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Applications in Engineering Science xxx (xxxx) xxx



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Experimental characterization of pull-in parameters for an electrostatically actuated cantilever

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ABSTRACT

Keywords: Pull-In instability MEMS Cantilever actuators Experimental validation

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MEMS-NEMS applications extensively use micro-nano cantilever structures as actuation system, thanks to their intrinsically simple end efficient configuration. Under the action of an electrostatic actuation voltage the cantilever deflects, until it reaches the maximum value of the electrostatic actuation voltage, namely the pull-in voltage. This limits its operating point and is a critical issue for the switching of the actuator. The present work aims to experimentally measure the variation of the pull-in voltage and the tip deflection for different geometrical parameters of an electrostatically actuated cantilever. First, by relying on a nonlinear differential model from the literature, we designed and built a macro-scale cantilever switch, which can be simply adapted to different configurations. Second, we experimentally investigated the effect of the free length of the suspended electrode, and of the gap from the ground, on the pull-in response. The experimental results always showed a close agreement with the analytical predictions, with a maximum relative error lower that 10% for the pull-in voltage, and a relative difference lower than 18% for the pull-in deflection.

1. Introduction 1

This work experimentally investigates the pull-in instability of an 2 3 electrostatically actuated cantilever beam, which reproduces the typical behavior of the micromechanical switching blocks in MEMS and NEMS 4 applications. The interesting properties of the MEMS devices typically 5 arise from the behavior of the active parts, which, in most cases, are 6 in the forms of cantilevers (Ke et al., 2005; Espinosa et al., 2006). Can-7 tilever beams represent a very efficient solution in the field of MEMS 8 applications (Ionescu, 2015; Zhang et al., 2014). The fundamental com-9 ponent of MEMS and NEMS cantilever devices is a suspended electrode 10 above a fixed conductive substrate and actuated by a voltage difference, 11 12 which exploits the switching of the flexible electrode between two stable positions (Loh and Espinosa, 2012; Chuang et al., 2010). A physical 13 schematic of the MEMS cantilever beam is show in Fig. 1a, where V_{out} 14 and V_{PI} represent the input voltage applied to the micro-beams and 15 16 the critical pull-in voltage of the system, respectively. Under the action 17 of the electrostatic forces, the flexible micro-cantilever beam deflects towards the substrate (Fig. 1b) thus increasing the electrostatic force 18 between the two electrodes. It comes that the flexible micro-cantilever 19 becomes unstable, and then, at a critical voltage, named the pull-in 20 voltage, the flexible electrode tip pulls-in onto the substrate (Fig. 1-21 22 c), thus creating an electrical connection (Knapp and De Boer, 2002; 23 Gorthi et al., 2006). This actuation scheme has been used in many micro-nano scale devices, such as manipulators, tweezers, accelerometers, pressure sensors, memory devices and energy harvesting systems (Spaggiari et al., 2016). The purpose of these components is to process very fast communications (Eric Garfunkel, 2009) in addition to a smarter and very smaller micro-nano devices (Noghrehabadi et al., 2013). The planar technologies represent the most common actuation mechanism used in micro-nano MEMS devices giving their tiny size, low mass and high resonance frequency as well as the electrostatic actuation (Passian and Thundat, 2011). Since the critical pull-in voltage defines the oper-³³Q2 ating voltage and power dissipation of the system, it must be accurately determined.

The first works on the nonlinear pull-in phenomenon are reported by 35 Taylor (1968) and Wickstrom and Davis (1967) dating in the late 1960s. 36 In the last years, Dequesnes et al. (2002) propose the use of parametrized 37 continuum model that aims to calculate the pull-in voltages in nanoelec-38 tromechanical switches. The work of Ramezani et al. (2008a) focused on 39 a general analytical method for the calculation of the pull-in instability 40 in nano-cantilevers under electrostatic actuation. In particular, the work 41 investigates a typical micro-nano actuator composed by a flexible beam 42 and of a fixed plate with a very small gap separation between the two 43 electrodes. The electromechanical behavior of the cantilever beams can 44 be described by fourth-order nonlinear ordinary differential equation 45 (ODE) and no exact solution can be obtained (Ramezani et al., 2008a). 46 In this case, the modeling of the nonlinear response of the device must 47

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A. Sorrentino, G. Bianchi and D. Castagnetti et al.





