ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB379

TOPOLOGICAL OPTIMIZATION ON SRF CAVITIES FOR NUCLEAR AND HIGH ENERGY PHYSICS

H. M. Gassot*, University Paris-Saclay, CNRS/IN2P3/IJCLab, Orsay, France

Abstract

Topological optimization has been developed since more than thirty year. The progress of additive manufacturing boosts the development in topological optimization since the design can be completely innovated and realized by 3D printing. The potential for cost reductions thanks to weight minimization give an interesting perspective for small production of niobium superconducting radio-frequency cavities, commonly used in accelerators. The traditional manufacturing technologies of cavity are based on multi-stage processes while additive manufacturing technologies can built fully functional parts in a single operation. In the frame of recent project of demonstrator of energy recovery linacs (ERLs) at Orsay, it is particularly important to know the potential of additive manufacturing for SRF cavities. The focus of this work is to built a preliminary perception of topology optimization for some basic problems of superconducting cavities mechanical design. The purpose of this work is limited as simulation models.

INTRODUCTION

The research and innovation become the locomotive of the development of accelerator [1]. Within the master project of 3D metal printing supported by in2p3 [2], the studies by topology optimization for the accelerator components have been associated, IJCLab is involved in ”Accelerator innovation Pilot Project”, within this project, the niobium cavity's additive manufacturing is started at CERN [3]. The high potential exists in accelerator technologies research and development as regard of the 3D printing with topology optimization. For example, a recurrent question for superconducting cavities design is how to make the compromise between the cavities stiffness and the cavities cost including niobium consumption and cavities manufacturing which are onerous. It is a typical stiffness optimal problem for topology optimization using lightweighting strategies.

FROM PARAMETRIC OPTIMIZATION TO TOPOLOGY OPTIMIZATION

Despite decades of research, some fundamental questions still exist regarding the Lorentz forces on the high gradient superconducting cavities deformation [4]. Using the parametric optimization, we make the choice of the model based on the given parameters and their value range. In the paste, we have made parametric optimization for cavity wall thickness and stiffeners positions [5], we have to achieve each simulations in a functionally situation with a set of design parameters like cavity wall thickness, stiffeners positions and analysis the simulation result after each simulation in order to find the optimal stiffener position. Even boundary conditions and material parameters are considered to be classic, maintaining the mechanical radiation pressure make this complex loads depending topology optimization, it is not always possible by commercial code. As a consequence, an investigation on a non commercial code is dedicated. In a non commercial finite element code Cast3M [6], a new procedure has been included since 2018 [7]. It is based on SIMP (Solid Isotropic Material with Penalization) method. The SIMP method associate each finite element a density function $\rho(x)$ whose values varies between 0 and 1: 0 as void 1 as material. Historically, Sigmund has find a practical way in numerical solution for topological optimization [8]. In practice, the criterion on density for the objective function which minimize the compliance under mechanical constraint determinate an optimized material distribution according to this criterion. Thinks to elimination of all elements with density less than the criterion, the time of resolution is reduced. An intuitive topology optimization is realized for a bridge. The optimized mass distribution is illustrated with a volumetric density of 0,3, Fig. 1.

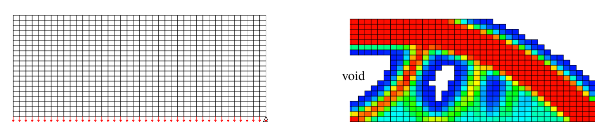

Figure 1: Finite element distribution and optimal material distribution.

TOPOLOGY OPTIMIZATION FOR A MULTICELL CAVITY

As particularity, the high gradient superconducting cavity like ILC 9-cells cavities in pulsed mode necessitates mechanical optimization under a specific charge constraint: the radiation pressure. The Lorentz radiation pressure are not uniformly distributed on the cavity inner wall, Fig. 2. In usual parametrical optimizations, the given parameter for mechanical stabilities is stiffening rings position and its value range. In this work, we use topology optimization. At past, we have studied an alternative stiffening method using thermal spray technique for a multicell elliptical cavity [9]. The depot schema is limited by the manufacturing constraints which make this alternative stiffening solution very heavy. In this work, we realize the topological optimization lightweighting simulations with same mechanical constraints. Started from the optimized stiffening schema of thermal spray solution, Fig. 3 left side, progressively, as the mass density decrease, the topology optimization give

* gassot@ijclab.in2p3.fr

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB379

solutions, Fig. 3 right side, to Fig. 4. Finally as we approach to a certain mass density, we recognize a stiffening schema close to stiffening rings optimized by classic parametric solution. This design could be realized by one step additive manufacturing. At present state of the art, the design issues from topology optimization for additive manufacturing becomes vital. Even some thermal spray process can be transformed to additive manufacturing [10], we hope that the topology optimization which is very interesting for material save and optimization times reduction become the gaps between the design and additive manufacturing for future cavities fabrication.

