NONPARAMETRIC MATHEMATICAL MODELING OF BEAMS SPOILED FROM ELASTIC MASSES MEMS OF THE DOBLE BRIDGE TYPE

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Abstract. *The technology MEMS (Micro-Electro-Mechanical Systems) is innovative and stands out for an applications unlimited range, especially in the sensor and actuator design. From use of micromachining techniques, millions of devices are manufactured on a single silicon wafer. However, it is known that the processes used in the manufacture also present limitations. This fact results in making some damaged structures during the manufacturing process. The main problem observed is the break beams elastic masses deformable. So, it is necessary to develop a methodology that makes the identification of these defects before marketing. Therefore, this paper aims at to detect the breaks in beams elastic masses by using nonparametric mathematical models from System Identification theory. The object of study is an elastic mass, whose structure follows the double bridge typology used in comb-drive transducers. The structure was modeled from the finite element method in ANSYS® software. Simulations of the intact and damaged structure behavior were realized to obtain data regarding the force and the elastic mass displacement. From the collected data, a spelling database or signatures was created using the computational tool Matlab®. Through qualitative analysis of nonparametric models was possible to detect the fractured beam.*

Keywords: Faults; Elastic Deformation; Comb-drive; Signature.

1. INTRODUCTION

MEMS are micrometer order transducers to perform sensing and actuating functions (Maluf and Willians, 2004). The applications of these microtransducers have increased over the last years and the multidisciplinary is an aspect to be considered when evaluating the scientific research importance in this technological field, it covers industries such as automotive, medical, telecommunications, aerospace, military and others. Miniaturization, reliability, production low cost, economy energy and low environmental impact are peculiarities that justify the importance of the MEMS study. These advantages are ensured by employing micromachining techniques in the manufacturing process, where millions of structures are fabricated on a single silicon blade. Thus, dynamic devices of easy integration that have different functions are produced. Among the several devices designed by this technology, one that stands out is the actuator translational called comb-drive (Ribas *et al.,* 2000). This structure is constituted by capacitive combs interlaced without physical contact and an elastic mass composed by elastic beams. Figure 1 shows a comb-drive with a longitudinal translatory action (Beyeler, [s.d]).

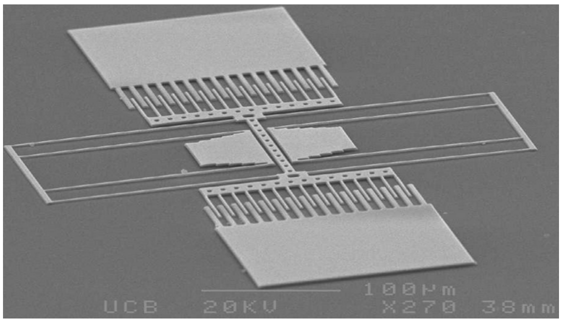


Figure 1: Actuator and sensor Comb-drive of longitudinal translation.

Production processes allow that millions of devices to be made at once, on the other hand it is emphasized that several devices produced have failed in operation. In this context, it is important that the techniques used in the tests are improved (MEMS Journal, 2011), (Ling; Wang, 2006). The test costs of MEMS are high and can reach 50% of the device total value (Reimbold, 2008). Therefore, it is important to develop methodologies that encourage the understanding of the operating dynamics of these devices, especially in the faulty aspects (Oliveira, 2010). The diagnosis of defects prevents losses and that damaged pieces reach the market. The breaking or rupture of beams elastic masses is one of the most common defects (Gerhardt, 2003), in this way, scientific research in this area offers optimization perspective of the testing phase, production process, and quality control for these devices.

A possible solution to this problem is the comparison of collapsed structures operating standards, with damaged structures. In this context, the nonparametric mathematical modeling, from System Identification theory, is an effective alternative, because it emphasizes the graphical analysis (Aguirre, 2004) and the comparison process becomes easier when graphs illustrating the behavior of structures exist. And through the peculiarities inherent to the graphics by devices in tests, it can be inferred about the collapsed structure. In this sense, the research proposes the use of nonparametric mathematical models as a method for detecting and identifying collapsed beams in MEMS elastic masses of the double bridge type.

