13th International Research/Expert Conference
”Trends in the Development of Machinery and Associated Technology”
TMT 2009, Hammamet, Tunisia, 16-21 October 2009

MULTIOBJECTIVE OPTIMIZATION OF INTRACORONARY STENTS BY GENETIC ALGORITHM

Giacomo Sciuto, Roberto Muscia
Dipartimento di Ingegneria Meccanica, Università di Trieste Via Alfonso Valerio n.10 – 34100 Trieste, Italia

ABSTRACT

In this paper an innovative balloon-stent design method, which conjugates 3D finite-element approach, is presented. The method is based on a large strain and large displacement formulation, with multi-objective optimization using Genetic Algorithm (GA). This procedure allows us to automatically obtain new geometries that improve stent performance and to analyze the relationship between geometrical parameters and objectives.

Keywords: stent, design methods, FEM, optimization, stress, genetic algorithm

1. INTRODUCTION

Atherosclerosis is the major cause of death in western countries; this cardiovascular disease consists in the reduction of arterial lumen and in the consequent ischemic pathology (due to the reduction of Oxygen flow downstream the occlusion). Atherosclerosis can be treated using MIS (Minimally Invasive Surgery) like *stenting* technique. Stent is a tubular-wire-mesh-like structure that is designed to act as a durable support structure for the artery; typically it is mounted on the balloon of an angioplasty catheter which is inserted into the site of the blockage, the balloon is inflated and the stent is deployed (expanded) into position. The balloon is then deflated and removed leaving the stent as a permanent implant to keep the artery open, thereby ensuring adequate blood flow to the downstream organs. Stent, according to its main bio-medical functions, should show the following (mechanical) peculiarities: small axial foreshortening (to simplify the positioning near the atheroma), high radio-opacity (to check its position using X-Rays), high corrosion-resistance, high flexibility (to simplify its passage through the arteries during implantation), high fatigue resistance (fatigue is due to cardiac pulsations), uniform deformation (to avoid spot contacts with artery wall) and small blood-flow interaction. In particular, the thickness of the stent should be as smaller as possible to avoid stagnation and restenosis [1-3]. Geometrical characteristics are deeply involved in the stent efficiency and the selection of the correct combination of topological variables to reach the maximum bio-compatibility of he prosthesis is often a very difficult operation. Multi-objective optimization is a very performing way of getting the best combination(s) of geometrical variables taking into account of a large number of aspects of the stent operative life.

2. OPTIMIZATION

The optimization is a powerful device that may be used in mechanical design to obtain a better layout, starting for example from an existing and well-known configuration of the object of study. Generally, optimization procedure can be resumed in 5 steps: i) define a coherent numerical model (it must be sufficiently realistic), ii) choose the objective(s) of optimization, iii) parametrize the geometry, iv) choose a correct mesh, and v) choose the algorithm of optimization. In this paper this approach has been applied to stent design.

Figure 1. Stent Palmaz-Schatz

Table 1. Main characteristics of Palmaz-Schatz stent

Total Length	10mm
Initial/Final Diameter (referred to balloon)	2.9mm/5mm
Thickness	0.05mm
Axial cells	4
Circumferential cells	12
Material	AISI316L

3. NUMERICAL MODEL

The numerical model has been tested on a Palmaz-Schatz stent, by *Johnson&Johnson*, using the FEM code ABAQUS standard. This obsolete kind of stent is presently object of studies by several authors [4-6], because of its geometrical simplicity, easy parametrization, and wide database of its mechanical behaviour. More complicated stent models are also available [7], but if we perform an optimization based on this kind of models the time computation becomes excessive.

Fig. 1 shows an image of the stent that has been considered in this paper, and its main peculiarities can be found in Table 1. By using its symmetry and periodicity planes, it has been possible to limit the study of the whole stent to the study of only one cell (RUC+, Repeated Unit Cell [4,5]). The cell has been constrained imposing a *symmetry constrain* in the node situated in the axial planes (see the Symmetry line in Fig. 2) and *no axial displacement* in the nodes that connect the cell to the rest of the stent (see the Z-disp line in Fig. 2); it is interesting to underline that the distal zone of the prosthesis is free to get deformed both in radial and axial directions. The expansion of the medical prosthesis has been driven modelling the expansion-balloon as a rigid cylindrical shell that increases its diameter from 2.9 mm to 5 mm. The material has been imposed by the user, setting point by point the real stress-strain curve. A large strain and large displacement formulation has been used. The geometry has been meshed using 8064 C3D8R elements disposed on 4 radial layers. Contact surfaces have been characterized using tangential interaction (coefficient of friction $\mu_f = 0.25$) and normal interaction (using a Penalty Method Algorithm) to avoid interpenetration. Results are in agreement with the ones obtained in [4,5] with the same stent, under the same load.

