Dedicated to innovation in aerospace

NLR-TP-2020-285 | August 2020

Additive Manufacturing Design in Aerospace: Topology Optimization and Virtual Manufacturing

CUSTOMER: Netherlands Aerospace Centre

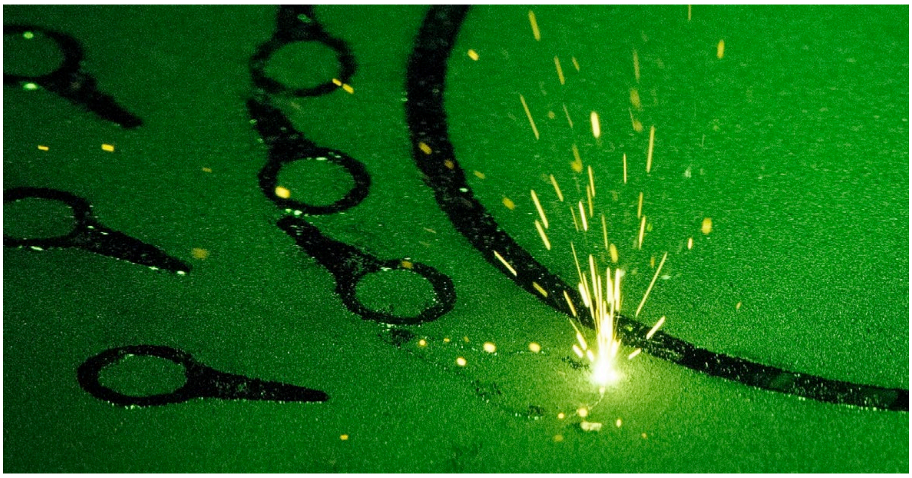
NLR – Royal Netherlands Aerospace Centre

EXECUTIVE SUMMARY

UNCLASSIFIED

Dedicated to innovation in aerospace

Additive Manufacturing Design in Aerospace: Topology Optimization and Virtual Manufacturing



Problem area

The spectacular success and the fast development of topology optimization and additive manufacturing techniques are intrinsically related to each other. Topology optimization is a powerful and cost-effective tool to create innovative concepts in engineering. While most of the organic designs from topology optimization are generally too complex for classic manufacturing techniques, the emergence of additive manufacturing technologies have finally made it possible to fabricate these high performance and efficient designs, which are of particular interest for aerospace applications.

Description of work

In this paper, implementations of advanced topology optimization methods are presented. First, the combined application of structural and fluid topology optimization design for laser powder bed fusion (L-PBF) process has been investigated. Next to this, design aspects regarding the support structures needed for metal L-PBF printing are incorporated. Then an approach to incorporate an overhang manufacturing constraint within topology optimization is described.

REPORT NUMBER
NLR-TP-2020-285

AUTHOR(S)
L. Paletti
W.M. van den Brink
R. Bruins
E. van de Ven
M. Bosman

REPORT CLASSIFICATION
UNCLASSIFIED

DATE
August 2020

KNOWLEDGE AREA(S)
Computational Mechanics and Simulation Technology
Aerospace Collaborative Engineering and Design
Structures and Manufacturing Technology

DESCRIPTOR(S)
Topology Optimization
Additive Manufacturing
Metal
Virtual Manufacturing
Fluid Structural optimization

Results and conclusions

Two practical advancements in the field of topology optimization are presented. The first describes the implementation of a fluid-structural topology optimization approach which combines a minimization of flow pressure drop and a minimization of the wall thickness for a hydraulic manifold component. The second presents the implementation of overhang constraint in the topology optimization method.

Applicability

The methods described can be applied in all projects concerning the design of parts for metal additive manufacturing. Results obtained can be directly applied to real-life, industrial cases.