The remainder of this paper is organized as follows. Section 2 presents the operating principle of the comb-drive actuators, and the role that elastic mass of the double bridge type performs. Section 3 presents the nonparametric mathematical modeling via System Identification theory applied to MEMS elastic masses. Section 4 shows the results and discussions. Finally, Section 5 presents the conclusion and the proposal for future works.

2. DOUBLE BRIDGE ELASTIC MASSES

The comb-drive actuator displacement x(t) occurs due to the mechanical force action *f(t)*, as Figure 2 shows. Mobility is guaranteed by the resonance frequency that is defined from the geometric parameters and the elastic mass material properties. According to the beams arrangements in the elastic masses three typologies are considered: single bridge, double bridge and double hinge (Reimbold, 2008). This paper discusses the typologie double bridge, since it is widely used in military and telecommunication aplications (Tang, 1990). Its structure consist a mass of "back and forth", four beams, and four anchors (as Figure 2). The beams are inclosed in the rigid mass of the center, and the anchors at the extremities. This typology distinguished by geometric simplicity, absence of joints, and unidirectional displacement, it has only one freedom degree. When it is integrated to the comb-drive actuator, devices are formed such as accelerometers, tweezers and switches, among others.

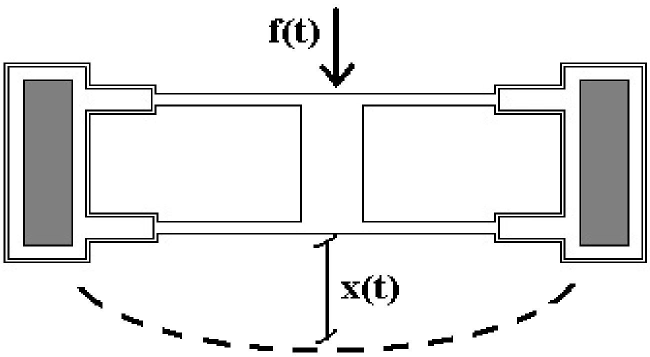


Figure 2. Double Bridge Elastic Mass.

3. SYSTEM IDENTIFICATION

The System Identification theory is a tool that allows to obtain mathematical models of systems, from input and output data, as illustrated in Figure 3. It is useful when the mathematical model obtained from physical laws (phenomenological modeling, or box- white) is complex and difficult to determine. It is highlighted that Ljung (1999) divides the modeling of System Identification into two categories, the first consists of parametric methods, in which the mathematical models are formulated from equations, and the second consists of the nonparametric methods, in which the model is not necessarily an analytical model.

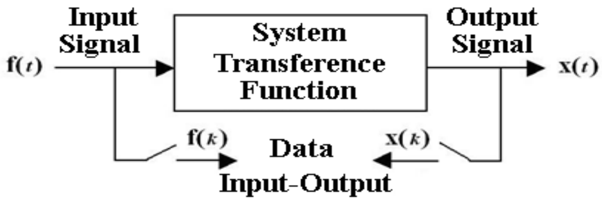


Figure 3: System Identification.

The parametric methods use parameterized mathematical structures, to describe the dynamic behavior of the original system. On the other hand, nonparametric methods result in a graphical representation that characterizes the original system dynamics. This division is related to the shape of the identified model and not necessarily to the algorithm or method used to find the model (Aguirre, 2004). In this way, the relationship between the input and output signal in the graph allows to identify problems in the structure studied. These nonparametric methods are called compaction methods, and the compacted response or resulting graph, is called signature.

For applying these techniques is required little or no system prior knowledge, however, the input and output signals data are essential for obtaining the model. Data are collected from the device terminal, so the possibility of a mechanical or electrical collapse is reduced. The signature method is non-invasive, and passive to be used in the mathematical modeling of devices with smaller dimensions than 100 µm.

4. DATA COLLECT

To perform the data collection was necessary to model the double bridge elastic mass, from the finite element method, in the *software* ANSYS ®. Thus, the data collection relating to the system displacement when submitted to a mechanical force, is performed. The material chosen for the structures and the simulation was the polysilicon, it is the most used in the manufacturing of MEMS devices. Figure 4 shows the finite element selected for simulation, the SOLID45, since it satisfies the characteristics of the elastic material, in the mechanical response simulation, of micro systems (Reimbold, 2008).

