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Design for additive manufacturing method for a mechanical system downsizing

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Abstract

Thanks to the opportunities offered by additive manufacturing (AM) processes, design rules are evolving to lead to lighter and stiffer parts with really more complex shapes than those obtained by conventional processes. Worldwide, new tools of assistance to the design are developed, gathered under the naming "Design for Additive Manufacturing" (DfAM). However, most of the DfAM methods suggested in the literature remain focused on only one component and are not considering the product as a system of components. Moreover, optimizations are mainly limited on reducing the mass or the number of parts, and more rarely on adding some functions.

In this article, a new approach is presented to realize a multifunctional optimization of a mechanical system (MS). A methodology is first proposed in order to improve a product by using the AM opportunity. Then, to quantify the improvements of an optimized system, a new design indicator appointed "functional improvement rate" is defined. Finally, a case study, applied to a compressed-air Wobbler engine, is presented to demonstrate the relevance of the methodology and the functional improvement rate. The design adapted to traditional manufacturing is compared to a part-by-part optimized design and a multifunctional optimized design, both adapted to additive manufacturing.

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Keywords: DfAM; Additive manufacturing; Topology optimization; Multifunctional optimization

1. Introduction

The emergence of Additive Manufacturing (AM) processes upsets our knowledge in terms of design. Indeed, in AM, parts are built layer-by-layer, allowing the realization of any shape, which cannot be done by conventional processes like machining. A new way of design is thus emerging.

For a while, help to design for additive manufacturing (DfAM) mainly had arisen from tests. These tests were aimed to verify the manufacturability and the quality from a particular geometry shape [1] or to study the impact of the orientation of the piece on the board [2].

Since 2010, design methodologies based on rules emerged. For example, Rodrigue and Rivette [3] proposed a method allowing to adapt an assembly designed for conventional processes in the additive manufacturing.

Then more global methods integrating the opportunities as well as the constraints of additive manufacturing were worked

out [4]–[6]. All of those methods have in common the following stages which are essential for the design in AM:

- Requirements analysis
- Structural optimization
- Interpretation of results
- Rendering
- FE Analysis
- Final design

These steps were the subject of miscellaneous improvements as the integration of knowledge jobs at strategic moments. Klahn et al. [7] proposed two possible design strategies. For the first one the functions are put in the foreground, the second ensues from the manufacturing processes constraints.

More recently, frameworks for validating if the design is sound and to avoid rookie mistakes is described in [8]–[9].

Many studies have allowed to highlight the optimization of

a part by keeping its initial architecture. It allows a gain of mass and a reduction of the number of parts.

But the opportunities acquired by the use of AM allow to realize optimization with positive consequences for the product architecture (placement of the connections for example). It allows moreover to reduce the dimensions [10]. Nowadays, increasing added value of a product is one of the major axes of research. Burkhart and Aurich [11] suggest to choose the best part of a product to do with additive manufacturing regarding the environmental impact and the number of possible optimizations.

This paper presents a global method of design for additive manufacturing with multifunctional optimization applied to a mechanical system (MS). A criterion called functional improvement rate is proposed to compare the various improved products and to quantify the added-value. Finally a case study will illustrate the validity of our approach.

2. Methodology for mechanical system optimization

2.1. Literature review

The most commonly used optimization is the topologic one. This optimization leads to a design concept by imposing objectives and constraints. The imposed objectives functions are usually weight reduction, compliance decrease, or Eigen frequency increase.

Thanks to the design opportunities of AM, it is possible to further improve the design concept by considering other functions as objective. The Table 1 proposes to classify some papers on classical optimization (where mass and mechanical behavior are the objectives), and other specific functions. This table specifies also whether the study is on a part or on a mechanical system.

Table 1. Classification of some additive manufacturing optimization studies.

Reference	Classical optimization	Specific function optimization	One part study	Kinematic or non-assembly system	Improved functions
[3]	X			X	
[5]	X		X		
[6]	X		X		
[7]		X	X		Functionality
[10]	X		X		
[14]	X		X		
[15]	X	X	X		Biomimicry
[16]	X	X	X		Surface quality
[17]	X		X		
[18]	X		X		
[19]	X	X			Internal components
[20]	X		X		
[21]	X		X		
[22]	X	X			Multi-component
[23]		X		X	Non-assembly system
[24]		X		X	Non-assembly system
[25]		X	X		Balancing
[26]	X	X	X		Aesthetic

In the DfAM framework proposed by Kumke et al. [8], one of the steps is the optimization of specific product properties where specific functions are analyzed.