NLR
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113
e) info@nlr.nl i) www.nlr.nl

Dedicated to innovation in aerospace

NLR-TP-2020-285 | August 2020

Additive Manufacturing Design in Aerospace: Topology Optimization and Virtual Manufacturing

CUSTOMER: Netherlands Aerospace Centre

AUTHOR(S):

L. Paletti	NLR
W.M. van den Brink	NLR
R. Bruins	NLR
E. van de Ven	Technical University Delft
M. Bosman	GKN Fokker

NLR – Royal Netherlands Aerospace Centre

CUSTOMER	Netherlands Aerospace Centre
CONTRACT NUMBER	---
OWNER	NLR
DIVISION NLR	Aerospace Vehicles
DISTRIBUTION	Unlimited
CLASSIFICATION OF TITLE	UNCLASSIFIED

APPROVED BY:		Date
AUTHOR	L. Paletti	24-08-2020
REVIEWER	A.J. de Wit	24-08-2020
MANAGING DEPARTMENT	A.A. ten Dam	25-08-2020

Summary

The spectacular success and the fast development of topology optimization and additive manufacturing techniques are intrinsically related to each other. Topology optimization is a powerful and cost-effective tool to create innovative concepts in engineering. While most of the organic designs from topology optimization are generally too complex for classic manufacturing techniques, the emergence of additive manufacturing technologies have finally made it possible to fabricate these high performance and efficient designs, which are of particular interest for aerospace applications. In this paper, implementations of advanced topology optimization methods are presented. First, the combined application of structural and fluid topology optimization design for laser powder bed fusion (L-PBF) process has been investigated. The combination of fluid optimization and structural optimization is demonstrated by a novel approach combining OpenFOAM and Abaqus. Next to this, design aspects regarding the support structures needed for metal L-PBF printing are incorporated. Then an approach to incorporate an overhang manufacturing constraint within topology optimization is described. Applying this method allows for the reduction, or even the elimination, of support structures needed during the print. In this way, the amount of post-processing needed for the removal of supports is reduced, together with the amount of material used, leading to cost savings.

Contents

Abbreviations

ACRONYM	DESCRIPTION
AM	Additive Manufacturing
DNW	German-Dutch Wind Tunnels
L-PBF	Laser Powder Bed Fusion
NLR	Royal Netherlands Aerospace Centre
SIMP	Solid Isotropic Material with Penalization
STL	Stereolithography

1 Introduction

Topology optimization is defined as a numerical method that aims at optimizing matter distribution within a defined design space, under a set of boundary conditions and a set of loads and constraints [1]. In more simple terms, topology optimization tries to find the “best” shape for a component, a shape which can minimize stress and strain hot spots in response to specified conditions, while, at the same time, minimizing weight. Topology optimization is only one of various optimization methods for structural designs developed and employed in engineering applications; its successful application in the aerospace industry is linked to the effectiveness of topology optimization to generate lightweight and high performance design. Topology optimization has been investigated since the beginning of the 20th century, but its modern applications, in combination with finite element methods, was established in the 1980s, with the development of commercial software [1]. The introduction of topology optimization algorithms offers an alternative to a more traditional approach to engineering design, consisting of an initial design (usually developed based on previous engineering experience), which is subsequently iteratively modified using analytical calculation methods, until a final design meets all requirements in terms of loads and constraints. By applying topology optimization algorithms, the desired design is generated starting from a neutral design space, without the influence of existing design, and it can automatically satisfy all given loads requirements, without the need of manual modifications after the optimization process. Topology optimization can be applied to a broad variety of problems, ranging from structural mechanics to multi-physics domain such as fluid flow, thermal-fluid interaction, aero-elastics and acoustic-structure problems.

The complex shapes obtained by applying topology optimization may include organic-looking curvatures or convoluted inner cavities; such shapes have proved difficult to realize by means of conventional manufacturing processes. Additive manufacturing (AM) processes can be used to fabricate the topology optimized geometry (almost) directly. In fact, it is important to remark that specific AM process-related constraints are not integrated in the mathematical optimization algorithms. Therefore, topology optimization results must be customized for AM, to ensure that the manufacturing constraints, such as minimum feature size, support structures and overhang constraints, are taken into account. Incorporating all those constraints manually is a time-consuming task and reduces the optimality of the design. A possible solution is to incorporate manufacturing constraints [2], together with other requirements, such as structural integrity requirements [3, 4, 5], as constraints directly in the topology optimization process.

This paper provides an overview of the approaches to fluid-structure topology optimization and to topology optimization with manufacturing constraints developed at NLR.