The grid-independence has been checked meshing the model with 32000 C3D8R elements and an error lower than 2% in the stress field has been observed.

3.1. Objectives

Once checked that the model is in agreement with reality, it is necessary to choose which objectives to achieve. Bearing in mind that stents should avoid spot contacts with arteries (due for example to dog-boning), should resist to fatigue stress and should compromise as less as possible the blood flow, the following objectives have been chosen: i) reduce dog-boning, reduce the stress ii) in the central zone and iii) in the distal zone, and iv) reduce the radial thickness.

3.2. Parametrization and mesh

Parametrization and mesh generation have been developed using the open source code *pyFormex 0.7. pyFormex* was (originally) intended by Verhegghe at Ghent University for the automated design of spatial structures and the generation of complex three-dimensional geometries by means of sequences of mathematical transformations; the code is an ongoing and open source project: the program can be used, studied, modified and distributed under the conditions of the GNU General Public License (GPL). The geometry of half a cell has been split

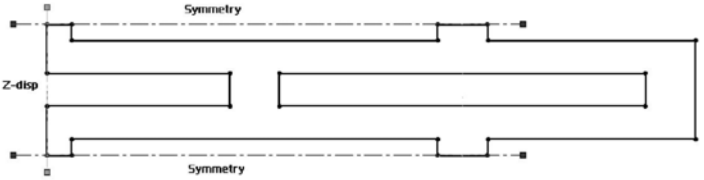

Figure 2. RUC+ and boundary conditions

into 11; lengths and heights of rectangles have been connected using mathematical expressions so that the cell geometry could be defined using 7 parameters which do not affect the topological class of the stent; total length and initial/final diameter of the stent have not been changed during the optimization, because of their main physiological functional role. In Table 2 the variation field and the step of variation for each parameter are reported.

Table 2. Geometrical parameters, field, and step of variation.

Parameter	Field of variation	Step
Number of axial cells (*N_AX*)	2 – 12	1
Number of circumferential cells (*N_CIRC*)	2 – 24	1
Radial Thickness (*S*)	0.04 – 0.2 [mm]	0.01 [mm]
Length of distal circumferential panel (*L_CIRC_DIST*)	0.1 – 0.8 [mm]	0.01 [mm]
Length of distal axial panel (*L_AX_DIST*)	0.01 – 1.5 [mm]	0.01 [mm]
Percentage of stent axial length for the axial panel (*P_AX*)	0.1 – 0.9	0.01
Percentage of stent circumferential length for the axial panel (*P_CIRC*)	0.2 – 0.9	0.01

3.3. Optimization Algorithm

Because of the large number of geometrical variables and the number of objectives, a MOGA (Multi Objective Genetic Algorithm) has been selected as optimization algorithm. A total amount of 560 simulations (10 generation, 56 individuals) has been done automatically for a total time of 14 day-long simulation using a single core Pentium 4 with 1GB of RAM.
The optimization has been brought on inside *modeFrontier4.0* by *E.STE.CO*.

3.4. Results

The optimization has highlighted a set of new designs that improves the original geometrical configuration. In Fig. 3 the solution space using a bubble-chart has been reported: the x axis represents the Von Mises stress [MPa] in the central zone, the y axis represents the Von Mises stress [MPa] in the distal zone, the chromatic scale represents the thickness [mm] of the stent and the diameter of the circles represents the dog-boning (expressed as difference between the final diameter [mm] of the stent in the central zone and final diameter [mm] in distal zone).

