Proceedings of the 7th GACM Colloquium on Computational Mechanics for Young Scientists from Academia and Industry
October 11-13, 2017 in Stuttgart, Germany

Virtual simulation of deformation behavior of NiTi stents used in minimally invasive surgery

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Micro Abstract
Recently isogeometric analysis (IGA) is developed to bridge gap between design and computation analysis. It represents and calculates geometries using non-uniform rational B-splines (NURBS). IGA uses high-order, high-regular basis functions aiding in higher accuracy and minimal computation efforts unlike finite element method. The project aim is efficient simulation of the deformation behavior of carotid NiTi stents in throat arteries which leads to a step closer in realizing real-time simulation.

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Introduction

Cardiovascular diseases are one of the main reasons of death in western countries. In such diseases, arteries develop a plaque resulting in narrowing (stenosis) and hence reducing the blood flow through them. Stenosis leads to stroke which often occur without prior warning.The future clinical intervention seems to progress towards treatment involving percutaneous minimally invasive surgery techniques using high-tech implants which are deployed to the pathological area. One such family of implants are called as stents, which are characterized by their complex geometries and unique material properties.

Self-expandable stents are made of Nickel Titanium (NiTi). The pseudoelastic effect exhibited by NiTi is a result of diffusionless transformation of the microstructure of the material from martensite to austenite phase and this helps in maintaining the flexibility (strains of 10% can be recovered) of the stent structure. Stent flexibility is evaluated by performing bending on stents and are of greater significance in the stent delivery process.

Finite element analysis (FEA) is a popular tool to perform such evaluations in order to test different configurations before prototype testing. Inspite of being a popular tool FEA poses problems in terms of approximating the geometry and accuracy of the approximated solution. The low-order and low-regularity polynomials used in discretization of continuum domain do not capture the exact geometry unless highly fine meshes are used. Isogeometric analysis (IGA) is a recently developed computation tool which bridges the gap between computer aided design (CAD) and computation analysis. IGA replaces low-order and less smoother FEA basis functions with high-order, high-regular basis functions used in CAD while retaining isoparametric framework. Non-uniform rational B-splines (NURBS) were initially chosen as basic environment for IGA due to their extensive use in CAD community [1].

In the current study the bending behavior of stents is analyzed using classical FEA and IGA in a finite deformation regime. This is based on cantilever beam bending test proposed by Müller-Hülsbeck et.al [2].

Basics of NURBS and IGA

In this section a brief outlook on trivariate NURBS is given. For further information please refer to the work of Hughes et.al. [3]. NURBS are constructed from B-splines which are expressed as piecewise polynomials and are widely used in CAD and computer graphics. A pth order B-spline $\mathbf{C}(\xi)$ is obtained by a combination of B-spline basis functions and coefficients $\mathbf{B}_i$ defined in real space and are named as control points as follows:

$$\mathbf{C}(\xi) = \sum_{i=1}^{n} N_{i,p}(\xi)\mathbf{B}_i \tag{1}$$

n is the total number of basis functions and control points. The parameter space of the curve is described by a variable ξ. A knot vector Ξ is defined as a non-decreasing vector with real values.

$$\Xi = [\xi_1, \xi_2, \xi_3, ...\xi_{n+p+1}] \tag{2}$$

The knots ξ_i partition the parameter space into knot spans. Given a knot vector Ξ B-spline basis functions are recursively defined as

$$N_{i,0}(\xi) = \begin{cases} 1 \;\; if \;\; \xi_i < \xi < \xi_{i+1} \\ \\ 0 \;\; otherwise \end{cases} \tag{3}$$

$$N_{i,p}(\xi) = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_{i,p-1}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+,p-1}(\xi) \tag{4}$$

A pth order NURBS curve is defined as

$$\mathbf{C}(\xi) = \sum_{i=1}^{n} R_{i,p}(\xi)\mathbf{B}_i \;\; , with \;\; R_{i,p}(\xi) = \frac{N_{i,p}(\xi) w_i}{\sum_{\hat{i}=0}^{n} N_{\hat{i},p}(\xi) w_{\hat{i}}} \tag{5}$$

where w_i are the projection weights and $N_{i,p}$ are pth order B-spline basis functions. NURBS curves retain all the properties of B-spline curves like high continuity and regularity. The above equation can be extended to solids as follows

$$\mathbf{V}(\xi_1, \xi_2, \xi_3)_d = \sum_{i=0}^{n_1} \sum_{j=0}^{n_2} \sum_{k=0}^{n_3} R_{i,p}(\xi_1) S_{j,q}(\xi_2) T_{k,r}(\xi_3) (\mathbf{B}_{i,j,k})_d \tag{6}$$

where $(\mathbf{B}_{i,j,k})_d$ are coordinates of control points, p,q,r are polynomial degrees and $R_{i,p}, S_{j,q}, T_{k,r}$ are the NURBS basis functions in each parametric direction respectively. The described NURBS basis functions are then introduced as a galerkin isoparametric method based on those shape functions in IGA [1].