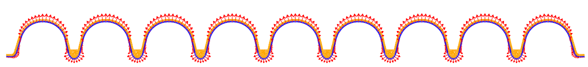

Figure 2: Lorentz radiation pressure on 9 cells cavities.

The modeling should take into account the fact that a superconducting cavity need a minimal thickness of niobium wall for superconducting proprieties. While the outside wall can been made of other material.

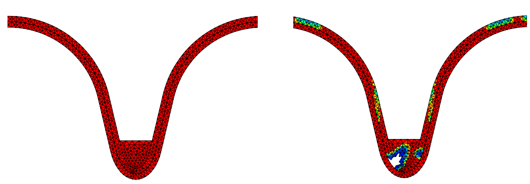

Figure 3: Topological lightweighting optimization.

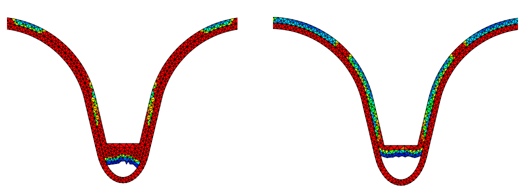

Figure 4: Mass density, left: 0.87, right: 0.69.

Comparing to wedded stiffening system, topology optimizations show the possibility to have a more advantageous one step solution from 3D metal printing technology.

802 MHz ERLS CAVITY STUDIES

Some prototype cavities resonating at 802 MHz were built at Jefferson Laboratory (JLab) in the frame of a collaboration with CERN for LHeC (Large Hadron electron Collider) and FCC (Future Circular Collider) initiatives [11]. Based on the geometry of 802 MHz single-cell prototype, topology optimization is performed under inner pressure load in the vertical position, Fig. 5 left. The mechanical design criterion is to find the minimum cavity wall thickness in order to minimize niobium consumption in respecting maximum elastic stress limits. The classical parametric simulations of mechanical deformations are illustrated, Fig. 5 right. Topology optimizations have been performed with the same constraints with different cavity wall thicknesses.

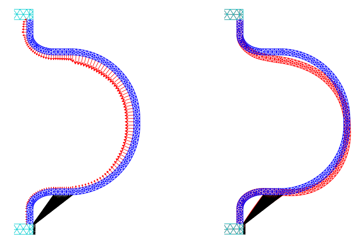

Figure 5: Pressure load and mechanical deformation.

A series of topology optimizations design solutions with stiffener are illustrated at Figs. 6 and 7 for different thickness. It show that the cavities wall could have a more or less regular thickness for a same objective. These kind of organic shape proposed by topology optimization is difficult to realize in the past, while now the progress in additive manufacturing make it possible.

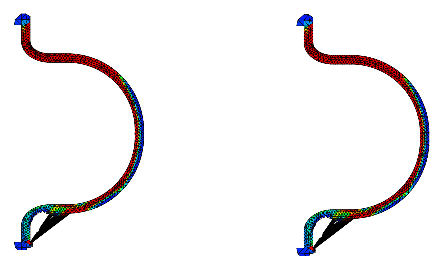

Figure 6: Topological lightweighting optimization.

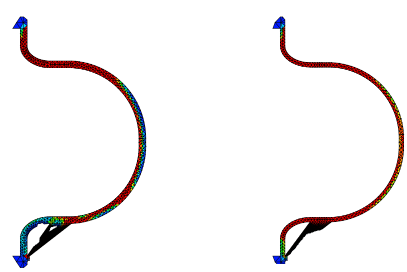

Figure 7: Wall thickness, left: 3mm, right: 2mm.

STATE OF ART OF NIOBIUM BASED 3D PRINTING

However, Niobium-based 3D printing is still challenging since it is still a confidential research subject. Other investigations are necessary to improve niobium 3D additive manufacturing technology for cavities performances.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB379

Concerning the niobium-based additive manufacturing, two powder bed fusion technologies to process such as Electron beam melting (EBM) and selective laser melting (SLM) were evaluated. On one hand, the Jefferson Science Associates in cooperation RadiaBeam technologies held the first investigation on niobium densification by Electron Beam Melting metallic additive manufacturing (EBM) [12]: a single cell 3.8 GHz prototype cavity with stiffering support was fabricated and tested, but the performance of the prototype is under-expected; on the other hand, CERN processed different samples and a 6 GHz niobium prototype cavity in the Selective Laser Melting (SLM) Solutions [2], the problem is the poor RRR (Residual of Resistance Ratio). From literature, some refractory metals have the metallurgical properties close to niobium, especially the high melting temperature, Table 1.