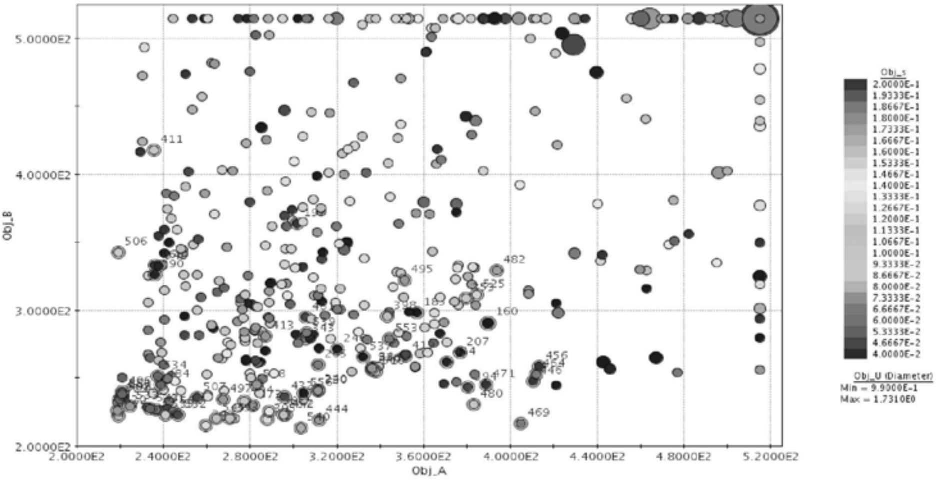

Figure 3. Bubble-chart 4D. In X and Y axis: Von Mises stress [Mpa] inside the stent; chromatic scale: stent thickness; diameter of the circles: dog-boning. The circled individuals: Pareto Frontier.

Observing the chart it is possible to note that: i) the optimization cycle “finds” a lot of bad configurations that collapse, situated among the extremities of the axis (the Von Mises stress reached the maximum value of 515 MPa), ii) in many solutions the maximum stress has been reduced (referring to the starting geometry), iii) *dog-boning* has been set to zero in best configurations, iv) in some cases the radial thickness has reached the value of 0.04 mm. Using the definition of *Pareto Frontier,* a set of 60 individuals that dominate on the other ones has been isolated (red circled in Fig. 3). These configurations have some common peculiarities: i) large number of circumferential cells (18-24) and small number of axial cells (2-4); ii) the parameter *P_AX* reaches the value of 0.74±0.1 mm and *P_CIRC* the value of 0.25±0.08 mm. Comparing these values to the ones of the starting configuration it is possible to note that new best-performance geometries have a lot of circumferential cells (18-24) and the circumferential width of the axial panels is quite small. Referring to the stent radial thickness (*S*), only 6 individuals -in the *Pareto Frontier*- reduce the starting value from 0.05 mm to 0.04 mm. At least, through the *t-Student* parameter it has been possible to extrapolate correlation (direct or inverse) between geometrical variables and objective functions. The obtained results are put into Table 3.

Table 3. Results of statistical analysis through t-student parameter.

Variable	Min. of thickness	Min. of central Von Mises stress	Min. of distal Von Mises stress	Min. of dog-boning
N_AX	DIRECT	-	DIRECT	-
N_CIRC	-	INVERSE	INVERSE	INVERSE
S	-	-	-	-
P_AX	-	-	INVERSE	-
P_CIRC	DIRECT	-	-	-
L_CIRC_DIST	-	-	-	-
L_AX_DIST	-	-	-	-

4. CONCLUSIONS

In this work, a new approach to stent design has been illustrated: starting from the performances of an existing stent (Palmaz-Schatz, *Johnson&Johnson)* computed using a finite element analysis brought on using ABAQUSstandard, 4 amendable features in stent performances have been detected. The geometry of the stent has been parametrized using 7 geometrical variables and using optimization 60 dominant individuals (among 560 individuals computed) have been found. These new 60 configurations have some features in common (many circumferential cells, few axial cells, small dog-boning and longitudinal panels with small circumferential width). The statistical analysis using the *t-Student* parameter has permitted explore relationships (if any) between geometrical variables and objectives. Furthermore, this new approach to design allows us to link several fields in stent studies. For example, adding CFD simulations (with CFD objectives) in the same optimization cycle it would be possible to find a set of multi-physic optimized individuals.

5. REFERENCES

[1] Pache J., et. al.: Drug-eluting stents compared with thin-strut bare stents for the reduction of restenosis: a prospective randomized trial, European Heart Journal, (26) 1262-1268, 2005.

[2] Pache J., et. al.: Intracoronary Stenting and Angiographic Results: Strut Thickness Effect on Restenosis Outcome (ISAR-STEREO-2) Trial, J Am Coll Cardiol (41) 1283-1288, 2003.

[3] Briguori C., et. al.: In-stent restenosis in small coronary arteries: Impact of strut thickness, J Am Coll Cardiol (40) 403-409, 2002.

[4] Jua F., Xia Z., Sasaki K.: On the finite element modelling of balloon-expandable stents, Journal of the Mechanical Behaviour of Biomechanical Materials, 86-95, 2008.

[5] Chua S.N., MacDonald B.J.: Finite element simulation of stent and balloon interaction, Journal of Materials Process Technology, 591-597, 2003.

[6] Sciuto G.: Analisi strutturale ed ottimizzazione preliminare di una classe di stent coronarici, Master Thesis, Università di Trieste, 2008.

[7] De Beule M.: Finite Element Stent Design, PhD Thesis, Ghent University, 2008.