Fig. 1. The MEMS cantilever beam under different electrostatic voltage: no applied voltage (a), applied voltage lower than the critical pull-in limit (b), applied voltage at the pull-in (c).

take into account the dispersion forces of van deer Waals (vdW) and 48 Casimir (Ramezani et al., 2006; Soroush et al., 2010). Both the inter-49 molecular forces and the electrostatic actuation, influence the critical 50 pull-in effects in MEMS-NEMS devices. Several numerical procedures 51 and analytical methods can be traced in literature in order to estimate 52 53 the pull-in parameters. The first approximated analytical approaches are the 1D based lumped model (Chowdhury et al., 2005), linearization 54 methods (Noghrehabadi et al., 2012; Duan et al., 2013) or on Taylor 55 series expansion of the loading term (Ghalambaz et al., 2011). In ad-56 57 dition, numerical or approximate techniques to generate reduced-order 58 models are used; the most popular methods are the differential quadrature method, Adomian decomposition method, Galerkin method and fi-59 nite element method (Di Maida and Bianchi, 2016). On the other side, 60 these approximated methods may provide large errors as the cantilever 61 62 tip deflection increase closer to the pull-in stable position. Furthermore,

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Applications in Engineering Science xxx (xxxx) xxx

these approaches give non-specified estimates of the pull-in stability pa-63 rameters. By contrast, more accurate methods may provide the lower 64 and upper bounds of the pull-in parameter, in order to ensure safely 65 operating condition in the device. In particular, Radi et al. (2017), pro-66 pose an accurate analytical approach for estimating the lower and upper 67 bounds to the critical pull-in characteristics for microcantilever actua-68 tors. The proposed model aims to predict the critical factors, geometri-69 cal and electromechanical, of electrostatically microcantilever actuators 70 that lead the transition between two stable positions. In a second work, 71 Radi et al. (2018) consider the effect of the compressive axial load on 72 the pull-in voltage, to obtain an accurate estimate of the stable actuating 73 range. A variety of recent works on the pull-in analysis and modeling 74 are reported in literature (Fakhrabadi et al., 2013; Krylov, 2007; De and 75 Aluru, 2004; Nayfeh et al., 2005; Chaterjee and Pohit, 2009; Zhao et al., 76 2004; Bochobza-Degani and Nemirovsky, 2004; Luo and Wang, 2002). 77 In summary, a review describing the pull-in instability phenomenon, 78 modeling and analysis for MEMS-NEMS devices is represented by the 79 review report of Zhang et al. (2014). Generally, every electromechani-80 cal device can be affected by pull-in instability (Somà, 2007): some de-81 vices rely on the pull-in instability for the switching operation such as 82 sensor and actuators, while in other devices such as micro-mirrors and 83 radio frequency oscillators the pull-in instability is an undesired effect 84 (Van Beek and Puers, 2012; Juillard, 2015). This supports the need for 85 a simple and accurate model to predict the critical pull-in voltage. One 86 of the main practical limitation comes from the pull-in voltage value: on 87 the one hand, low pull-in voltage reduces the power consumption but 88 increases the uncontrolled switching deflection thus causing failure. On 89 the other hand, high pull-in voltage allows to avoid undesired failure 90 but increase the power consumption, thus enhancing the device perfor-91 mance. The pull-in instability effects and the mechanical response of 92 these actuators are defined by three main issues. First, the choice of the 93 material of the MEMS-NEMS devices and the modeling of the boundary 94 support for the elastic structures (Noghrehabadi et al., 2013; Rinaldi 95 et al., 2005), both for the static and dynamic/vibrational electrostatic 96 simulation of the deflected beam. Second, the presence of dispersion 97 of the intermolecular surface forces. The interaction forces of van deer 98 Waals and Casimir depending on the gap separation between the two 99 electrodes. As the gap decrease, namely below 20 nm for metals, the 100 intermolecular forces becomes dominant, affecting the deflection and 101 the stress-strain behavior of the nano-cantilever (Soroush et al., 2010; 102 Ghalambaz et al., 2011). Third, the size dependency, also called size 103 effect, that influences the mechanical properties of thecantilever when 104 the size scale decrease rapidly (Stölken and Evans, 1998; Nix and Gao, 105 1998). With regard to the experimental characterization of the pull-106 in instability in MEMS devices, a number of proposal can be found in 107 literature in order to evaluate the nonlinear static behavior of micro-108 electrostatic actuators (Somà et al., 2019; Ballestra et al., 2008). First 109 experimental validation and analysis on the pull-in instability have been 110 performed by Taylor (1968), Wickstrom and Davis (1967) and Siddique 111 et al. (2011). Poelma et al. (2011) evaluates the pull-in phenomenon for 112 electrostatically paddle cantilever from 3D imaging reconstruction. Al-113 ternatively, Somà focused on detecting the mechanical fatigue limits in 114 response to the pull-in voltage actuation in gold micro-beams specimens 115 (Somà and De Pasquale, 2009; Soma et al., 2017), and experimentally 116 validated the residual stress in electrostatically actuated radio frequency 117 micromechanical systems (RF-MEMS), (De Pasquale and Soma, 2007; 118 Somà and Saleem, 2015). The understanding and control of the pull-in 119 instability represents, even now, a great technological challenge (Zhang 120 et al., 2014). As a consequence of the high cost in the implementation of 121 miniaturized specimens, combined with the need of specific instrumen-122 tation, is not simple to examine the robustness of the theoretical predic-123 tions for different type of actuator configurations. However, analytical 124 approaches consider negligible Casemir and vdW surface forces, when 125 the dimension of the cantilever beams shift to the micro scale, and con-126 sequently, in the millimeter scale. This work focuses on the experimental 127 characterization of the critical pull-in voltage and the tip deflection of a 128