Depending on the field of application, a specific function should be placed as an objective. Thompson et al. [12] propose some examples like aesthetic for jewelry or fashion, heat transfer for injection molding, pressure drop for hydraulic system etc... In [13], a classification of functions was drafted in four families of requirements: fit, improve functionality, parts consolidation, and aesthetics.

For a mechanical system, designers use to enhance their concept by improving the tightness, guides precision, and by reducing friction or the number of part. In additive manufacturing, with the ability to produce complex shapes (internal and external), these functions can be improved differently. To achieve this, designers have to use a methodology. Without a new approach to product design, only a small part of the potential of AM will be used. Those specific functions can be: acoustic, aerodynamics, aesthetics, consolidation, balancing, comfort, heat exchange, external and internal geometry, friction, pressure drop, sealing sustainability etc. It is obvious that some functions can ensue from other functions. The optimization of each function may be improved or decreased, e.g. depending on the use, roughness should be increased or decreased.

2.2. Global methodology

In this section, a global design methodology, including specific function optimizations, for a mechanical system is proposed and the calculation of the functional improvement rate expound.

2.2.1. Scope

The methodology can be applied to design a part or a mechanical system (MS) and can be performed regardless of the additive manufacturing technology used. A MS is a system composed of moving parts as a multibody system.

The methodology consists of 3 stages with 11 steps, starting by requirements and ending on the manufacturing preparation, as shown in Fig. 1.

2.2.2. Detail of the first stage: Introduction

This stage is composed of two steps.

• First step

It consists in drafting specifications. External functional analysis must be carefully described.

Improved functions should be defined (like increasing efficiency or decreasing mass). Each improved function, modifies one or several features. For efficiency it can be friction, drop pressure or sealing. A list of all the features should be done. It will be used in a next step. Then a kinematic and mechanical analysis must be led.

• Second step

This step consists in internal functional analysis of each rigid body or part. The functions of all functional surfaces are detailed. A check with the list of features is done to verify if the functional surface has an impact on it. Ideal shapes which allow performing this function are proposed. For example to improve the grip of a part in the hand, the ideal shape is the handprint. If necessary those functional surfaces are sized (Hertzian contact stress, length of guide etc). Then to define

the design space, simple geometrical shapes such as planes, cylinders, are proposed to represent them.

Some functions cannot be reached by surfaces realized by additive manufacturing. That is why, in this section, external component should be chosen and sized. These components allow doing a function such as a guide (bearing, bushing, pre-manufactured axis...), positioning (paw of centering...) or others (sensors, cabling...).

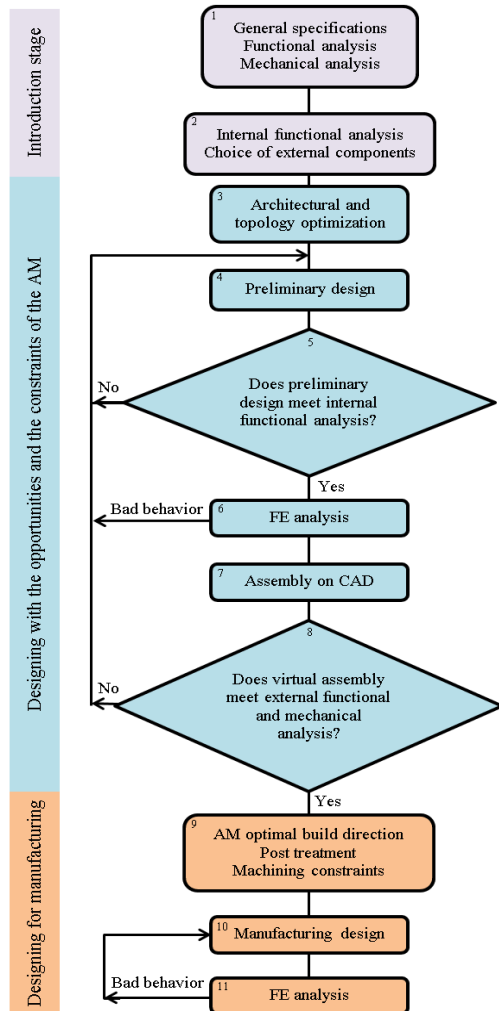


Fig. 1. Multifunctional optimization methodology.

