Supplementary data for article "A mechanical model of a non-uniform Ionomeric Polymer Metal Composite (IPMC) actuator"
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Description of the algorithms

Algorithms, that solve the set of equations (12)-(23) for F and $k(s)$, are presented below. Force can be found with first algorithm and curvature with the second. Only specifications are given. No implementation details are discussed.

Algorithms are implemented in LabView 8.0. Source code can be downloaded from https://www.ims.ut.ee/mediawiki/upload/d/d0/IPMC_Mechanics_Source.zip. Implementation of algorithms is in file "Get Segment of Relation.vi" and "Get Curvature.vi" correspondingly. An application that finds the output force and neutral curve of the sheet using previously mentioned algorithms can be found in file "Get Force and Neutral Curve.vi" (see figure 1). An application that does not require LabView can be downloaded from https://www.ims.ut.ee/mediawiki/upload/f/fe/IPMC_Mechanics.zip.

The application is easy to use. Find and click the "Run Continuously" button on the toolbar. On the bottom part of the window is a slide control for position of the object. Change the position of the object and observe the corresponding force and neutral curve in real time. The parameters of the actuator can be modified by pressing on the appropriate button on the top part of the window.

1. Relations of parameters

1.1. Input data

- parameters of the model,
    - IPMC sheet properties
        - length l,
        - initial curvature $k_0(s)$,
        - beam stiffness D,
        - EIBM $M_e(s)$;
    - radius of the trajectory R,
- parameters of the algorithm,
    - bounds and sample densities for position s_F and force F_{sheet},
    - optional input data (along with default values)
        - Number of segments - 1000,
        - Parameters of root finding algorithm: tolerance - $1 \cdot 10^{-6}$, limit - 100.

1.2. Output data

- segment of relation $\left(s_F(q), F_{sheet}(q), p(q), \phi(q), F(q)\right)$.

1.3. Comments

With the algorithm introduced here a segment of 5-ary relation over $\mathbb{R}$ between
1. the position on sheet, where the force F_{sheet} is applied s_F,
2. the force applied to the sheet F_{sheet},
3. the position of the trajectory p,
4. the angle between the normal of the sheet and the tangent of the trajectory ϕ,

    5. the force applied to the object F

for given l, $k_0(s)$, D, $M_e(s)$, R can be found. The relation is a set of curves (usually only one) in 5 dimensional space. This algorithm finds a segment of one curve, that contains the least position s_F. It can be given in parametric form as $\left(s_F(q), F_{sheet}(q), p(q), \phi(q), F(q)\right)$, where q is the parameter.

The segment found by the algorithm is such that $s_F(q)$, $F_{sheet}(q)$ are inside bounds given within input data. The wider bounds we set the larger part of the relation we get. The larger is the sample density inside the bounds the higher is the accuracy of the approximation.

The relation between position p and force F does not have to be surjective – meaning that for a single position several forces may relate. If we want to establish a surjection from positions to forces, we may relate position with the smallest force by the absolute value. In that way a functional relationship for calculations found.

The bendable IPMC section of the sheet is approximated with constant curvature segments of equal length. Thus number of segments used for bendable section needs to be specified. 1000 segments were used for simulations conducted in this paper.

The algorithm makes use of a root finding algorithm. Like all such methods error tolerance needs to be specified. Also the number of computation cycles is limited, to avoid endless looping.

2. Curvature

2.1. Input data

- parameters of the model,
  - IPMC sheet properties
    - length l,
    - initial curvature $k_0(s)$,
    - beam stiffness D,
    - EIBM $M_e(s)$;
  - radius of the trajectory R,
  - force application position on sheet s_F,
  - force applied to the sheet F_{sheet},
- optional input data (along with default values)
  - Number of segments - 1000.

2.2. Output data

- curvature of the bendable section of the sheet - $k(s)$.