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Applications in Engineering Science xxx (xxxx) xxx



Fig. 2. The elastic micro-nano cantilever scheme subject to electrostatic actuation.

macro-scale size cantilever beam, with the aim to validate a theoretical 129 micro-mechanical model proposed by Radi et al. (2017, 2018). Specifi-130 cally, we designed and built a simple millimeter-scale cantilever, which 131 was actuated through an ad-hoc electric circuit able to reproduce the 132 same pull-in phenomenon observed in the micrometric scale. The tests 133 investigated different cantilever configurations to examine the effect of 134 135 the free length of the suspended electrode and the gap from the ground on the pull-in response. The proposed device is simply adaptable, low 136 cost, and simple to manufacture. The experimental results exhibit a very 137 good agreement with the analytical predictions (Radi et al., 2017, 2018). 138 139 In particular, we obtained a relative difference between the experimental and analytical values of the pull-in voltage in the range between from 140 0.7% up to 10%, whereas the relative difference of the pull-in deflection 141 falls in the range from 1.1% up to 18%. 142

143 2. Material and methods

Fig. 2 shows the configuration of the system examined in this work, 144 145 which corresponds to the cantilever geometry and actuation scheme described in the works of Radi et al.> (2017, 2018). Two plates compose 146 the system: the flexible electrode (1), on top, and the ground (2), sub-147 148 ject to an electrostatic actuation (3), and separated by a dielectric layer (4). In order to evaluate the variation of the pull-in factor voltage with 149 respect to the geometrical dimensions of the device, we examined differ-150 ent cantilever configurations. In particular, we tested different lengths 151 of the beam in combination with different gaps of the dielectric layer. 152

153 2.1. The macro-scale model

Fig. 2 shows the generic elastic micro/nano cantilever of length, I, 154 155 width, w and thickness, t, clamped at one end, with z = [0, l], and subject to electrostatic actuation and intermolecular surface forces (Radi 156 157 et al., 2017, 2018). In particular, we considered the non-dimensional deflection, u = v/d, and the axial coordinate, x = z/l, where v is the 158 deflection, and d is the initial gap between the two electrodes, respec-159 tively. The system can be described mathematically by the following 160 161 fourth-order nonlinear ordinary differential equation (ODE):

$$u^{IV}(x) = \frac{\gamma\beta}{1-u(x)} + \frac{\beta}{[1-u(x)]^2} + \frac{\alpha_W}{[1-u(x)]^3} + \frac{\alpha_C}{[1-u(x)]^4}$$
(1.1)