2.2.3. Detail of the second stage: Designing with the opportunities and the constraints of the AM

The six steps of this stage lead to generate a design as it should be at the end of the manufacture and post-treatment. The additive manufacturing technology and material should be selected.

• Third step

This step consists of two optimizations. The first one takes place in the case of redesign. As Ren and Galjaard [10] have done with the steel node, the “architecture” of skeleton outline

has to be improved. It means that, the joint’s center may be closer for example, or better located, that way, the performance and functionality should be improved and the volume decreased, while respecting the functional analysis.

Then the topology optimization must be set by defining boundary conditions, and choosing optimization objective and constraints.

• Fourth step

From the optimization results, the preliminary design is realized in CAD. It is the design’s interpretation which has to follow as closely as possible the optimization results. Then all the functions previously cited can be analyzed and designed to improve the mechanism (as adding a cavity for enhancing cooling for instance). The choice of the solution comes from classical designer thinking, experience and knowledge. For example, the choice of a pivot connection is the result of a behavior comparison between direct contact / bearing / ball bearing / hydrostatic bearing / hydrodynamic bearing etc. The solution’s choice will be improved thanks to the additive manufacturing capabilities without any constraint. Ideal shapes cited in step 2 are now designed.

Such Salonitis [27] has presented, with the axiomatic design method, that links between functional requirements design parameters and process variables should be considered. So, after the improved functions, the additive manufacturing constraints should be taken into account. The minimum thicknesses, shrinkage of parts, the minimum clearance for direct manufacturing of joints, are some examples of manufacturing constraints to be considered.

• Fifth step

Each rigid body is checked to respond to the internal functional analysis. If not, the preliminary design will be amended accordingly.

• Sixth step

Mechanical behavior is analyzed by finite element analysis. The preliminary design will once again be changed accordingly.

• Seventh step

The realization of the virtual assembly of the rigid body in CAD will verify non-interference, the good insertion of external components, performance of maintenance ...

• Eighth step

From the CAD assembly and mechanical studies conducted in the first step, the designer can analyze behavioral differences between what is expected and obtained results.

A feedback on the design of the previous preliminary design will be necessary if the requirements are not met. The resulting model is the detailed design. This is the complete model of the mechanism.

2.2.4. Detail of the third stage: Designing for manufacturing

• Ninth step

This is the step for the manufacturing preparation. How to place the workpieces on the board to optimize the production

quality, quantity and location support, production time, cost... The functional surfaces requiring machining must be identified. Constraints of the AM machine used must be taken into account (e.g. removing support, heat dissipation).

- Tenth step

These reflections lead to probable changes to the design, such as machining allowance, overhang decrease to reduce support. That is why, another design should be done, it is the manufacturing configuration design, which will be product by additive manufacturing.

- Eleventh step

This final step is verifying the last design mechanic behavior taking into consideration the cutting forces and assembly force (for press-fit for example). The manufacturing configuration design may be changed accordingly.

2.3. Functional improvement rate

2.3.1. Literature review

In the literature an improve rate is used in order to:

- compare a conventional with an additive manufactured part,
- choose the best design strategy,
- choose the best solution,
- choose the part proposing the higher added value.

The first point concerns most of previous case studies. For example, the new design of a hinge studied in [14] is 64% lighter than the original. The percentage of improvement is generally used for a unique function.

Salonitis and Zarban [28] illustrate the second and third points. Three ways to design a part are proposed, and a multi-criteria decision is used to choose the best design. This corresponds in some way to determine the solution with the greatest added value. Campbell et al. [29] explain that AM can enhance the E3 value of product. E3 value categorize product value into, economic, ecological and experience value. Into the experience value, improving functionality of a product is offer by AM.

At least, Burkhart and Aurich [11] propose to count the number of possible optimizations to choose which part will be additively manufactured. In addition to weight, specific functions as heat conduction or fluid dynamics may increase the added value of an additive manufactured part.

2.3.2. Scope

The functional improvement rate (FIR) allows performing the four points cited previously and also quantifying the improvement of several functions. FIR takes into account the sense of the improvement i.e. if the increasing of the feature is considered as an added value or not.

2.3.3. Calculation of the functional improvement rate

Each optimized function improves mechanism's features. To determine the FIR, the features to be improved are listed with the desired type of gain (positive or negative) and the value. The gain's type shows if the increase or the decrease of the feature is considered as an added value or not. A weight for each feature can be assigned.