2 Structural-Fluid Topology Optimization

2.1 Structural Topology Optimization

Topology optimization applied to structural problems is so far, the most applied in real cases. Its most common objective is to reduce the compliance of the part, which translates in increasing its stiffness. The most used methods for structural topology optimization are the density-based method and the Solid Isotropic Material with Penalization (SIMP) method. Such methods work on a domain which gets subdivided in smaller elements; each element is characterized by a density value, which becomes the design variable in the structural optimization. This density value is iteratively recalculated by the specific optimization algorithm, based on the given objective function and constraints. The algorithm establishes, based on the objective function and constraints, if an element needs to be void or contain material.

2.2 Fluid Topology Optimization

The topology optimization of fluid flow is conceptually similar to the density based structural topology optimization: instead of the governing stiffness equations, the Navier-Stokes equations are used. It is only since 2003 that topology optimization for fluid flow started to get traction [6]. While in structural topology optimization the design variable is usually the density of each element, in the case of fluid flow optimization an artificial porosity term is introduced, which assumes a similar role as the density variable. The approach assumes initially the design domain to be fully fluid (with a porosity value of 0). Then a local criterion is applied, to verify if each element is productive or counter-productive with regard to the objective function. This local criterion is typically realized via finite element porosity with the use of Darcy's law. As an element becomes counterproductive, its porosity is updated up to the value of 1, which acts as a solid. The approach described in [6] assumes a Stokes flow, at very low Reynolds numbers ($Re < 1$) and without accounting for the inertia effect of the fluid. Those assumptions are realistic only for very viscous fluids, like oil or microfluidic applications. The approach has been later extended to moderate Reynolds numbers with inertia effects [7] and to unsteady flow [8].

2.3 Fluid-Structural Topology Optimization

While structural topology optimization is very mature and various approaches have already been successfully implemented in several commercial software (for example, Abaqus Tosca), the commercial software approaches of fluid topology optimization still face several limitations, as they are computationally expensive. Therefore a continuous adjoint method is implemented in OpenFOAM to reduce the number of equations to be solved, which would be otherwise proportional to the number of elements in the model. Also additional constraints need to be implemented, which can ensure a stable convergence towards a closed and manufacturable geometry: a standard volume constraint and a perimeter constraint. The perimeter is a quantity directly proportional to the weight of a hydraulic manifold. In two dimensions the perimeter will be a length, and in three dimensions it will be an area. By penalising the perimeter, the constraint will reduce its length or area (depending if the problem is in two or three dimensions), directly reducing the weight of the manifold. Once the optimization is concluded, the resulting internal pressure distribution inside the fluid domain is extracted and imported in Abaqus Tosca, as input for the structural topology optimization. In the structural optimization, the local wall thickness around this fluid domain can be optimized. Instead of assuming a constant wall thickness, material can be added or removed as necessary, based on the internal pressure field. Details of the derivation of this combined fluid-structural optimization approach are given in [9] and an example of its application is given in the next section.

2.4 GKN Fokker Hydraulic Block Manifold

Several applications can benefit from the combined implementations of fluid topology optimization and structural topology optimization, for example hydraulic manifolds. A demonstrator for fluid-structural topology optimization has been supplied by GKN Fokker. A titanium Ti-6Al4V hydraulic connection block manifold in several versions (with four, six and eight connections) has been considered. Currently, this component is manufactured using milling and it presents sharp corners in the internal channel, where debris and dirt can collect. Therefore, redesigning the internal channels is necessary to avoid loss of hydraulic performances. At the same time, the internal channels can be optimized by taking advantage of fluid topology optimization. By combining the fluid optimization with the structural optimization, it could be possible to also reduce the weight of the component, while still satisfying the requirements in terms of applied loads (no structural failure below a pressure of 620 bar in the channels) and possibly minimizing the amount of supports needed.

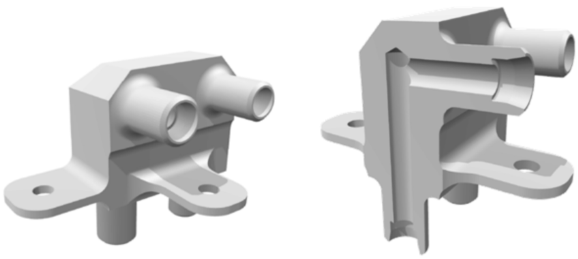


Figure 1: Example of one of the original designs for the hydraulic block manifold

The redesign is performed in two steps. In the first step of the design, the fluid optimization is performed. The resulting channel shape is then extracted and used for the second step, during which the internal pressure is applied in the channel and structural analyses and topology optimization are performed.