162

$$u(0) = u'(0) = 0, \ u''(1) = u'''(1) = 0$$
(1.2)

163 Where $\gamma = 0.65 \text{ d/}w$ is the fringing coefficient. Moreover, the non-164 dimensional positive parameters β , α_W and α_C are proportional to the 165 electrostatic, van der Waals and Casimir forces, respectively, namely:

$$\beta = \frac{\varepsilon_0 w V^2 l^4}{2d^3 E I}$$

$$\alpha_W = \frac{Awl^4}{6\pi d^4 E I}$$

$$\alpha_C = \frac{\pi^2 h c wl^4}{240 d^5 E I}$$
(1.3)

Where $\varepsilon_0 = 8.854 * 10^{-12} \text{ C}^2 \text{N}^{-1} \text{m}^{-2}$ is the permittivity of vacuum, h =166 $1.055*10^{-34}$ Js is the Plank's constant divided by 2π , $c = 2.998*10^8$ m/s 167 is the speed of light, A is the Hamaker constant, V is the electric volt-168 age applied to the electrodes, E is the Young's modulus of the beam 169 material and I is the moment of inertia of the beam cross-section. As 170 show in Eq. (1.3), the parameters β , α_W and α_C affected considerably 171 the values of the pull-in instability factors and then the operation point 172 of the device. In particular, when the dimensions of the cantilever beams 173 increase, the values of the intermolecular force parameters α_W and α_C 174 decrease, consequently, if the dimensions of the actuator shift to the 175 millimeter-scale the effect of the van der Waals and Casimir forces be-176 comes negligible (α_W and α_C values fall in the range of $10^{-25} \div 10^{-28}$). 177 In this operating condition, named the "macro-scale condition", only 178 the electrostatic force determines the pull-in instability threshold of the 179 beam. In addition, for an elastic material with a specific Young's mod-180 ulus, *E*, the value of the parameter β allows to predict the value of the 181 pull-in voltage with fixed geometrical parameters, w, t and l. By chang-182 ing the geometric ratio, γ , the value of β changes and consequently the 183 pull-in actuation voltage, see Eq. (1.1). In particular, the pull-in voltage 184 for the macro-scale actuated cantilever beam, which depend on β , can 185 be expressed by the following formula: 186

$$V_{PI} = \sqrt{\beta \frac{2d^3 EI}{\varepsilon_0 w l^4}} \tag{1.4}$$

Where, $I = \frac{w^3}{12}$, is the moment of inertia for a rectangular crosssection area.

The macro-scale cantilever beam is able to reproduce the same 189 electro-mechanical behavior observed in the micrometric scale (Radi 190 et al., 2017, 2018). In the present investigation, we focused on the 191 macro-scale model, where the intermolecular forces are negligible. 192 While keeping constant the ratio between the geometrical dimensions 193 of the system, it is possible to obtain a macro-scale model of the can-194 tilever by increasing the dimensions of the micro-system (Rollier et al., 195 2006). The corresponding critical pull-in deflection for the macro-scale 196 model (Radi et al., 2017, 2018), named v_{PI} , fall in the range 44% ÷ 55% 197 for a high fringing coefficient, specifically for $\gamma = 0 \div 3.25$, which corre-198 sponds to an air gap, d, five times greater than the width of the flexi-199 ble beam, w (Soroush et al., 2010; Ramezani et al., 2008b). To simplify 200 the experimental approach, the authors suggest these following approxi-201 mated equations to compute the pull-in parameter considering the fring-202 ing field effect, β_{PI} for the pull-in voltage, and u_{PI} for the normalized 203

<u>ARTICLE IN PRESS</u>

A. Sorrentino, G. Bianchi and D. Castagnetti et al.

204 pull-in deflection:

$$\beta_{PI} = \frac{1.67}{1+0.41\gamma}$$

$$u_{PI} = 0.6395 - \frac{2084}{10862+3069\gamma}$$
(1.5)

