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1-D EQUIVALENT CIRCUIT FOR RF MEMS CAPACITIVE SWITCH

In this paper the equivalent circuit for an accurate model of the RF (Radio Frequency) MEMS (Micro Electro-Mechanical Systems) capacitive switch is presented. The capacitive switch consists of a thin metal membrane, which name is bridge suspended over central conductor and connected at both ends to the ground conductor of CPW (coplanar waveguide). The equivalent circuit was created based on multi-physic modelling, elements analogues, and electrical equivalences. Mechanical and electrical forces are included in the equivalent circuit as current sources. The usefulness and effectiveness of the model was verified through results comparison with the commercial APLAC software and mathematical modelling in Matlab software. The novelty of the paper is the equivalent circuit, which is useful to simulate linear and non-linear cases of the RF MEMS capacitive switch and also the novelty is an implementation of the equivalent circuit in LTSpice, which is a freeware circuits simulator.

KEYWORDS: RF MEMS switch, equivalent circuits for MEMS, multiphysics modeling

1. INTRODUCTION

The interest of MEMS technology and RF MEMS capacitive switches, which are made in this technology is increasing rapidly. The MEMS devices are replacing elements such as PIN diodes or switching field effect transistors (FET). Application of MEMS devices is mainly in mobile phones, smart-phones, defence systems, radar systems, aerospace, RF wireless systems, wireless sensors. For such wide area of application, it is an essential issue to have effective, accurate, robust and at the same time simple methods to design and simulate capacitive RF MEMS switches.

One of the method of the RF MEMS design are multi-physics simulation methods, based on electrical equivalent circuits. In this paper such approach is presented, it is also presented the usage of the LTSpice circuits simulator to simulate and modelling of RF MEMS device. The electrical equivalent circuit in the circuits simulator LTSpice was created, based on algebraical, mathematical models but also on elements analogues and electrical equivalences. Non-linear, behavioural current sources, which are defined in LTSpice were used [1]. These sources represent phenomena of mechanical and electrical energy exchange, which indeed takes place inside of the real RF MEMS capacitive switch.

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2. ELEMENTS ANALOGUES

Using of elements analogues is the method, which is very often used in many areas of engineering domain. Similar practice is present in methods, used to analyse MEMS devices, where mainly similarities between the electrical phenomena and the mechanical phenomena or between the electrical phenomena and the thermal phenomena are used. In this article electro-mechanical analogues were used. The final electrical equivalent circuit, which was created, was inspired by analogues presented in commercial software APLAC [2].

The essential analogy is to present forces as electrical currents. For this purpose arbitrary behavioural current sources are used. In these sources current, "force" is variable, which is changing under influence of proper variable voltages. In the considered model, there are few forces presented with the use of behavioural current sources. These forces are: spring force, which value is equal to multiplication of spring constant and displacement (where the displacement is represented and proportional to proper voltage Uz); electrostatic force, which is dependent from geometrical parameters and material parameters like in typical capacitor, electrostatic force also depends from two voltages, one is the voltage applied between air gap of two plates and the second voltage is the voltage, that represents displacement; resultant force, which directly depends from voltage Uv, which is representing velocity. Damping force is also presented as electrical current but in our approach not as current from current source but as current flowing through resistor. This resistor is acting as a conductance with the value equal to damping coefficient. To present mass, analogy to capacitance of capacitor was used. Mechanical element with the mass M was presented as capacitor with the value of the capacitance equal to M. On Fig. 1 are presented elements analogues used in the article.
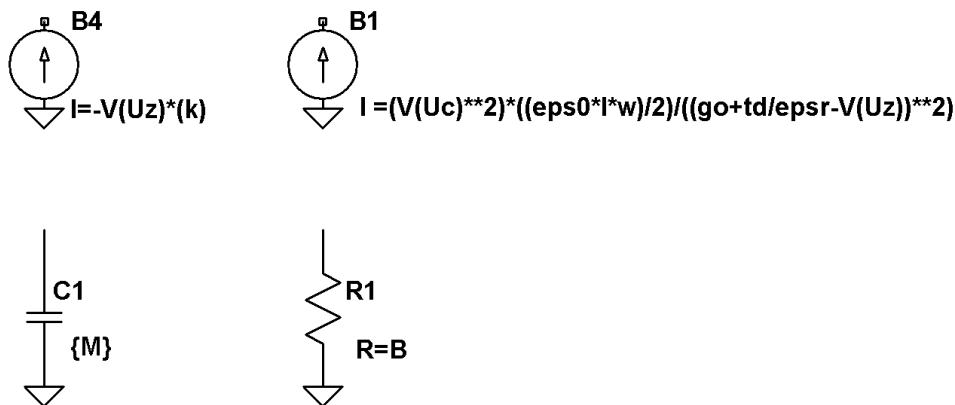