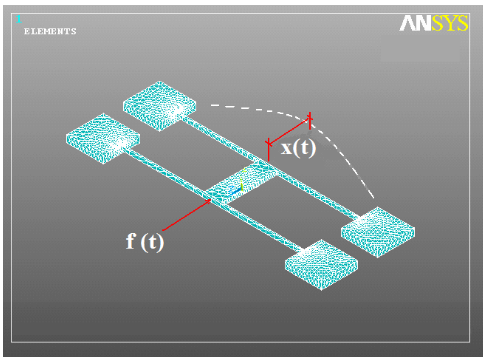


Figure 4. Double Bridge elastic mass using SOLID45.

To facilitate the understanding of the results obtained from simulations, the beams are classified in two ways, positive beams localized at the right side of the mass, and negative beams localized at the left side of the mass, as shown in Figure 5. Also, Figure 5 illustrates the region and nodes monitored to obtain the data regarding the force and elastic mass displacement.

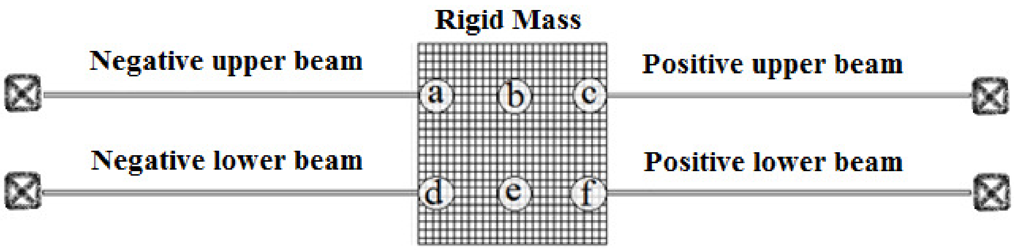


Figure 5: Identification of beams and monitoring nodes of Double Bridge elastic mass.

5. RESULTS AND DISCUSSION

The first results show the intact structure performance. The forces are applied to the nodes located at the upper center of the rigid mass and distributed with a force of 0,0467µN on each node, generating a force resulting of 0,14µN. This is the limit force, so that the structure does not collapse during operation (Reimbold, 2008). The simulation and collecting of force and displacement data are carried out, for each node shown in Figure 5. Using the Transfer Function concept are obtained the nonparametric mathematical models from Matlab® software, also called in the literature as signature (Ribas *et al*, 2003). Thus, graphics database are created that allow to determinate a standard behavior for intact and collapsed structures. Figure 6 shows the results for each node in the intact elastic mass, they are used as reference standard for the diagnosis of the collapsed beams.