Using the analytical procedure described in Radi et al. (2017, 2018), 205 lower and upper bounds are obtained for the pull-in parameters. Then, 206 207 these estimates are used to fit the coefficients of the approximated relations (Eq. (1.5)) using the interpolation method available in Mathe-208 matica (Wolfram Research Inc 2020). The approximated curves fit very 209 well with the lower and upper estimates of the pull-in voltage (Fig. 3a) 210 and deflection (Fig. 3b) respectively, thus ensuring the accuracy of the 211 212 approximated Eq. (1.5). Moreover, the approximated Eq. (1.5) for the voltage β_{PI} perfectly agrees with the approximated model introduced 213 214 by Osterberg and Senturia (1997) and Ballestra et al. (2008).

215 2.2. Prototype development

First, the work focused on the design and prototype development of 216 an adaptable millimeter-scale model of the MEMS device. The system 217 is composed by two different parts: the mechanical one, formed by the 218 switching system, the actuated cantilever, and the electrical part consist-219 ing of an electric circuit that regulates the input actuation on the device. 220 In particular, the implemented device includes different pins output for 221 222 the connection to the signal acquisition and monitoring system that reg-223 isters the electrostatically response of the system.

224 2.3. Actuated cantilever

The dimensions of the macro-scale model, and the related pull-in factors of the system, are affected by the geometric aspect ratios of the electrodes and by the value of the gap. From the work of Rollier et al. (2006), it is possible determine the cantilever's parameters relating to a system described by the Euler's theory, where, the geometric aspect ratios of the plates are represented by:

$$R_{1} = \frac{w}{l}$$

$$R_{2} = \frac{d}{l}$$

$$R_{3} = \frac{t}{l}$$

$$R_{4} = \frac{t}{w}$$
(2.1)

As show in the work of Somà (Ballestra et al., 2008), by keeping 231 constant the ratio R_4 , the value of the pull-in voltage and deflection is 232 233 affected by the values of the total free length of the flexible electrode, 234 l, and from the gap, d. The increase in the scale, corresponds an increase of the voltage actuation for the cantilever beam. For this reason, 235 a preliminary analysis of pull-in voltage and deflection was conducted 236 with the aim to identify possible cantilever lengths, *l*, and predict the 237 maximum pull-in voltage for different beam configurations (see Section 238 "Test plan"). Hence, the maximum admissible pull-in voltage was set, 239 for the macro-scale model, at 3000 V, for a gap, d, in the range be-240 tween 0.5 and 1 mm. Fig. 4 shows the case of planar plates with constant 241 R_4 . The switching system is composed of two plates with a rectangu-242 243 lar cross-sectional area, the suspended and flexible electrode, and the fixed ground, both made of steel C100S with nominal Young's modulus, 244 245 E = 210,000 MPa, and a Poisson's ratio, v, equal to 0.3. The electrodes 246 of the system are simply obtained from a commercial steel tape, with the aim to have planar and lightweight beams. The plates of the system have 247 248 a thickness, t = 0.2 mm, and a width, w = 12.7 mm, which correspond to an $R_4 = 0.0157$. The free length, *l*, of the suspended electrode was 249 set initially equal to 50 mm, while the gap between the two electrodes 250 was set equal to 0.6 mm and obtained through a simple bi-adhesive tape 251 252 (Fig. 4), which makes easier the assembly of the flexible electrode on the

Applications in Engineering Science xxx (xxxx) xxx



Fig. 3. The normalized pull-in voltage, β_{PI} , with respect to the variation of the fringing coefficient, γ (a), the normalized deflection u_{PI} with respect to γ (b). The continues curves represents the approximated solution, and the black dot and the empty circle the analytic estimate for the upper and lower bounds, respectively.

dielectric support. The flexible electrode was placed on the bi-adhesive 253 tape by pliers and then, the gap height *d*, was measured by an altimeter. 254 From the analytical model of Radi et al. (2017, 2018), it is possible to 255 calculate the pull-in parameter β of the system (see Eqs. (1.1) and (1.5)) 256 for fixed *w*, *t*, *l* and *d* and the corresponding analytical pull-in voltage, V_{PI} (see Eq. (1.4)). 258

2.4. Power circuit

Due to the macro scale, the device requires a high actuation volt- 260 age to reach the pull-in. For this reason, we used a high voltage DC-DC 261

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Applications in Engineering Science xxx (xxxx) xxx

A. Sorrentino, G. Bianchi and D. Castagnetti et al

Fig. 4. Millimeter scale device implemented.