Material model

A 'closed-cell' stent model is generated using 'Rhinoceros Version 5 SR14 64-bit'. The constructed surfaces are used to generate a NURBS patch. The NURBS data for all patches are exported as text files using GEO PDEs plugin [4] and in-house Matlab codes are used to create stent geometry (Figure 1) compatible with FEAP software.

The order of the patches for the longest links of stent in circumferential and longitudinal directions is quartic and in thickness is quadratic. For remaining patches the order is quartic, linear and linear along circumferential, longitudinal and thickness directions respectively. Knot insertion is performed on selected long links of the stent using in-house matlab routines to compare the performance of IGA with respect to number of degrees of freedom.

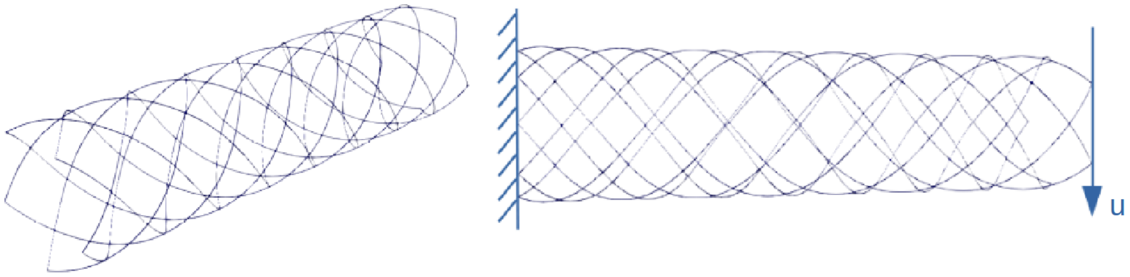

Figure 1. Left: Extended IGA-stent model; Right: Boundary conditions on the stent

The equivalent finite element meshes are generated directly by non uniform division of each from the NUBRS model. The finest NURBS model is used for creating finite element mesh using in-house routines. The FE mesh is further refined (h-refinement) using non uniform subdivision of each patch. For FEA mesh trilinear brick elements with full integration are used.
In order to capture the behavior of self-expanding NiTi stents, the phenomenological model proposed by Christ et.al. [5] in the context of finite deformations is adopted. The constitutive material parameters are obtained from Christ et.al. [5] which were fit to experimental tests of Helm and Haupt [6,7].

Analysis setup

Bending test is performed considering the proposal by Auricchio et.al. [1,8]. The stent is clamped at one end and displacement of u = 8.5 mm are applied to the control points (Figure 1) at the free end. The resultant reaction forces at the free end are considered as a reference measure to compare the ability of IGA and FEA to efficiently simulate stent bending.

Results

In the current section the results of the stent bending simulation with respect to the different refinements of FEA and IGA models are explained. Initially the convergence of all the IGA and FEA models with respect to the reaction force at the free end against number of degrees of freedom of the stent are analysed (Figure 2). The force-displacement curves for all the iterations of FEA and IGA are shown in Figure 2. The above results clearly show the advantage of