2.4.1 Fluid topology optimization

For the fluid topology optimization the OpenFOAM software is used. This allows to calculate the flow through the channel and to reduce the pressure drop in the flow. The objective function is minimal pressure drop or energy dissipation in the flow. The constraints are related to the reduction of the volume and perimeter of the channel. The design space is the entire reference design (Figure 1). Assuming laminar parameters, the flow calculated from the fluid optimization is stable, an important condition for the determination of the sensitivities and the convergence of the optimization. A smooth flow between inlet and outlet can be observed, with a reduction of velocity in the channel. This allows avoiding including turbulent effects, which could result in oddly shaped channels where dirt could collect. The energy loss in the flow is calculated and presented in Table 1 for all designs of the hydraulic block manifold.

Table 1: Comparison of the flow energy loss values for a selection of the original and optimized designs

Table No. 1

	Design 1	Design 2
Reference energy loss [J]	1.27e-7	1.25e-7
Optimized energy loss [J]	1.91e-8	1.78e-8

From these OpenFOAM flow calculations the geometry of the flow channels could be extracted and translated to STL files. Further smoothing of the flow channels is necessary before using the geometry for the structural topology optimization (Figure 2).

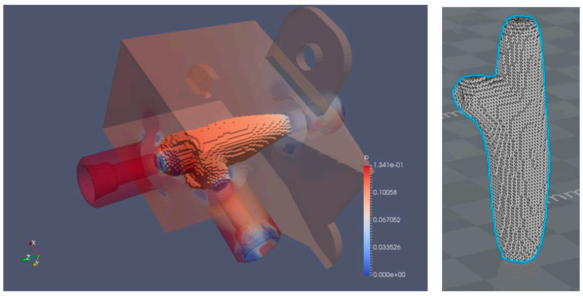


Figure 2: Results from the OpenFOAM fluid optimization and the extracted shape of the internal channel

2.4.2 Structural topology optimization

The structural topology optimization is performed in Abaqus Tosca software. The reference design is used as design space and the smoothened channel geometry is translated into a cavity in the design space (Figure 3). The pressure is then applied on the cavity/channel.

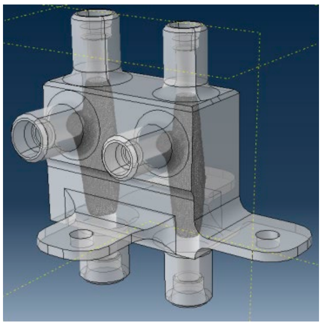


Figure 3: Structural topology optimization design space with optimized internal channel as cavity

The structural topology optimization is performed by assuming the connectors and the mounting brackets with the holes are maintained and in some areas the design space is increased. A stiffness optimization (strain energy objective) is performed with a defined volume constraint. The resulting optimized designs show a quite consistent wall thickness of approximatively 3 to 4 mm, and a weight reduction of around 40% to 50% compared to the original geometry.

2.4.3 Final design and manufacturing considerations

The final geometry is shown in Figure 4 (left). After finalizing the print geometry, the data are transferred to Materialise Magics software to prepare for printing. Several orientations of the part are evaluated (Figure 4, right). By changing the orientations of the parts the amount of supports needed can be minimized. This is most important in the channels since supports at those locations are difficult to remove. Still a considerable amount of supports is necessary, in particular due to overhang angles.

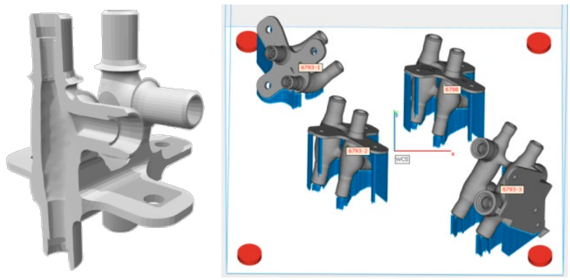


Figure 4: Left: optimized result after flow optimization and structural optimization; Right: evaluation of printing orientation and supports

