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Paris, July 9th 2018

Review of Katarzyna Szepietowska PhD dissertation untilted « Polynomial Chaos Expension in Bio- and Structural Mechanics » from Gdańsk University of Technology

Scientific discipline : Civil Engineering

The original scientific work proposed by Ms. Katarzyna Szepietowska is dedicated to the modelling and simulation of implants used in the ealing of ventral hernias. As many uncertainties appear in these simulations, a probabilistic approach is proposed. The propagation of uncertainties in the inputs is studied using the polynomial chaos expansion and different methods are used to evaluate the influence of the number and the location of the sampling points involved in this non-intrusive method. This thesis has been supervised by Pr. Izabela Lubowiecka (Gdańsk University of Technology) and Pr. Eric Florentin (Institut National des Sciences Appliquées) and the auxiliary supervision has been carried out by Benoit Magnain (Institut National des Sciences Appliquées). The theme of this thesis is of major importance as the efficiency of hernia repair has a very important clinical, societal and economic impact.

The document is structured around 5 chapters:

- Chapter 1 is dedicated to the introduction to the clinical problem and to the state of the art on the biomechanics modeling of these kinds of problem. This chapter is very clear, and the level of clinical details provided in the document is the good one for an overview of the hernia surgery. The table that synthetize the literature review is a very efficient way to have a global view on all the proposed works in the literature and introduces the need of a probabilistic approach due to the fact that many uncertainties appear in the modeling of the abdominal wall and could have a big influence on the results. The need of a personalized model is obvious as material properties, geometries, muscle control are really individually depending but these data a rarely available and a probabilistic approach could be a very efficient way to model our lack of knowledge. As the models used for this kind of application are usually nonlinear geometrically and physically, non-intrusive approaches (such as the polynomial chaos: PC) seem to be the good choice. However, the accuracy of the non-intrusive PC can greatly depend on the number and the location of sampling points and a sensitivity analysis provided in chapter 2 is essential to master the accuracy and the computational cost.

- Chapter 2 introduces the mathematical background of the uncertainties quantification and the sensitivity analysis. Once again, this description is very clear with of lot of references to previous works in the literature. Sampling-based methods (Monte Carlo method and Latin hypercube sampling) and spectral methods (Karhunen-Loève expansion and PC expansion) are recalled and details are provided to present their intrusive and non-intrusive integration. I could just regret that the intrusive way is just mentioned, and advantages and drawbacks of intrusive and non-intrusive integrations are not discussed. The end of the chapter is dedicated to sensitivity analysis with a specific focus on the Sobol's approach.
- Chapter 3 gives the comparison of regression point choice methods. In this chapter, the numerical Design of Experiments (DoE) is discussed regarding the fact that we are in the computational field and a we will get the same result with the same set of parameters. Ms Szepietowska divides her presentation in two classes: random or quasi-random approaches and deterministic approaches. It leads her to test 7 methods: Sobol's sequence (S1), Halton's sequence (S2), the closest to the origin from combination of roots of polynomials (M1), D-optimal points of univariate polynomials with and without weight function (M2a, M2b), randomly drawn subset of univariate D-optimal points (M3), D-optimal design chosen from a random set of points with and without weight function (M4a, M4b), and finally D-optimal design chosen from candidate set sampled by LHS method (M5). These methods will be compared on numerical examples using estimators such as the reference error, the error in calculating the Sobol's indices, the root mean square error and the error of the PC metamodel. The first example is based on a 1D cable model of the implant proposed in the literature. This simple model can also be used for a sensitivity analysis to identify the most influential parameters. The second model is based on a 2D modeling using a membrane structure once again coming from the literature. As pointed out by Ms Szepietowska, the position of the sampling points is dependent on the studied problem. Nevertheless, she was able to draw some conclusions. When the problem is quite simple (1D), all methods give similar results for polynomial order greater than 2. When the problem is more complex (2D) and then could generate more variability, there are significant differences within the applied methods in terms of accuracy and computational cost.
- Chapter 4 is dedicated to the uncertainty propagation and the sensibility analysis. One of the key-elements in such approaches is the reduction of the number of variables as the computational cost can be very expensive. For the 2D example, it is clear that 2 supports have a strong influence on the solution (4^{th} and 7^{th}). Global sensitivity analysis finding the optimal truncation is then presented using the mean, standard deviation and 95 percentiles. The results on the implant orientation are then correlated with clinical data. Several configurations are tested including position of the supports with random imperfections. Finally, the method is tested in

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2 complex cases: the membrane model of an abdominal wall with an implant and a civil engineering application on a corner joints demonstrating by this way that the proposed approach is very general and can be applied in a lot of different fields. The last part of the chapter is dedicated to the conclusion. This study has been able to highlight that, with the simplified model, the material properties are the most influential parameter followed by the displacement of the hernia edges. On the other side, the initial force and the initial length if the cable have a low effect. For the membrane model, it has been demonstrated that superiority of the applied methods depends on the number of variables, that it was possible to reduce their number and that this kind of approach could greatly hep the surgeon to adapt the optimal orientation of the implant. Finally, the uncertainty quantification and sensitivity analysis performed on the local model of the membrane subjected to the intra-abdominal pressure have shown that the pressure play a major role followed by the elasticity module of the abdominal wall.

- Chapter 5 introduces the conclusions of this work. Ms Szepietowska has been able to propose a methodology to incorporate with success uncertainties in models related to ventral hernia. It has been demonstrated that non-invasive polynomial chaos can be implanted to solve this kind of problem despite the complexity of the modeling (non-linearity, non-smoothness, high input variability, etc.). The reduction of the number of variables is a key factor and the sensibility analysis provided in this work can greatly help to do the right choices.

The work presented by Ms Szepietowska is very original and has a great potential. The need of planning in surgery is really increasing as results of the surgery could be optimized with an optimal placement of the implant. For a personalized planning, two options can be chosen: to have access to the personalized geometry and material properties of the patient (very complex) and to perform a personalized simulation or to build an uncertain model taking into account our lack of knowledge of some of the simulation parameters. In this thesis, the second option has been chosen and this work has been able to propose a methodology to incorporate uncertainties in very complex biomechanics problems in a non-invasive way. A specific task has been deployed to reduce the number of unknowns in order to reduce the computational time and as it has been demonstrated that the optimal approach could depend on the number of parameters. This work rises several open questions:

- It has been a deliberate choice to use a non-intrusive method that leads to the choice of dedicated points. What difficulties do you see in leading an intrusive approach with your case?
- For the non-intrusive approach, projection or regression can be applied. What were the reasons why regression has been chosen and will the projection method lead to the same sensibility to the chosen points?
- Is there a way to detect if a sampling point could a priori be a point of interest?
- Is it possible to build a meta-model once the most influential parameters are founded in order to reduce the computational cost?

To conclude, I would like to say that this work has a great potential to help biomechanists in their planning procedure. The choice to use a non-invasive method is very flexible for its deployment in any computational code. I give then my Authorization of Defense for this very interesting research work.

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