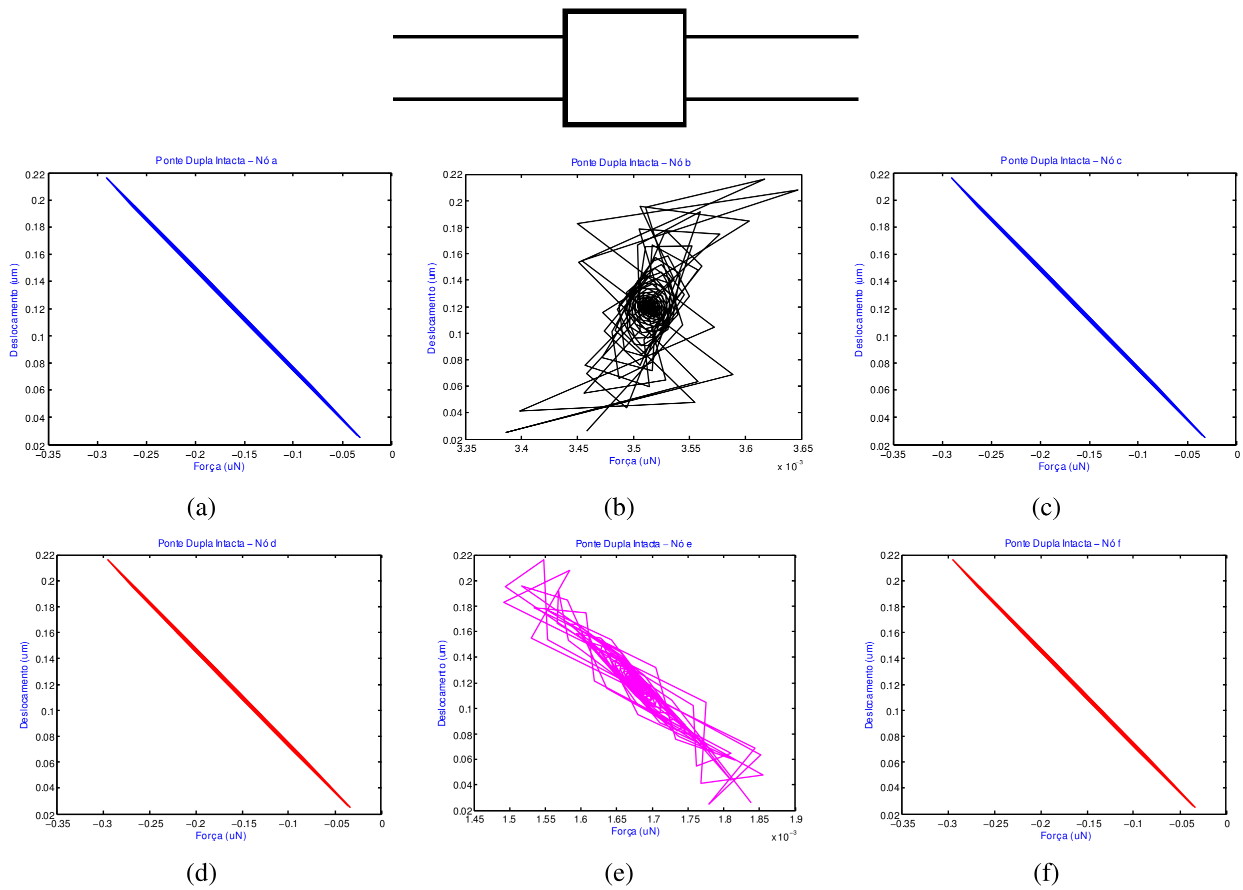


Figure 6: Force x Displacement on each node to intact beams.

Figure 6 shows graphics database in which is possible to observe a behavioral standard or signature that is related to each of the nodes located to the left (a, d), and the right (c, f) of the mass rigid. The behavior of these nodes, a, c, d, f, is presented as straight lines with negative inclination. Signatures relating to central nodes (b, e) located in the rigid mass center, are discrepant relative to the sides nodes. The standard performance of each node in the simulation of the intact structures favors to detect MEMS elastic masses collapsed. Once the signatures of the tested structures are different from signatures shown in Figure 6, one can conclude that there is failure in the beams considered, and the elastic masses should be discarded. The MEMS elastic mass which are in good operating condition are selected.

After the MEMS elastic mass test with intact beams, simulations are performed with the collapsed beams. Tests for detecting the failure are initiated by rupturing the positive upper beam. For all the beams analized the failure is located at ¼, ½ or ¾ of the beam length in relation to rigid mass. Signatures generated are compared with the signatures of the intact structure, that are considered reference standards.