Fig. 1. Elements analogues used in equivalent circuit, elements in LTSpice

3. MULTI-PHYSICS PHENOMENONS IN MEMS RF SWITCH

Presented in the previous chapter, elements analogues allow mapping of the multi-physic phenomenons, which are occurring in the capacitive RF MEMS switch. In our approach was used simplified mechanical model of the capacitive RF MEMS switch, which is presented on Fig. 2. This model contains mass-spring system with mass M of the bridge, spring with damping coefficient B, spring constant K (spring constant is dependent from bridge geometry and material properties) and transducer, which exchanges mechanical and electrical energy, inside capacitive air gap, between two rectangular plates. When we apply voltage U_c to the transducer plates the electrostatic force Fe will appear and will move the plate. This force is described by following formula [3]:

$$F_e = \frac{U_c^2}{2}\left(\frac{w\varepsilon_0}{(g_0 + t_d/\varepsilon_r - z)^2}\right) \tag{1}$$

where l-length, w-width, t_d-thickness of the bridge, g_0-gap between the bridge and pull-down electrode in state position, z-displacement from the up-state position.
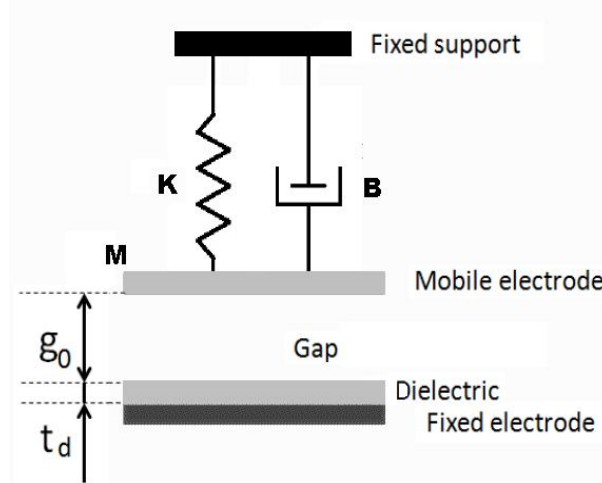

Fig. 2. Simplified mechanical model of the capacitive RF MEMS switch

When the applied voltage will be reset, so force Fe will vanish. Due to the resilient force of the spring, plate will return to the position before displacement. This plate movement in dynamic state is described by Newtonian dynamic equation [3]:

$$M\frac{d^2z}{dt^2} + B\frac{dz}{dt} + Kz = F_e \tag{2}$$

The obtained equation can be solved with the use of Matlab software.

4. EQUIVALENT CIRCUIT IN LTSPICE

To easily use multi-physic model, without necessity of mathematics calculations the circuits simulator LTSpice was used. Element, which makes possible multi-physic modelling in LTSpice is behavioural current source [4]. This element enables to make, that the resulting current dependent from any variable voltage in node of the electrical circuit [5]. Additional it is possible to make, that the resulting current depends from the node voltage and also from constant parameters, which are introduced as mathematical functions. These two functionalities enable to fully imitate, in the form of the equivalent circuit the multi-physic phenomenons, which take place in the simplified model of the capacitive RF MEMS switch. On Fig. 3 electrical equivalent circuit is presented. In this circuits the elements analogues, presented in the second chapter were used.

R=(B*pwr((1.2-(V(Uz)/go)), (-3/2)))

C1

{M}

R1

B4

I=-V(Uz)*(k)

Uz

B3

I=V(Uv)

C4

1

Ufinal

B2

V=go-min(V(Uz),2.5u)

Uc

V1
PULSE(0 50)

B1

I =(V(Uc)**2)*((eps0*l*w)/2)/((go+td/epsr-V(Uz))**2)