The functional improvement rate is calculated as follows:

$$FIR_{(NewDesign/OldDesign)} = \frac{\sum_{i=1}^n W_{f_i} \cdot G_{f_i} \%}{n} \quad (1)$$

$$G_{f_i} \% = \delta \cdot \left(\frac{\hat{f}_{i,NewDesign}}{\hat{f}_{i,OldDesign}} - 1 \right) \quad (2)$$

With :

- $FIR_{(NewDesign/OldDesign)}$: functional improvement rate between an old and a new design,
- n : is the number of features,
- f_i : feature of the function i ,
- W_{f_i} : weight of the f_i feature. $\sum_{i=1}^n W_{f_i} = 1$,
- $G_{f_i} \%$: the gain of the feature,
- $\delta = \pm 1$: + if the increase of the feature is considered as an added value and – on the contrary.

3. Validation of the proposed methodology

To test the method, a compressed air engine, named E_c (for conventional engine), made by conventional processes is studied. To demonstrate the value of our methodology, two ways to re-design this mechanism for additive manufacturing are studied. Foremost, a part-by-part optimization is performed. This concept engine is called E_{AM1} . It is optimized without regarding the different steps of the methodology. Then secondly, the method presented in section 0 is applied. The concept engine so designed is E_{AM2} .

3.1. Case study

The considered engine has four rigid bodies. All parts of this system are produced by conventional ways. The operating principle is explained on Fig. 2. Kinematic and structural engine behaviors are known for an inlet pressure.

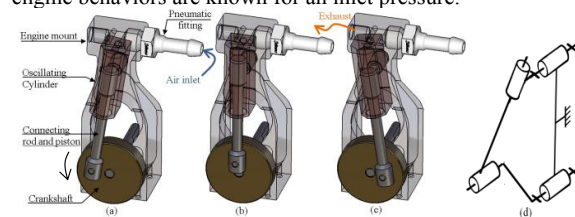


Fig. 2. Intake (a), neutral (b), exhaust (c) phases of the engine E_c . Skeleton outline (d).

The objective of this study is to use the entire capability offered by additive manufacturing processes in order to improve efficiency. The chosen additive manufacturing technology is Selective Laser Melting (SLM), and the materials used are cobalt-chromium and aluminum alloy. Crankshaft and guide shaft are made by conventional way.

3.2. Results

Figure 3 shows the first part-by-part optimized concept engine E_{AM1} and the multifunctional optimized and downsized one E_{AM2} . The topology optimization objective is minimizing the volume with stress constraint. Both engines resist in request static and dynamic mechanics and have the same kinematic behaviour. The results are shown in Table 2. Some improvements cannot be quantified without experiments. The operation of some solutions is presented in the next section.

Table 2. Results of the different engine optimizations.

Criteria	Part or connection	Alloy	E_c	E_{AM1}	E_{AM2}	
Mass (g)	Engine mount	Cobalt-chrom.		171	171	
		Aluminum		109	106	
	Piston	Cobalt-chrom.		19	19	
		Steel	25			
	Cylinder	Cobalt-chrom.		44	33	
		Aluminum		26	20	
		Brass	74			
	Total	Cobalt-chrom.		234	223	
		Aluminum		208	151	
	Volume (cm ³)	Engine mount	Cobalt-chrom.		20,37	20,65
Aluminum				40,1	32,23	
Piston		Cobalt-chrom.		2,26	2,22	
		Steel	3,2			
Cylinder		Cobalt-chrom.		5,16	3,86	
		Aluminum		6,25	4,87	
		Brass	8,3			
Total		Cobalt-chrom.		40,40	38,43	
		Aluminum		62,5	42,00	
Inertia (kg.mm ²)		Piston	Cobalt-chrom.		9,78	9,49
	Steel		15			
	Cylinder	Cobalt-chrom.		8,71	5,65	
		Aluminum		3,24	2,74	
		Brass	15			
	Sealing	pivot connection Engine mount /Cylinder		X	X	/
Sliding pin connection piston /Cylinder			X	X	/	
Planar connection Cylinder /Engine mount			X	X	/	
Friction		Pivot connection Engine mount/Crankshaft		-	-	/
		Pivot connection Engine mount /Cylinder		-	-	-
		Sliding pin connection piston /Cylinder		X	/	//
Pressure drop	planar connection Cylinder /Engine mount		X	/	/	
	Engine mount Cylinder		X	/	/	
Thermodynamic	Cylinder		X	X	/	

Legend:

- - Identical to the previous solution
- / improved design
- // more improved design
- X not considered

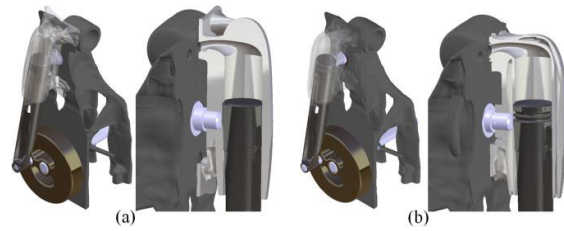


Fig. 3. (a) Part-by-part optimized concept engine E_{AM1} ; (b) Multifunctional optimized concept engine E_{AM2} .