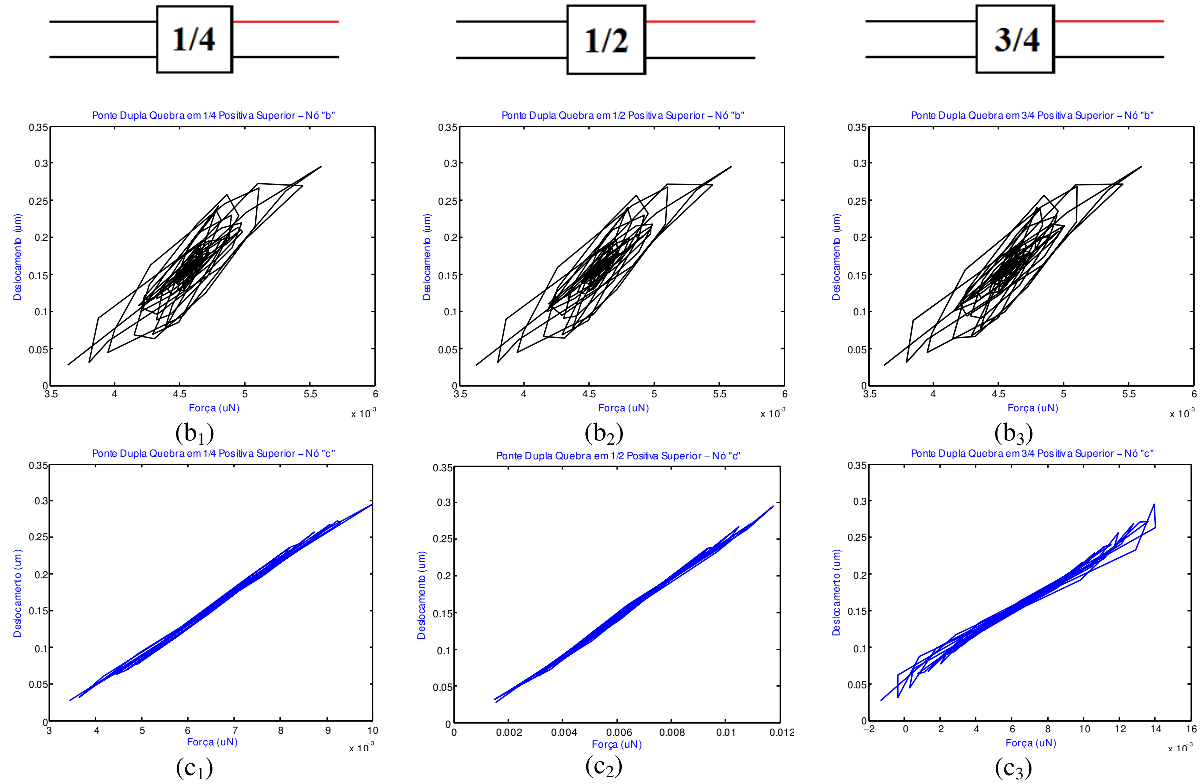


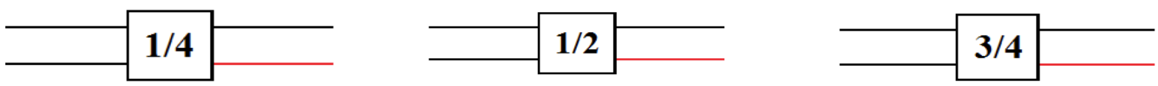
Figure 7: Collapse of the positive upper beam of the elastic mass Double Bridge. Node b: (b_1) collapse in 1/4; (b_2) collapse in 1/2; (b_3) collapse in ¾. Node c: (c_1) collapse in 1/4; (c_2) colapse in 1/2; (c_3) colapse in 3/4.

Figure 7 shows the simulations results for the nodes (b, c) of the positive upper beam collapsed. From the "signature" is can identify that exist a collapsed beam , and also determine the position of this beam in relation to rigid mass. Figures 7 (b1), 7 (b2) and 7 (b3) show the behavioral performance of the node "b" of a collapsed beam and their deviations from the "signature" of this node, in the intact structure (see Figure 6 (b)). The presence of this feature identifies the collapse of a upper beam in the MEMS elastic mass, but does not indicate its location (left ou right).

Figures $7(c_1)$, $7(c_2)$ and $7(c_3)$ show the behavioral performance of the node "c" of a collapsed beam, it is observed that they show a positive slope when compared with the signature in Figure 6 (c) of structure intact. This difference in slope is associated to the collapsed beam localization. MEMS elastic masses that follow this behavior standard have fracture in positive upper beams (i.e., right).

Figure 8 shows the simulations results for the nodes (e, f) of the positive lower beam collapsed. Figures $8(e_1)$, $8(e_2)$ and 8(e3) show the behavioral performance of the node "e" of a collapsed beam and their deviations from the "signature" of this node, in the intact structure (see Figure 6 (e)). The presence of this rounded shape identifies the collapse of a lower beam in the MEMS elastic mass, but does not indicate its location.

Figures $8(f_1)$, $7(f_2)$ and $7(f_3)$ show the behavioral performance of the node "f" of a collapsed beam. It is observed that they do not have a standard behavior, when the beam is at the lower does not it is possible to accurately determine their location, more detailed studies are needed.