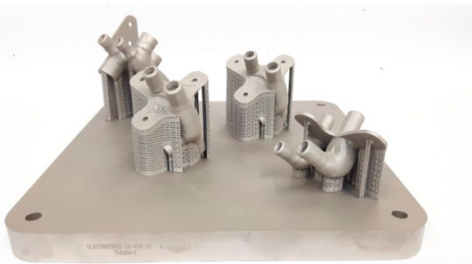


Figure 5: Printed hydraulic block manifolds

3 Manufacturing Constraints in Topology Optimization

As seen in the hydraulic manifold example, minimizing the amount of support structures needed during printing is an important consideration for the definition of a design for AM. In the case of a manifold, the attention towards the supports is linked to the difficulty of removing possible internal supports. In general, the support structures are a by-product of L-PBF process: they are necessary to avoid collapse of the structure and to dissipate the heat embedded in the structure during manufacturing, but they represent an additional cost in terms of material and post-processing. A current trend in design for AM is to incorporate constraints in topology optimization methods for reducing, or completely eliminating, supports [10]. One approach to minimize the use of support structures involves a so-called "overhang constraint", which can be explained as the ideal solution of designing parts for which no support is necessary. By design, this can be achieved by ensuring that the angles between overhang sections of the AM component and the base plate are above a given critical value (usually based on experience and dependent on the process and the material used). Another approach to implement such "overhang constraint", or overhang control, is to incorporate it in the topology optimization process. Research in this direction has been carried out at NLR and the developed approach is summarized here for an application to a two dimensional problem.

3.1 Overhang control filter

In [11] a method to implement overhang control based on a front advancement filter is presented. During the topology optimization loop, such filter suppresses regions which cannot be manufactured without the need for supports. The method proposed meets a number of practical requirements:

- the critical overhang angle is adjustable, to account for different choices of material and process;
- the overhang restriction works on unstructured meshes, to account for realistic design domains containing curvatures;
- the overhang restriction and adjoint sensitivities are computationally inexpensive;
- the overhang restriction is independent of the specific optimization problem considered.

A flowchart of the method is presented in Figure 6. The overhang control filter is applied on the filtered density field. The front propagation is coupled with the topology optimization by scaling its propagation speed with the density field: the front propagates at regular speed through dense regions, but slows down in void regions. To model this, a scaling field, function of the filtered density field and of the propagation speed, is calculated in the pre-processing step.

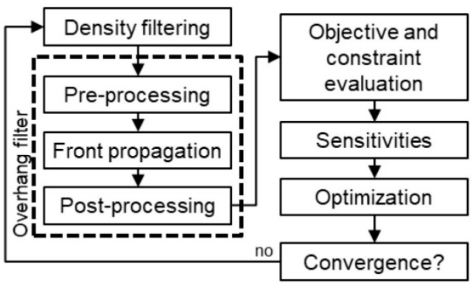
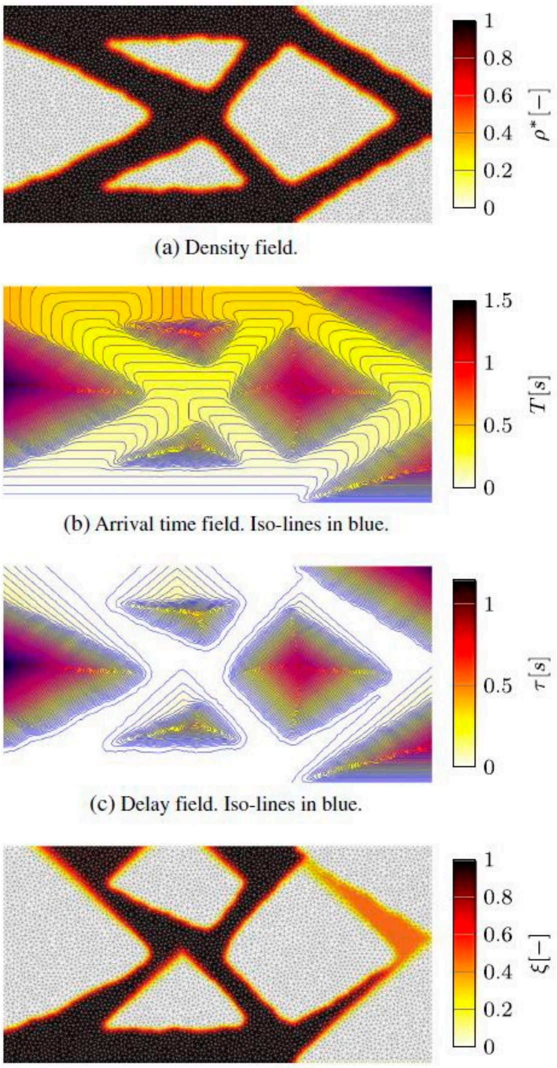