.tran 55u   ;dc V1 0 50 0.01

.param eps0=8.85e-12 l=100e-6 w=60e-6 k=6 go=2.5e-6 M=0.27792n B=(1/105.57u) dm=2.5u td=0.8u epsr=11
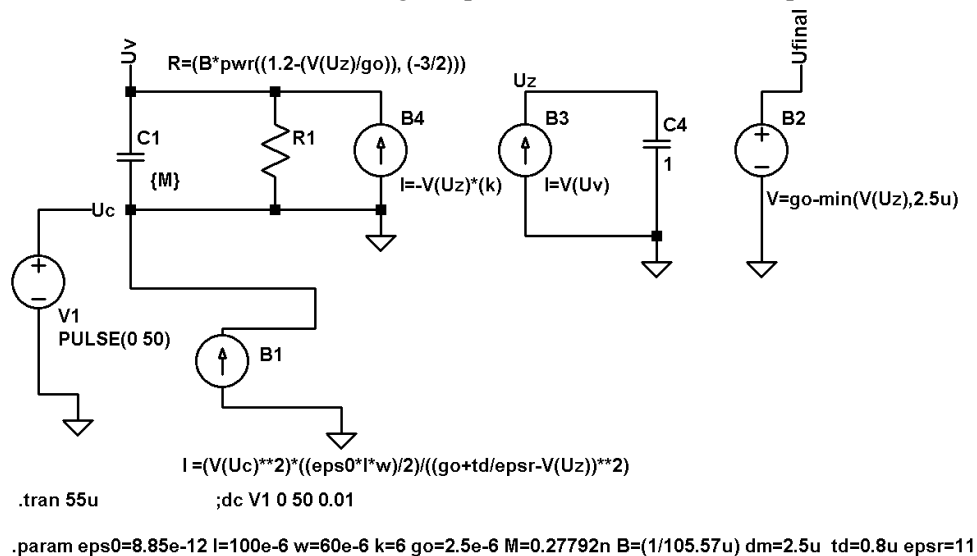
Fig. 3. The electrical equivalent circuit of the capacitive RF MEMS switch in LTSpice

Proposed circuit enables to obtain static characteristic of pull-in voltage versus displacement and dynamic (time) characteristic, which enable to obtain of the switching time. This circuit, prepared in LTSpice is the paper novelty, also the novelty is the possibility to obtain, in LTSpice dynamic characteristic for that simplified model of RF MEMS switch (Fig. 2). The proposed circuit contains three behavioural current sources, two voltage source, two capacitors and resistor. Source B1 is "force" Fe, source B4 is elastic "force" of the spring, source B3 is used as gyrator to convert voltage Uv into current, which represents resultant force. The capacitor C4 is used to obtain relation between velocity and the

displacement, which is represented as Uz. The voltage source V1 is biasing, applied voltage and B2 is a limiter, which models contact situation of two plates. The voltage Ufinal is the final voltage, which simulates displacement of upper plate and it is taking into account the limit of the gap between plates.

The presented equivalent circuit requires from the potential user only to introduce geometrical and material input data of the structure. To obtain the static characteristic, the dc analysis must be set and for the dynamic characteristic the time analysis must be set. For both characteristics the equivalent circuit is the same, because elements C1 and R1 don't have influence for the static characteristic. For both characteristics the voltages Uz and Ufinal were scaled and due to that fact μV, obtained in LTSpice represents μm of the displacement.

5. VALIDATION

The validation was made by analysis of two examples, first one is with constant values of M, B and K parameters, the second one has M and K constant and the damping coefficient is changing and is dependent from displacement z and gap g_0.

Mathematically first example is described by formula (2) and the second example is described by following formula [3]:

$$M\frac{d^2z}{dt^2} + B(1.2 - \frac{z}{g_0})^{-\frac{3}{2}}\frac{dz}{dt} + Kz = F_e \tag{3}$$
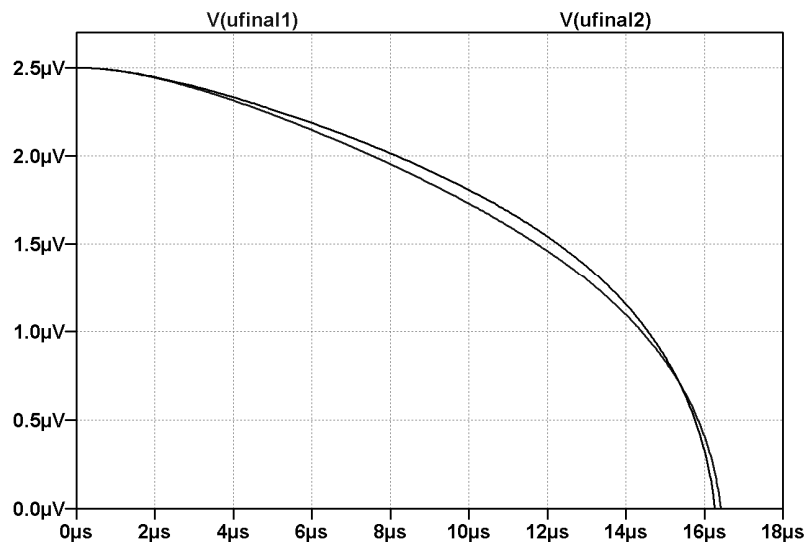

Fig. 4. Dynamic characteristics in LTSpice, case 1 B is constant, case 2 damping coefficient is changing