Fig. 5. The operating circuit of the converter.

converter (*EMCO CB101*) powered at 12 V through a power supply and giving an output voltage, V_{out} , in a range between 0 and ±10 kV. Fig. 5 shows the operating circuit of the device.

Specifically, we have the high voltage DC-DC converter, and a simple circuit that allows to regulate the output voltage, V_{out} , which is the actuation voltage for the flexible cantilever. The regulation circuit consists of a voltage divider with electric resistances, R_a and R_b . Based on the schematic in Fig. 5, the output voltage of the device, V_{out} , is related to the value of the resistances R_a and R_b (Fig. 5) through the following equation:

$$V_{out} = \frac{R_a}{R_a + R_b} * (10,000)$$
(2.2)

By keeping a high value for R_b , about 10 k Ω , the corresponding V_{out} 272 of the converter is provided by the value of R_a . By replacing the two 273 resistors R_a and R_b with a manual multi-turn potentiometer, we can 274 275 regulate the output voltage from the DC-DC converter, from 0 up to the pull-in threshold, V_{PI} , thus, the corresponding output voltage, V_{out} , 276 277 can be computed by Eq. (2.2). The critical value of the output voltage corresponds to the pull-in voltage, V_{PI} , as mentioned in Section 1. The 278 high voltage output pin of the converter is finally connected on the top 279 280 surface of the suspended electrode where the macro-beam is bonded. Fig. 6 shows the implemented electric circuit solution that includes all 281 the electrical components of the power circuit, that are the DC-DC con-282 verter and the potentiometer. It is remarkable that the value of the cur-283 rent trough the circuit is maintained very low, about 200 mA, far below 284 285 the possible critical value for failure. When pull-in occurs, the high volt-286 age converter turns off, avoiding high electric charge on the circuit.

287 2.5. Experimental set-up

The experimental validation aims to measure the critical pull-in voltage and deflection of the cantilever beam. Fig. 7 shows the schematic of the test bench for the experimental validation.

In order to measure the tip deflection of the suspended electrode, 291 we used a single point laser-doppler vibrometer (Polytec OFV-505 sen-292 sor head) with a tolerance on the position of 0.002 mm. The vibrom-293 eter points to the tip of the flexible electrode, in the vertical direction 294 with respect to the initial top surface of the flexible electrode (Immovilli 295 et al., 2013, 2011), Fig. 7. The vibrometer is managed by a National In-296 strument data acquisition board (NI 9211). The acquisition board also 297 measure the pull-in voltage connected to the device. Before applying 298 the actuation voltage to the device, we ensured that the beams were 299 discharged, in order to avoid early pull-in phenomenon due to residual 300 electrical charge in the electrodes. When the power circuit is on, the flex-301 ible micro-cantilever beam deflects towards to the substrate under the 302 action of the electrostatic forces provided by the high voltage converter, 303 and the vibrometer simultaneously and continuously recorded the cor-304 responding tip deflection, until the system reached the pull-in. The slow 305 regulation of the input voltage thanks to the potentiometer, prevented 306 voltage fluctuation during the actuation of the system and thus made 307 possible to acquire the effective pull-in voltage of the beam. The acquisi-308 tion board was connected to a pc that registered and processed the data 309 using an algorithm implemented in the LabVIEW environment (Bitter 310 et al., 2020). 311

2.6. Test plan

312

324

In order to assess the accuracy of the prototype, we tested some dif-313 ferent configurations of the cantilever to examine the influence of some 314 parameters on the pull-in. For this investigations we considered constant 315 nominal width, w = 12.7 mm, as reported in the work of Ballestra et al. 316 (2008), and nominal thickness, t = 0.2 mm, for all the specimens tested 317 (see Section "Actuated cantilever"). Specifically, we investigated three 318 levels of free length. *l*, in combination with two different gaps from the 319 ground, d. Table 1 reports the six cantilever configurations investigated 320 experimentally. For all the six configurations in Table 1, we performed 321 ten replications of the pull-in tests, for a total of 60 tests. Each of the six 322 configurations tested was manufactured as a completely new specimen. 323