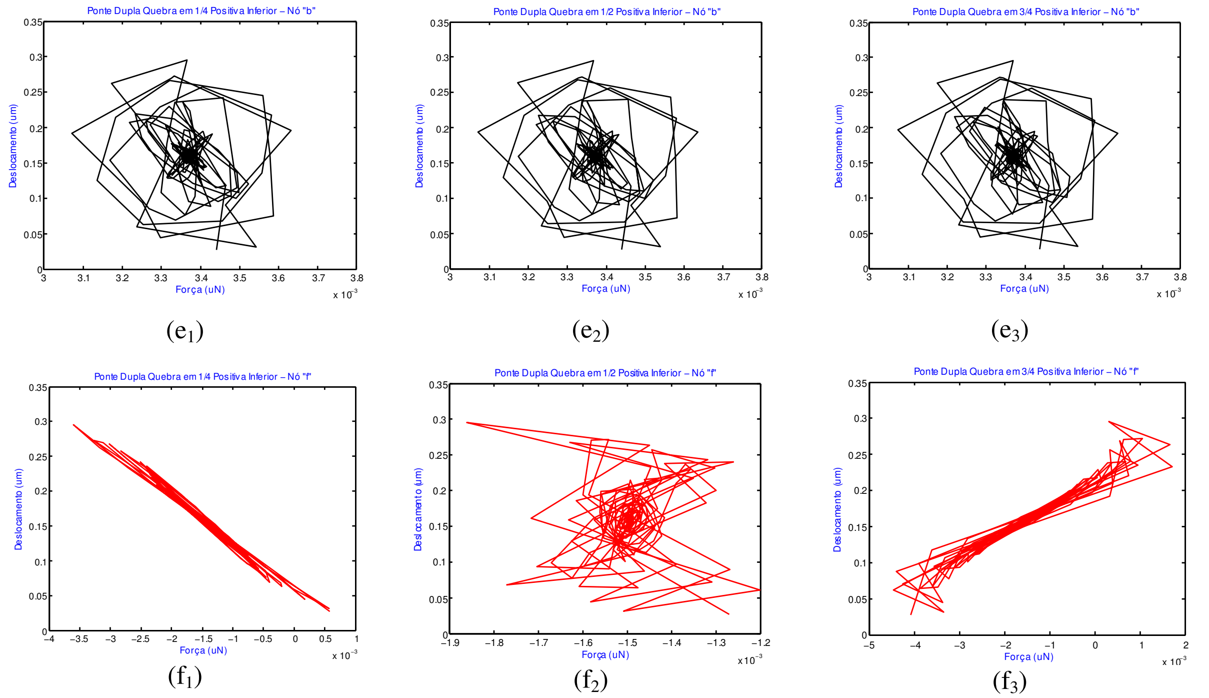


Figure 8: Collapse of the positive upper beam of the elastic mass Double Bridge. Node e: (e_1) collapse in 1/4; (e_2) collapse in 1/2; (e_3) collapse in ¾. Node f: (f_1) collapse in 1/4; (f_2) colapse in 1/2; (f_3) colapse in 3/4.

Figure 9 shows the simulations results for the negative upper beam.

