operational temperature. If range spans from 23°C through 70°C that change is fairly small. Resistance of the RF-MEMS is defined by design, as 50 Ω, in test case, and is partially related to flexible portion of bridge, being affected by the Joule effect. In absence of residual stress, temperature bringing to primary buckling is [3]:

$$T_{cr} = T_0 + \frac{1}{3\alpha}\left(\frac{\pi h}{L}\right)^2 \tag{2}$$

In test case it is 30°C. Microswitch is partially operated in pre buckling, then in post buckling. Relation between flexural displacement, u, and temperature in post buckling is [3]:

$$T(u) = T_0 + \Delta T + \frac{\pi^2 u^2}{4\alpha L^2} + \frac{\sigma_0}{E\alpha} \tag{3}$$

where σ_0 is the residual stress eventually present, and ΔT the increment of temperature to reach T_{cr}. Time to reach T_{cr}, assuming that temperature is only increased by the Joule effect, is found as:

$$t_{ref} = \frac{\gamma S^2 C}{\alpha \rho_0 L^2} ln[1+\alpha(T_{cr}-T_0)] \tag{4}$$

being C the specific heat coefficient of material per unit mass. This time is compared to the actuation time period, to find the corresponding number of cycles. In test case, for T_{cr}=30°C, t_{ref}= 70 μs. Buckling decreases the pull-in voltage from 34 V to 15 V.

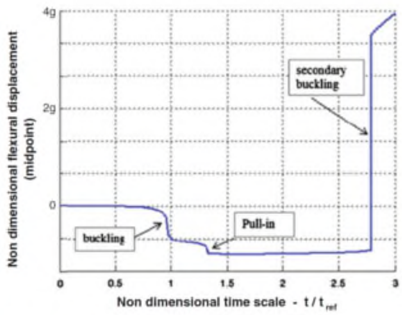

Figure 3. Typical period of mission profile for the RF-MEMS analysed.

4. Thermomechanical fatigue and life

Mission profile of microswitch is found, by previous analyses, as in Fig.3, where deflection of bridge in midpoint is compared to nominal gap, g, and represented for varying temperature as a function of dimensionless time. To avoid the secondary buckling, the microswitch should be either temporarily switched off, to allow heat dispersion, or directly cooled, to keep temperature constant. Stress distribution within the bridge structure, for each step of mission profile is then computed. This investigation is performed for some cross sections (clamp, quarter of line axis, middle) as in Fig.4. For each pull-in and pull-out, a mean temperature is assumed, and alternate and mean stresses are, respectively, calculated by the FEM model, considering the stress applied to lower and upper surfaces, in bending.

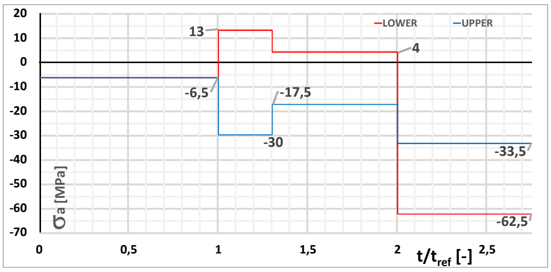

Figure 4. Example of periodic excitation for fatigue damage evaluation (at microswitch midpoint).

The microsystem life is then evaluated by applying the generalized Miner's approach, being extended to thermal fatigue, creep and oxidation [5]:

$$D_{tot} = D_{fatigue} + D_{creep} + D_{ox} = \sum_1^3 \sum_1^m \frac{n_i}{N_i} < 1 \tag{5}$$

where damage cumulated, D, is computed by comparing the actual number of mission cycles, n, and that required to failure, N, for all of m stress amplitudes previously detected (Fig.4). N is found, in high cycle fatigue, by correlating alternate stress to cycles to failure (S-N tests), for given mean stress and temperature. It is worth noticing that $D_{fatigue}$ is null, if, for each load amplitude, mean stress and temperature, the alternate stress is lower than material fatigue limit, as it happens in test case. D_{creep} is null if temperature for activating creep is never reached, as in test case. Therefore, life could be related to oxidation and wear, due to contact between electrodes and electric charge, and design parameters are evaluated as in microelectronics [7].

5. Conclusion

A procedure to design the RF-MEMS switch, leading to predict and distinguish material damage in operation, is defined. Reference temperatures for primary and secondary buckling, and creep are evaluated, to fix the operational range. System reliability, in test case, is reconducted to thermomechanical fatigue and wear, but fatigue contribution is nulled, if material fatigue limit in each thermomechanical excitation mode is larger. Once those conditions are assured, reliability is evalutated as in other microelectronic components, by testing. Future activity shall include a wide experimental validation of proposed approach, extended to other materials, as used in current applications.

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