3. Results

Table 2 compares the critical pull-in parameters for the six config-325urations investigated (see Table 1) where, V_{PI}^E and V_{PI}^A , represent the326experimental and the analytical pull-in voltages, respectively, and v_{PI}^E the corresponding pull-in deflections, using the analytical model327and v_{PI}^A the corresponding pull-in deflections, using the analytical model328provided by Radi et al. (2017, 2018).

In particular, for the experimental pull-in voltage and deflection, we 330 reported the mean value and the corresponding standard deviation for 331 the 10 replications performed. Figs. 8 and 9 show, respectively, the relation between the experimental pull-in voltage, V_{PI}^E , and the deflection, 332 v_{PI}^E , with respect to the variation of the gap, *d*, and of the total free 334 length, *l*.

A. Sorrentino, G. Bianchi and D. Castagnetti et al.

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Applications in Engineering Science xxx (xxxx) xxx

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Table 1

Nominal dimensions and related aspect ratios for the different specimens tested.

Specimen	<i>l</i> [mm]	<i>w</i> [mm]	<i>t</i> [mm]	<i>d</i> [mm]	R_1	<i>R</i> ₂	<i>R</i> ₃	R_4
1	50.00±0.02	12.7	0.2	0.60 ± 0.02	0.254	0.012	0.004	0.016
2	60.00±0.02	12.7	0.2	0.60 ± 0.02	0.212	0.01	0.003	0.016
3	70.00 ± 0.02	12.7	0.2	0.60 ± 0.02	0.181	0.009	0.003	0.016
4	50.00 ± 0.02	12.7	0.2	0.80 ± 0.02	0.254	0.016	0.004	0.016
5	60.00±0.02	12.7	0.2	0.80 ± 0.02	0.212	0.013	0.003	0.016
6	70.00 ± 0.02	12.7	0.2	0.80 ± 0.02	0.181	0.011	0.003	0.016

The critical pull-in values obtained experimentally and analytically are compared to the value of the critical pull-in factors obtained numerically by the shooting method (Osborne, 1969) implemented in the Mathematica software Mathematica (Wolfram Research Inc 2020). The diagrams in Figs. 10 and 11 relate the pull-in voltage, *y* axis of the graph, and the pull-in deflection, *x* axis of the graph, for the two different gaps considered.

343 4. Discussion

As shown in Figs. 8 and 9 it appears that both the variable free length, 1, and the value of the gap, *d*, of the device affected the amount of the pull-in voltage significantly: on the one hand, the higher the length of 346 the flexible electrode, *l*, the higher the value of the pull-in voltage. On 347 the other hand, by decreasing the value of the gap, *d*, the pull-in voltage 348 decreases according to the analytical prediction model (Radi et al., 2017, 349 2018). The experimental results in Table 2 exhibit a very good agree-350 ment with the analytical predictions from the model proposed by Radi 351 et al. (2017, 2018). In particular, the relative difference between the 352 experimental measurements and analytical values of the pull-in voltage 353 falls in the range between 0.7% and 10%, whereas the relative differ-354 ence for the pull-in deflection falls in the range from 1.1% up to 18% 355 (Table 2). In addition, Figs. 10 and 11 highlight that the pull-in critical 356 values provided by the shooting method (Osborne, 1969) closely match 357

Fig. 6. The electric board and the converter circuit implemented.

Fig. 7. Schematic of the testing benchmark.

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Applications in Engineering Science xxx (xxxx) xxx

A. Sorrentino, G. Bianchi and D. Castagnetti et al.

Table 2

Comparison between the experimental and analytical pull-in voltage and tip deflection.