For both examples static and dynamic characteristics were made, Figs. 4 - 5. The results were compared with mathematical computations in Matlab and in commercial software APLAC, Figs. 6 - 7.
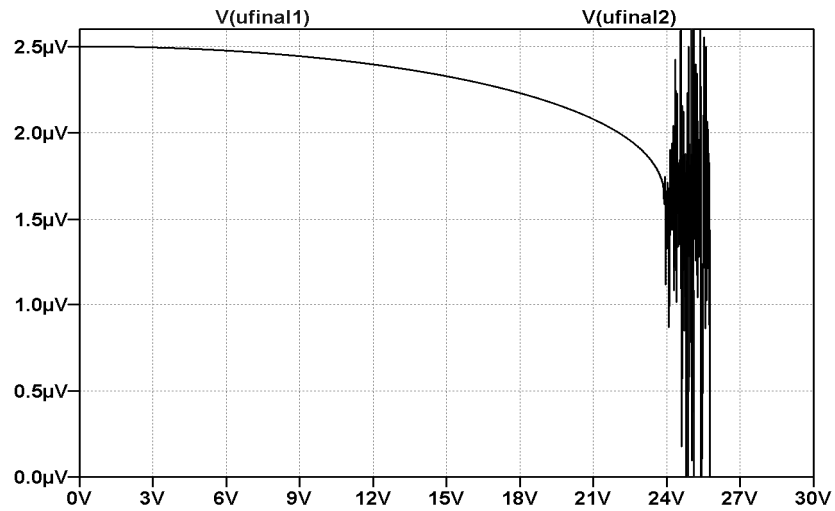

Fig. 5. Static characteristics made in LTSpice, case 1 B is constant, case 2 damping coefficient is changing
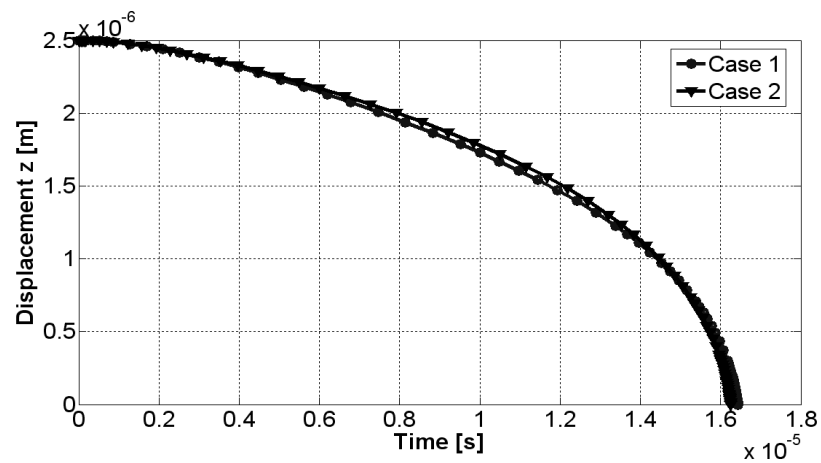

Fig. 6. Dynamic characteristics in Matlab, case 1 B is constant, case 2 damping coefficient is changing
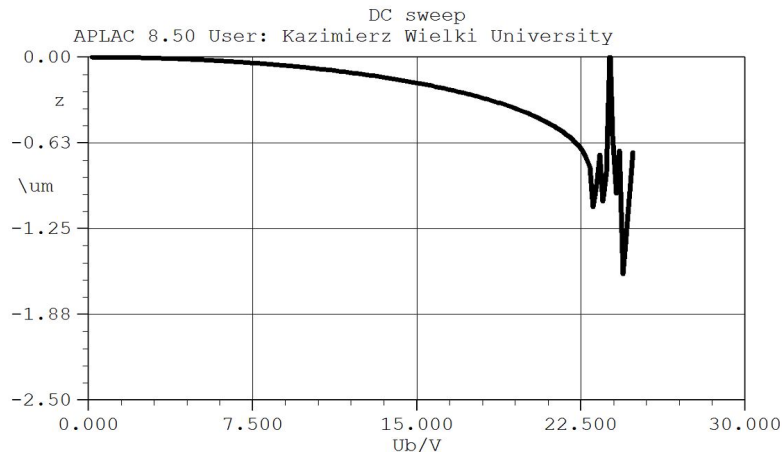
DC sweep
APLAC 8.50 User: Kazimierz Wielki University

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  0.00 ┤
       │
    z  │
       │
 -0.63 ┤
       │
  \um  │
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 -1.25 ┤
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       │
 -1.88 ┤
       │
       │
 -2.50 ┤
       0.000     7.500     15.000    22.500    30.000
                          Ub/V
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Fig. 7. Static characteristic made in APLAC, case 1 B is constant

6. CONCLUSION

The novelty, which is presented in the paper is the electrical equivalent circuit of the simplified model of capacitive RF MEMS switch, made in LTSpice. The novelty is also possibility to obtain dynamic and static characteristic for the case, when B is not constant but is changing. Obtained electrical equivalent circuit can be used in EDA (Electronic Design Automation) software for RF MEMS devices. The performed validation proved effectiveness, usefulness of that circuit for obtaining the dynamic and static characteristics.

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