3.3. Results analysis

For the E_{AM1} the optimization decreases disruptive mass and inertia. The shapes brought to the admission and the oscillating cylinder have for objective to decrease pressure drop.

E_{AM2} is based on the engine E_{AM1} and is designed to decrease: friction, thermodynamic losses, leakage, inertia losses, pressure drop and size.

Thanks to the step 2 of the multifunctional optimization methodology, the functional surfaces which may improve these functions are known. During step 4 of the methodology, all functions are improved. The Fig. 4 presents how the sealing between the piston and the oscillating cylinder can be improved. The grooves on the shape of the rod allow not only to realize drop pressure but also to create a controlled turbulence. The drillings increase this turbulence and send back the air upward.

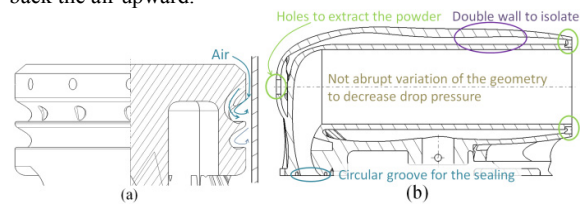


Fig. 4. Multifunctional optimized piston (a) and oscillating cylinder (b).

To collect the maximum of the thermodynamic work, the expansion should be adiabatic. To isolate the oscillating cylinder, a double wall is designed as shows Fig. 4.

The use of the exhaust compressed air can decrease friction between the crankshaft and the engine mount. An hydrostatic bearing is easy to implement as it is explained on the Fig. 5.

Then, the sealing can be enhanced thank to the pressure balancing shown in the blue frame of Fig. 5.

The improvement comparison of each design solution will be done in future work. For example, to quantify the friction impact, engine output power will be measured for a bearing and then for a hydrostatic bearing.”

Table 3 summarizes the different functional improvement rate obtained for the quantified improvement features, with the equations (1) and (2) and the following weight : $W_{mass}=W_{volume}=0,05$; $W_{piston inertia}=0,5$; $W_{Cylinder inertia}=0,4$.

FIR results between E_{AM2} and E_C proves a consequent functional improvement. These results will be higher by taking into account the optimized function results like friction, pressure drop, sealing and thermodynamic work.

Table 3 may also help designers to choose the material.

Table 3. Functional improvement rate between the different engines.

	FIR%
FIR _{Fc/EAM1cr-co}	8,9
FIR _{Fc/EAM2cr-co}	11,2
FIR _{Fc/EAM1alu}	12,8
FIR _{Fc/EAM2alu}	13,5

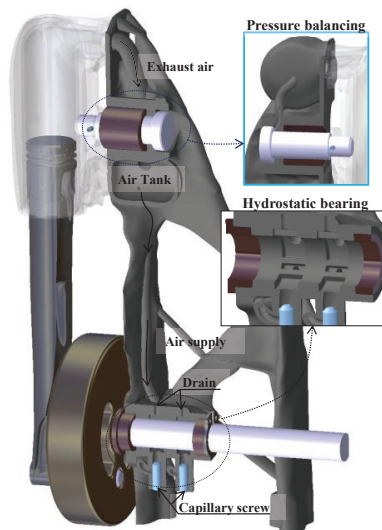


Fig. 5: Hydrostatic bearing and pressure balancing.

4. Conclusion and future perspectives

The main contribution of this paper is to demonstrate that with the multifunctional optimization method, a lot of feature improvements may be done. The method proposed in this paper has been applied to a mechanical system redesign. The study case shows that such a designed product uses full advantage of the AM processes to improve functions. These solutions cannot be made by conventional processes but easy to implement thanks to additive manufacturing.

A functional improved rate (FIR) has been defined in order to compare different solutions between an old and a new design. The functional improvement rate is an easy tool to use. Tests must still be made to complete the featured data.

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