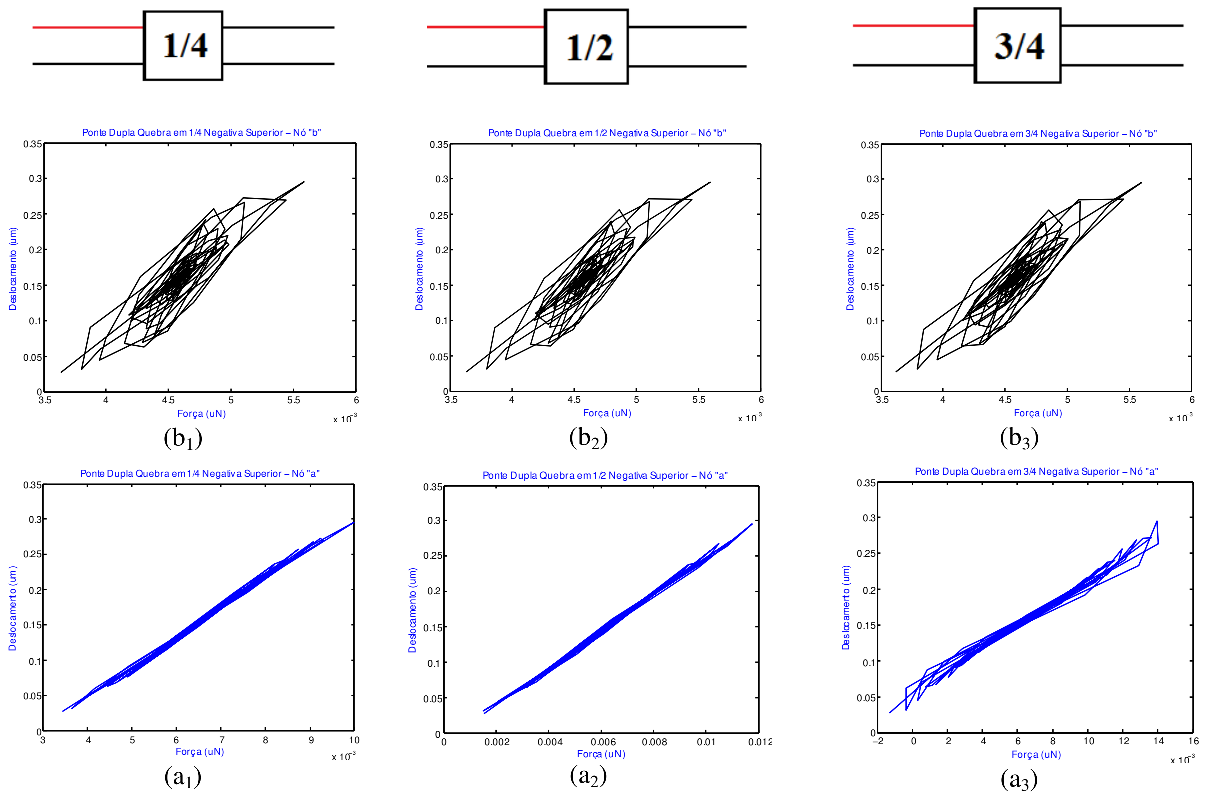


Figure 9: Collapse of the positive upper beam of the elastic mass Double Bridge. Node b: (b_1) collapse in 1/4; (b_2) collapse in 1/2; (b_3) collapse in ¾. Node a: (a_1) collapse in 1/4; (a_2) colapse in 1/2; (a_3) colapse in 3/4.

Figure 9 shows the simulations results for the nodes (b, a) of the negative upper beam collapsed. From the "signature" is can identify that exist a collapsed beam, and also determine the position of this beam in relation to rigid mass. Figures 9 (b_1), 7 (b_2) and 7 (b_3) show the behavioral performance of the node "b" of a collapsed beam and their deviations from the "signature" of this node, in the intact structure (see Figure 6 (b)). The presence of this feature identifies the collapse of a upper beam in the MEMS elastic mass, but does not indicate its location (left ou right).

Figures 9(a_1), 7(a_2) and 7(a_3) show the behavioral performance of the node "a" of a collapsed beam, it is observed that they show a positive slope when compared with the signature in Figure 6 (a) of structure intact. This difference in slope is associated to the collapsed beam localization. MEMS elastic masses that follow this behavior standard have fracture in negative upper beams (i.e., left).