Specimen	V_{PI}^E [V]	V^A_{PI} [V]	v_{PI}^E [mm]	v_{PI}^A [mm]
1	1261 ± 19	1337	0.262 ± 0.024	0.268
2	<mark>891 ±</mark> 42	929	0.263 ± 0.018	0.268
3	682 ± 25	682	0.273 ± 0.018	0.268
4	2047 ± 28	2052	0.298 ± 0.050	0.357
5	1423 ± 16	1425	0.359 ± 0.028	0.357
6	942 ± 93	1047	0. <mark>391 ±</mark> 0.016	0.357



Fig. 8. The experimental pull-in voltage variation for the different cases evaluated.



Fig. 9. The experimental pull-in deflections measured.



Fig. 10. The pull-in voltage, V_{PI} , with respect to the deflection,v, for different free lengths, l, and for a fixed gap, g, equal to 0.6 mm. The solid lines represent the numerical solution, the black dots the experimental estimates, and the white circles the analytical estimates, respectively.



Fig. 11. The pull-in voltage, V_{PI} , with respect to the variation of the deflection, v, for different free length, l, and for fixed gap, g, equal to 0.8 mm. The solid lines represent the numerical solution, the black dots the experimental estimates, and the white circles the analytical estimates, respectively.

the experimental measurements. From Table 2, we can observe a sig-358 nificant scatter in the values of the pull-in voltage and deflection, that 359 can be imputed to the following geometrical issues. First, the combined 360 effect of the inaccuracies in the air gap, *d*, and in the free length, *l*, of 361 the experimental device: for instance, according to the analytical model 362 (Eq. (1.4) and 1.5), a 0.01 mm variation in the gap, d, combined with a 363 0.1 mm variation of the free length, l, give a scatter of the pull-in voltage 364 from about 20 up to 47 V. Second, small inaccuracies in the positioning 365 of the mobile plate on the bi-adhesive gap gives not perfect alignment 366 on the clamped cantilever thus affecting the planarity between the two 367 electrodes. Third, the higher the free length, *l*, the higher the effect of 368 the weight of the flexible plate, see Table 2. Nevertheless, the proposed 369 analytical model by Radi et al. (2017, 2018), gives an accurate predic-370 tion of the experimental behavior of the system, also compared to pre-371 vious works in the literature (Ballestra et al., 2008) and Rollier et al., 372 2006). The proposed macro-scale model is a low-cost solution with the 373 only limitation of a high actuation voltage to reach the pull-in threshold 374 (Table 2). With regard to prototype manufacturing, the proposed solu-375 tion has the following advantages. First, the macro scale prototype is 376 more simple and quick to set-up, compared to a micro-nano scale so-377 lution. Second, by changing the cantilever configuration, it is possible 378 to test different macro-scale models, thanks to the fact that the elec-379 tric board of the prototype is external and isolated form the switching 380 part. Third, the macro-scale prototype implemented allows to recreate 381 the same switching phenomenon observed in the nano scale, with ex-382 ception of the Caseimir and vdW surface forces. In addition, considering 383 the fringing effect in the analytical model also for the macro-scale solu-384 tion (Eqs. (1.4) and (1.5)), the experimental results show a remarkable 385 improvement compared to the models in the literature, see Figs. 10 and 386 11. 387

5. Conclusions

The present work assesses a previous analytical model from the literature via experimental tests with the use of a simple millimeter-scale device, which was actuated through an ad-hoc electric circuit. The work aimed to measure the critical pull-in voltage and the deflection of an actuated cantilever beam for different configurations in order to validate the variation of the pull-in voltage with the geometrical parameters 394

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Applications in Engineering Science xxx (xxxx) xxx

A. Sorrentino, G. Bianchi and D. Castagnetti et al.

of the device provided by theoretical investigations. Analytical predic-395 tions closely match the experimental estimates, where the maximum 396 relative difference between experimental and analytical values of the 397 398 pull-in voltage is in the order of 10%, whereas the relative difference of 399 the pull-in deflection falls below 18%. The adaptable prototype devel-400 oped allowed to evaluate different cantilever configurations, then, the influence of the geometrical and electromechanical parameters for the 401 system on the pull-in instability. The proposed macro-scale prototype is 402 a very quick and smart solution from a manufacturing standpoint. 403

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- **Uncited reference** 407
- (Cheng et al., 2004). 408

Declaration of Competing Interest 409

All authors agree on the submission of the paper in the present form. 410

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