Table 1: Some Metallurgical Properties

Metal	Melting point (°C)	Density (g.cm^{-3} at 20°C)
Ti	1668	4,51
Zr	1855	6,49
Nb	2477	8,57
Ta	3017	16,6
W	3420	19,3

The perspective of possible synergy between some well know experiences on refractory metals and niobium additive manufacturing seems to an interesting track [13] Since, works have been done on niobium purity improvement, another track seems to be interesting which consists on the good distribution of grain size of niobium powder: it is well known that the thermal conductivity of niobium at low temperature increase with grain size, Fig. 8, which is distributed from 50 μm to 2 000 μm [14].

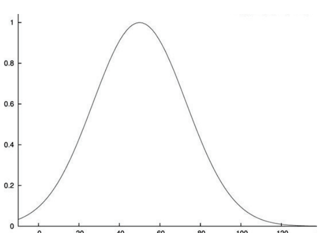

Figure 8: Grain size (μm) of niobium powder.

CONCLUSION AND PERSPECTIVES

The purpose of this work is limited as simulation models. In terms of structure design, the topology optimization change the way of simulation, save times and limits iterations. Also, it create a imagined beforehand product without prior-experiences. The passe between the design and the fabrication is almost direct, the choice of accessible shapes become vast. The results of topological optimization illustrated in this paper show an interesting one passe possibility to manufacture a multicell cavity with stiffening system, it will be un improvement because the classical manufacturing include the welding which degrade the mechanical properties.

The perspectives of an one-step processing route is interesting to reduce the cost of a small mass production. However, the niobium based 3D printing is still challenging since there are still many technical barriers for superconducting cavities use. Recently, a demonstrator for ERLs using superconducting cavities is in development. It could be encouraging for niobium-based additive manufacturing and topological optimization of niobium cavities. In other cases, this technology optimization could be a interesting for power coupler system and/or cavities cooling system.

REFERENCES

[1] Accelerator Innovation, https://aries.web.cern.ch/accelerator-innovation

[2] N. Delerue *et al.*, "Prospects of Additive Manufacturing for Accelerators", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 4118–4120. doi:10.18429/JACoW-IPAC2019-THPTS008

[3] R. Gerard, "Fabrication additive au CERN", https://indico.lal.in2p3.fr/event/4990

[4] H. Gassot, "Mechanical Stability of the RF Superconducting Cavities", in *Proc. 8th European Particle Accelerator Conf. (EPAC'02)*, Paris, France, Jun. 2002, paper THPDO039, pp. 2235–2237.

[5] S. Bousson, M. Fouaidy, H. Gassot, T. Junquera, J. Lesrel, J.-L Borne, *et al.*, "An Alternative Scheme for Stiffening SRF Cavities by Plasma Spraying", in *Proc. 18th Particle Accelerator Conf. (PAC'99)*, New York, NY, USA, Mar. 1999, paper MOP109, pp. 919–921.

[6] Cast3m, CEA/DEN, France.

[7] G. Le Guilliec, "Procedure d'optimisation topologique TOPOPTIM", 14th Colloque National en Calcul des Structures, May 2019, Giens, France.

[8] O. Sigmund, "A 99 line topology optimization code written in Matlab", *Structural and Multidisciplinary Optimization*, vol. 21, pp. 120–127, 2001.

[9] Huimin Wang-Gassot, "Etudes de la stabilité mécanique des cavités supraconductrices et de la méthode de rigidification par projection thermique de cuivre", Ph.D. thesis, University Paris-Saclay, Orsay, France, 2001.

[10] Hongjian Wu, "Process Modeling and Planning for Robotic Cold Spray Based Additive Manufacturing", Ph.D. thesis, University Technologique Belfort Montbéliard, Sévenans, France, 2020.

[11] FCC, http://cern.ch/fcc

[12] P. Frigola *et al.*, "Advance Additive Manufacturing Method for SRF Cavities of Various Geometries", in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THPB042, pp. 1181–1184.

[13] F. Lomello, private communication.

[14] H.M. Wen *et al.*, "Thermal, electrical properties and microstructure of high purity niobium for high gradient superconducting cavities", ICEC 20, Beijing, China.