Figure 6: Flowchart of the topology optimization procedure with overhang filter

Next, the arrival time of the propagating field is determined and, from this, in the post-processing step, the delay of the propagated front with respect to a reference arrival time field (which is the arrival timeif the part would have been completely printable). Finally, the printable density field, function of the delay function, is obtained, and used for the evaluation of the objective and constraints. The regions with no delay are considered printable, and are assigned a unitary density, while regions with increasing delay are assigned a reduced density, ranging between 0 and 1, and how aggressively overhanging regions are suppressed is controlled by an additional parameter.
Details of the derivation and application of such filter for a two dimensional case are given in [11] and an extension for a three dimensional case is given in [12].

3.2 Application to a 2D problem

A typical material distribution occurring during a topology optimization on an unstructured mesh is shown in Figure 7a.



(a) Density field.

(b) Arrival time field. Iso-lines in blue.

(c) Delay field. Iso-lines in blue.

(d) Printable density field.

Figure 7: The process of obtaining the printable densities (d) for a given topology (a), by performing a front propagation (b) and evaluating the delay field (c)

In such problem, the overhang control filter is applied to the material distribution as follows:

- Given a specified overhang angle, the front propagation is determined, resulting in the arrival time field (Figure 7b). In this example, due to the numerical implementation of the front propagation, rounding of the corners of the arrival time field iso-contour lines occurs. The rounding causes a small overestimation of the critical overhang angle, but it can be reduced easily by refining the mesh;
- From the arrival time field, the delay field is calculated (Figure 7c). In this field the non-overhanging area with no delay is already clearly visible;
- The printable densities are then evaluated, resulting in the actual material distribution (Figure 7d) Compared to the original density field, the overhanging regions are removed, and the top-right member that is close to printable has intermediate densities.

However, like every nonconvex topology optimization problem, the optimization with overhang filter is susceptible to converge to inferior local optima.

This means that material is added which does not contribute to the stiffness of the structure. A common method to avoid inferior local optima is to apply continuation which activates the overhang constraint in a gradual manner. First, the unconstrained problem is solved for a number of iterations, then the overhang control is added gradually over a subsequent number of iterations and finally the optimisation is completed with the constrained problem. This allows reducing the value of the initial density field and eventually it results in a higher objective function, for the same value of initial density field.

More examples of the application of this approach to two dimensional problems are given in [11]. An example of the application of the overhang control filter to a 3D problem is given in [13].

4 Conclusions and Future Work

In this paper two practical advancements in the field of topology optimization are presented. The first describes the implementation of a fluid-structural topology optimization approach which combines a minimization of flow pressure drop and a minimization of the wall thickness for a hydraulic manifold component. The second presents the implementation of overhang constraint in the topology optimization method. Results obtained in both cases can be directly applied to real-life, industrial cases.

While future work regarding the fluid-structural topology optimization is orientated towards implementing the method in commercial software, the future work regarding the overhang control shall focus on challenges which can arise with industrial applications. The implementation of overhang control filter could result in additional weight of the component when compared to the weight optimized solution. Therefore a trade-off study shall be performed between the cost of the added weight (in terms of additional material and/or lower efficiency) and the cost of supports removal and/or changes in design (when supports are needed, but impossible to remove). In fact, for some applications, the presence of supports is acceptable and the overhang control should not suppress them, and only be enforced where the supports cannot be removed, for example in internal regions.

5 Acknowledgements

The work on topology optimization was performed within the Private Public Cooperation project “Additive Metal Manufacturing Phase I” and will be continued in the Phase II follow up project.

6 Literature

[1] G.I.N. Rozvany, “A critical review of established methods of structural topology optimization”, Structural and Multidisciplinary Optimization, vol. 37, 2009, pp. 217-237.