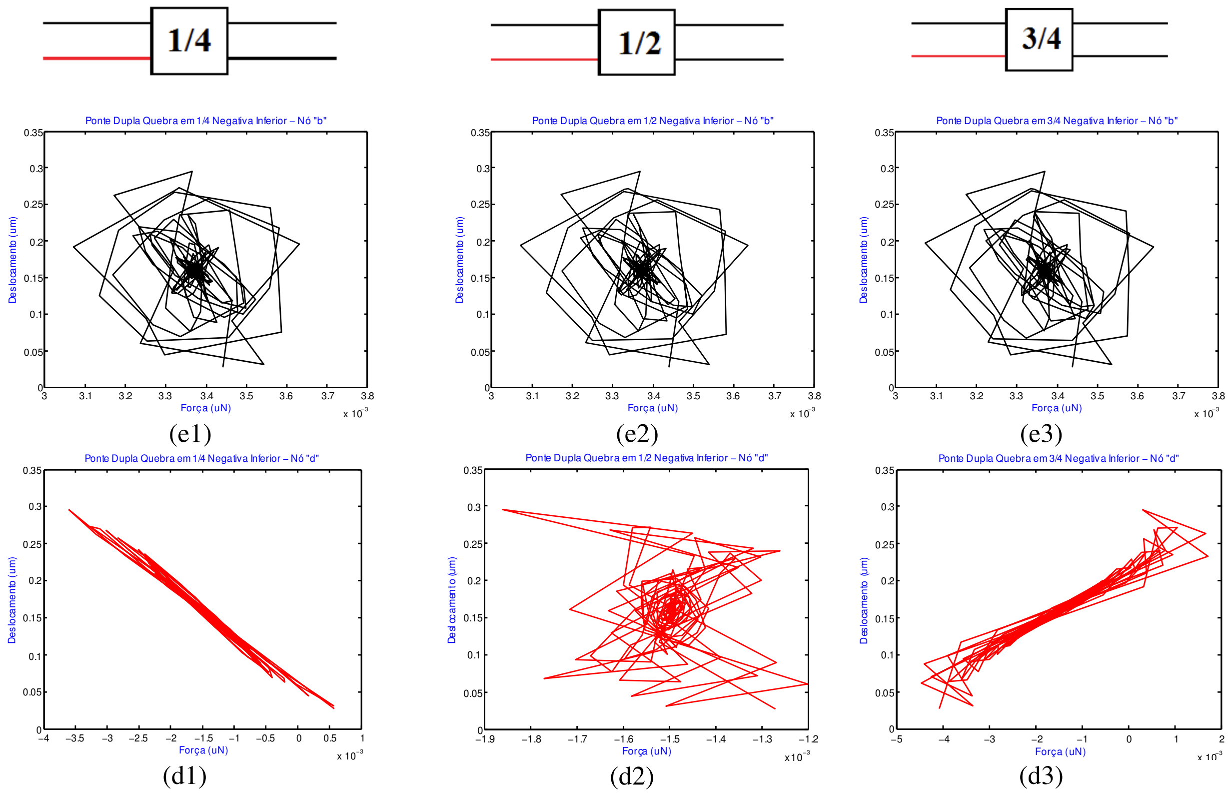


Figure 10: Collapse of the positive upper beam of the elastic mass Double Bridge. Node e: (e_1) collapse in 1/4; (e_2) collapse in 1/2; (e_3) collapse in ¾. Node d: (d_1) collapse in 1/4; (d_2) colapse in 1/2; (d_3) colapse in 3/4.

Figure 10 shows the simulations results for the nodes (e, d) of the negative upper beam collapsed. Figures 10(e1), 10(e2) and 10(e3) show the behavioral performance of the node "e" of a collapsed beam and their deviations from the "signature" of this node, in the intact structure (see Figure 6 (e)). The presence of this rounded shape identifies the collapse of a lower beam in the MEMS elastic mass, but does not indicate its location.

Figures 10(d_1), 10(d_2) and 10(d_3) show the behavioral performance of the node "d" of a collapsed beam. It is observed that they do not have a standard behavior, when the beam is at the lower does not it is possible to accurately determine their location, more detailed studies are needed.

4. CONCLUSION

This paper proposes a new methodology to determine the collapse in MEMS elastic masses caused by the fracture of a beam. The technique consists of the qualitative comparison of nonparametric mathematical models called signatures. The simulations results of the models form graphics database that allow to quickly and dynamically detect if a MEMS elastic mass acts in perfect condition or under collapsed, through a comparative analysis. The method developed stands out in relation to found in the literature, since its application allows both collapse detection, as the identification of upper or lower collapsed beam. Thus, the technique is innovative and offers the prospect of optimizing the testing phase on MEMS, as well as the design and manufacturing stages. For future works intend to investigate the detection of multiple beams fractured in a single elastic mass, and the position of the fracture on the beam precision.

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