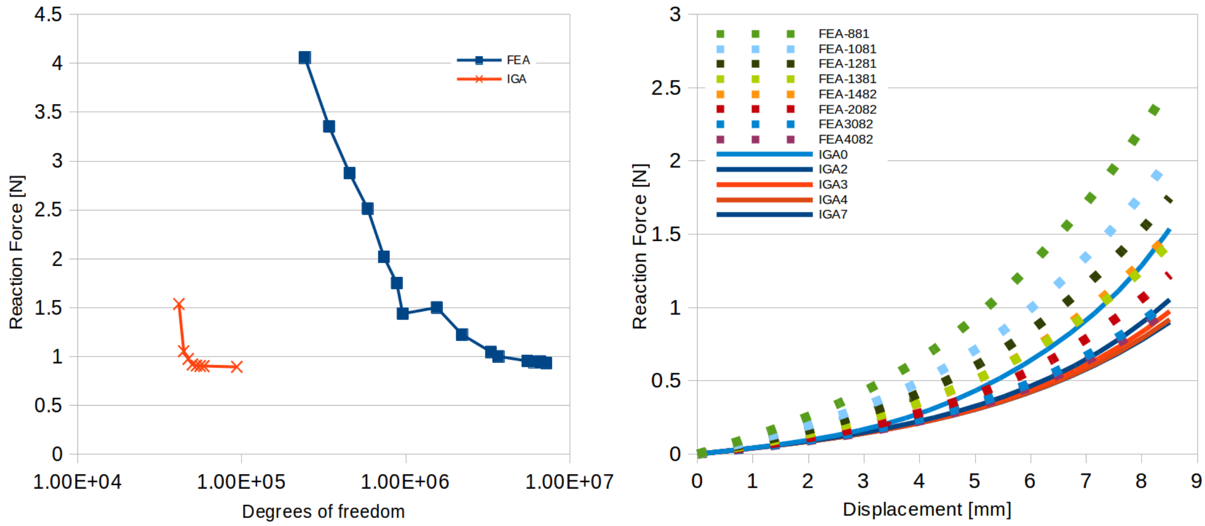

Figure 2. Left: Convergence plots; Right: Reaction force - Displacement plots for FEA & IGA models

IGA over FEA. It can be concluded from convergence plots that IGA converges faster than

FEA even with lesser degrees of freedom of order 10. Similar trend is observed in reaction force-displacement plot. A point to be noted here is that FEA meshes were generated from the finest IGA mesh and were subsequently subjected to h-refinements. From Figure 3 it is evident that FEA and IGA yield similar deformed configurations. The potential of IGA to simulate bending behavior of stent in comparison to FEA simulation in terms of performance with respect to less degrees of freedom is noteworthy.

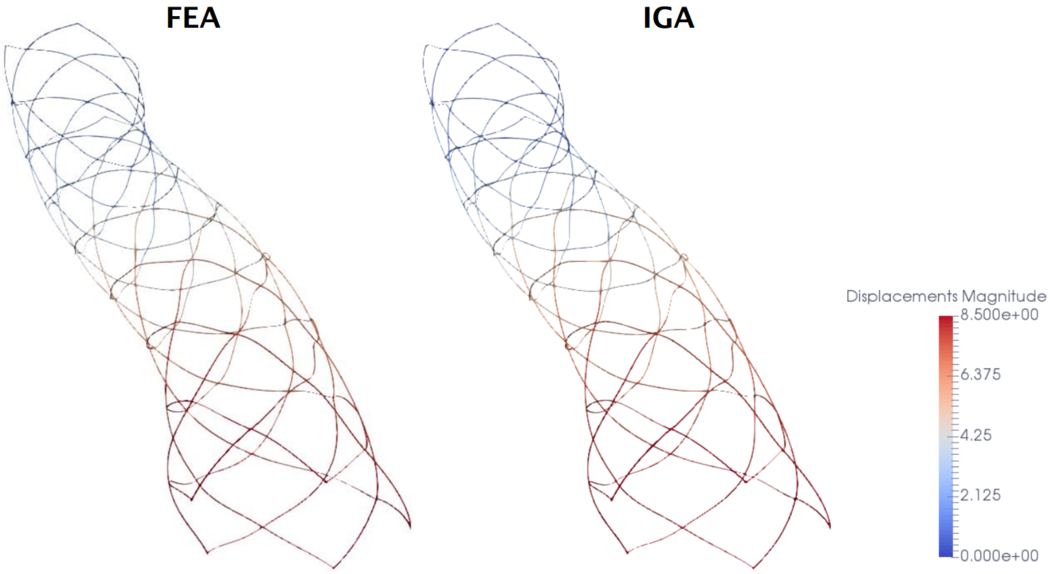

Figure 3. Displacement contour plot for FEA and IGA

Conclusions

In the current study bending simulation of stent is performed and compared betweem IGA and FEA simulations. In IGA the computation domain is accurately represented unlike the requirement of extremely fine meshes for FEA. This study demonstrates the superiority of IGA to produce numerical results better than the traditional FEA with relatively low number of degrees of freedom and lesser computation times. In future work the potential of IGA in realising contact between the stent and artery is planned along with fluid-structure simulations to simulate blood flow through the artery with stent.

Acknowledgements

This work is partly funded by the Federal Ministry of Education and Research within the Forschungscampus STIMULATE under grant number 13GW0095A and by the European Regional Development Fund under the operation number ‚ZS/2016/04/78123‘ as part of the initiative „Sachsen-Anhalt WISSENSCHAFT Schwerpunkte“.

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