[2] A.T. Gaynor, J.K. Guest, “Topology Optimization for Additive Manufacturing: Considering Maximum Overhang Constraint”, 15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 2014.

[3] H. Svard, “Topology Optimization of Fatigue-Constrained Structures”, Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden, 2015.

[4] E. Holmberg, “Topology optimization considering stress, fatigue and load uncertainties”, PhD Dissertation, Linkoping University, Sweden, 2015

[5] J. Oest, “Structural Optimizations with fatigue Constraints”, PhD Thesis, Aalborg University, 2017.

[6] T. Borrvall, J. Petersson, “Topology optimization of fluids in Stokes flow”, International Journal for Numerical Methods in Fluids, 2002.

[7] A. Gersborg-Hansen, O. Sigmund, R.B. Haber, “Topology optimization of channel flow problems”, Structural and Multidisciplinary Optimization, vol. 30, 2005, pp. 181-192.

[8] S. Kreissl, “Topology Optimization of Flow Problems Modeled by the Incompressible Navier-Stokes Equations”, PhD thesis, Technische Universitat Munchen, Germany, 2007.

[9] J.M. Verboom, “Design and Additive Manufacturing of Manifolds for Navier-Stokes Flow: A Topology Optimisation Approach”, Master Thesis, Technical University of Delft, Netherlands, 2017.

[10] J. Liu, A.T. Gaynor, S.Chen, Z. Kang, K. Suresh, A. Takezawa, L. Li, J. Kato, J. Tang, C.C.L. Wang, L. Cheng, X. Liang, A. C. To, “Current and future trends in topology optimization for additive manufacturing”, Structural and Multidisciplinary Optimization, vol. 57, 2018, pp. 2457-2483.

[11] E. van de Ven, R. Maas, C. Ayas, M. Langelaar, F. van Keulen, “Continuous front propagation-based overhang control for topology optimization with additive manufacturing”, Structural and Multidisciplinary Optimization, vol. 57, 2018, pp. 2075-2091.

[12] E. van de Ven, R. Maas, C. Ayas, M. Langelaar, F. van Keulen, “3D overhang control for topology optimization with additive manufacturing”, unpublished.

[13] E. van de Ven, C. Ayas, M. Langelaar, R. Maas, F. van Keulen, “Topology optimization for additive manufacturing: Fully printable compliant mechanisms”, Advancing Precision in Additive Manufacturing, Berkeley, CA, 2018, pp 40-44.

Dedicated to innovation in aerospace

NLR - Royal Netherlands Aerospace Centre

Royal NLR operates as an unaffiliated research centre, working with its partners towards a better world tomorrow. As part of that, Royal NLR offers innovative solutions and technical expertise, creating a strong competitive position for the commercial sector.

Royal NLR has been a centre of expertise for over a century now, with a deep-seated desire to keep innovating. It is an organisation that works to achieve sustainable, safe, efficient and effective aerospace operations.
The combination of in-depth insights into customers' needs, multidisciplinary expertise and state-of-the-art research facilities makes rapid innovation possible. Both domestically and abroad, Royal NLR plays a pivotal role between science, the commercial sector and governmental authorities, bridging the gap between fundamental research and practical applications. Additionally, Royal NLR is one of the large technological institutes (GTIs) that have been collaborating since 2010 in the Netherlands on applied research as part of the TO2 federation.

From its main offices in Amsterdam and Marknesse plus two satellite offices, Royal NLR helps to create a safe and sustainable society. It works with partners on numerous (defence) programmes, including work on complex composite structures for commercial aircraft and on goal-oriented use of the F-35 fighter. Additionally, Royal NLR helps to achieve both Dutch and European goals and climate objectives in line with the Luchtvaartnota (Aviation Policy Document), the European Green Deal and Flightpath 2050, and by participating in programs such as Clean Sky and SESAR.

For more information visit: **www.nlr.org**

Postal address
PO Box 90502
1006 BM Amsterdam, The Netherlands
e) info@nlr.nl i) www.nlr.org

NLR Amsterdam
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113

NLR Marknesse
Voorsterweg 31
8316 PR Marknesse, The Netherlands
p) +31 88 511 4444