2.3. Comments

In this section an algorithm is introduced, with computes the curvature $k(s)$ of bendable IPMC section of the sheet. Once we know curvature, neutral curve can be easily computed with (19) and (21). The algorithm requires input data s_F and F_{sheet}. If these parameters are not known and we have provided p instead, algorithm introduced in previous section can be used to find the corresponding s_F and F_{sheet}. Note that there can be several corresponding pairs of s_F and F_{sheet}. If we want to use only one, we may take the pair with the smallest corresponding $|F|$.
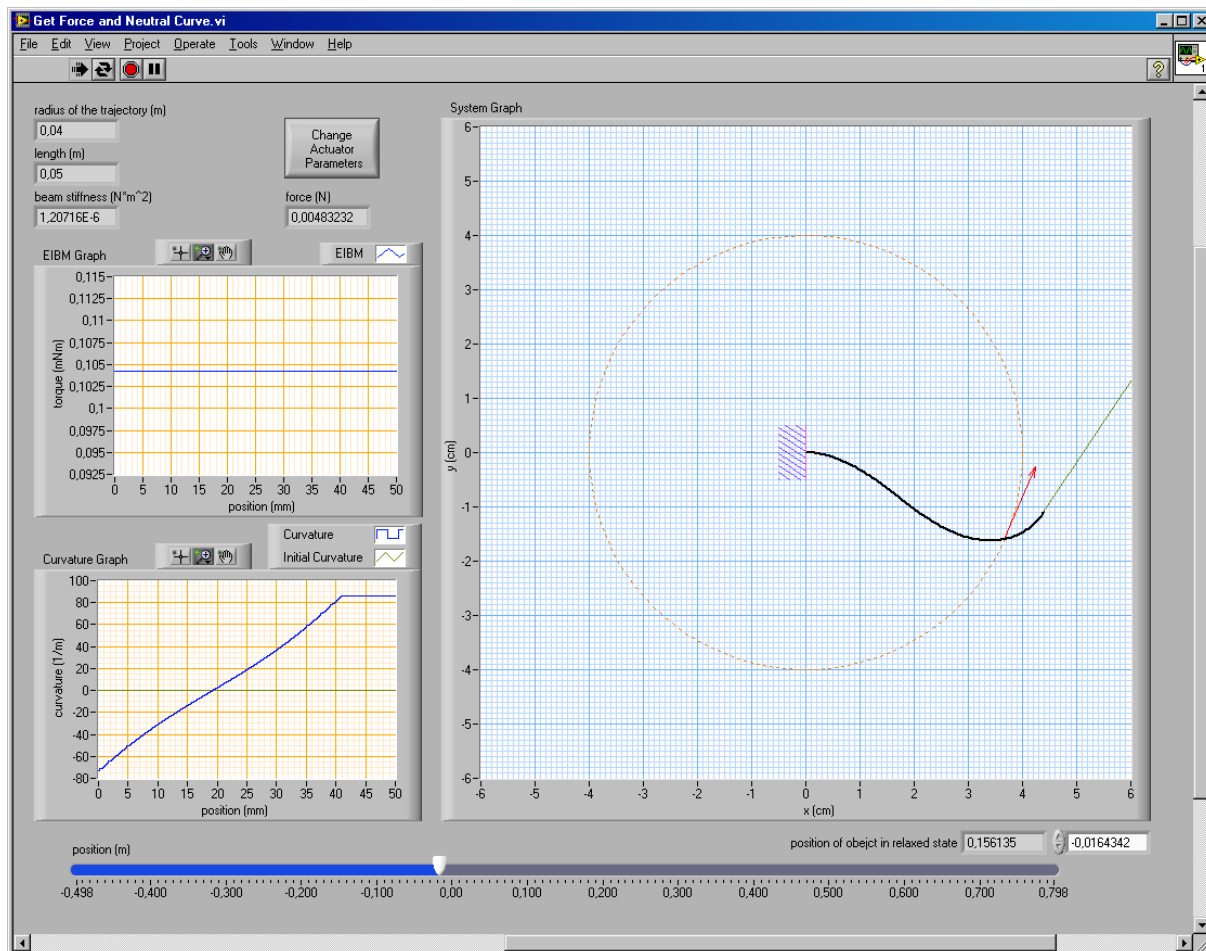
Figure 1 Application for finding the force and the neutral curve