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Additive manufacturing for freeform mechatronics design: from concepts to applications

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Abstract
This article presents developments of freeform mechatronics concepts, enabled by industrial Additive Manufacturing (AM), aiming at breakthroughs for precision engineering challenges such as lightweight, advanced thermal control, and integrated design. To assess potential impact in future applications, representative cases have been considered. First results are briefly described, which are already convincing and encouraging.

Keywords: freeform mechatronics, Additive manufacturing, high precision systems, topology optimization, lightweight, thermal control

1. Introduction

This article presents developments of freeform mechatronics concepts, enabled by industrial Additive Manufacturing (AM), see also [1] for prior work. Known precision engineering challenges such as lightweight, advanced thermal control, freeform design concepts for next generation high precision system architectures have been taken as targets for turning the design freedom of AM into system value, and will be evaluated towards simplified application cases. Some already convincing first results have been obtained, which will be briefly illustrated.

2. Lightweight motion system part application study

Mass reduction is a shared desire for many high precision motion systems. Lightweight parts will typically look like a closed rectangular box with an open structure inside. The question rises which open structure suits best to save mass but remain stiff with high resonance frequency. For insight, we concentrated first on unit cells, that can be manufactured with AM. Lightweight unit cell structures have been designed and analysed. Samples of blocks built from repeating unit cells (6 x 4 x 5 cells with approximately 6 mm size) have even printed (figure 1). By varying wall thickness per cell, the density and mechanical properties can be tailored to design requirements.

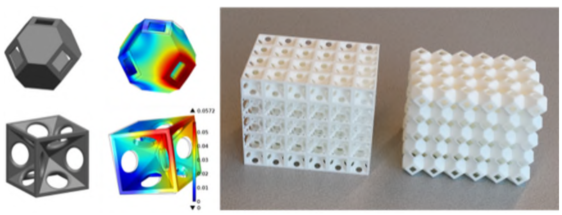

Figure1. Unit cells, mechanical analysis, and printed samples.

The idea to combine model based design tools such as topology optimization with the unit cell concept has been investigated. Basically, a part design volume must be gridded with unit cell dimensions, and a topology optimization algorithm is used to determine which type of cell to be placed at each position, such that the resulting part properties are optimal.

To make the step towards application, a baseline design of a performance critical motion body from a high precision positioning system is considered. Such a mechatronic system involves obviously powerful actuators for high accelerations, high resolution position metrology, and high bandwidth servo control loops. To define a feasible starting point, the existing design has been simplified somewhat by leaving out specific design details, remaining focus on primary design drivers such as mass, stiffness, and modal eigen frequencies. Figure 2 shows first lightweighting topology optimization results for this simplified performance critical motion body.

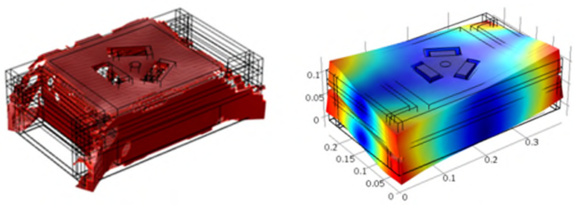

Figure 2. First topology optimization result, modal analysis.

Unit cell based topology optimization has been tried , but appeared to run into difficulties for this case. To further understand the possibilities and limitations, effect of user choices in formulating the optimization problem with various target criteria and boundary conditions, a more simple case has been considered. Encouraging results and insights already have been obtained, which build confidence that also more complex design optimizations, as the example above, can be tackled.

In parallel to such model based design optimization efforts, also a manual AM design approach has been taken, based on freeform engineering insight. Mass reduction leads to lower forces to get the same required acceleration. Lower force levels allow for lighter actuators, which we accounted for in our system evaluation study. Although also obtained from a simplified setting, to keep focus on the core challenges, already convincing results were found (table 1). Note that ultimately a moving mass reduction of about half of the baseline design will prove hard to achieve when all other additional design requirements should also be met.

Table1. Comparison between baseline and first AM design

	Baseline	AM design		Benefit
motion body	8	2,7	[kg]	-0,66
X/Y-Actuator mass (moving)	6	3,4	[kg]	-0,43
Z-actuator magnets	1,8	1	[kg]	-0,43
Other parts	3,7	3,7	[kg]	0
TOTAL MOVING ASSEMBLY	19,5	10,8	[kg]	-0,45
First eigen frequency	1370	1479	[Hz]	0,08

3. Freeform thermal control application study

Towards advanced thermal control, we conceived two freeform AM concepts. The first is based on forcing flow mixing within a spiral shaped cooling channel, which results in increased heat transfer (for example a factor 4 improvement, dependent on flow velocity) while flow remains laminar and additional pressure drop is minor. The second is based on designs resulting in local upward flow, which we call a thermal pixel. Basically, a target area can be covered by a x,y grid of thermal pixels, with a flow manifold underneath with supply and return channels (figure 3). Thus, a more effective heat transfer can be achieved, and more challenging, spatially distributed local thermal control will become a new option in thermal management and control when individual pixel cooling flows can be actively controlled. From flow control studies it appears to some extent possible to address individual pixels or desired target areas with desired cooling flow for suppression of (known, dynamic, local) thermal disturbances.

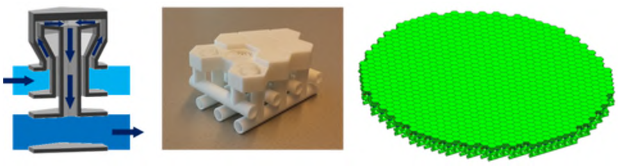

Figure 3. Thermal pixel concept, printed sample, pixel grid disk

Various cooling head layout have been studied (e.g. impingement jets, flow mixing, open structures), not only aiming at optimized thermal transfer but also evaluating pressure drop, required cooling flow, laminar or turbulent flow regimes, water heating, etc.
Ongoing application studies aim at matching cooling topology to spatially distributed heat loads. For optical elements in laser beam transport the uncontrolled thermal induced deformations poses a threat to optical performance, certainly when power levels are expected to increase in the near future.
First results indicate that thermal behaviour can be improved for static and known spatially distributed heat loads. More attractive would be to accommodate different heat load distributions (Gaussian distribution, uniform, etc.) with the same thermal pixel based mirror body, just by adjusting to the optimal cooling flow per pixel for each heat load distribution.
Active control with feedback and feedforward strategies is also an attractive option, but has nog been elaborated on yet.

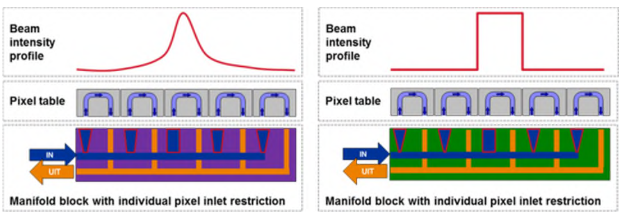

Figure 4. Same thermal pixel concept for different heat loads

4. Zero / tuneable thermal expansion structures

More longer term AM ideas look towards (combination of) materials or structures, for instance to achieve close to zero thermal expansion, which would be valuable for stability of equipment parts. Earlier work in this direction [2,3,4,5] are for several reasons of limited value for high tech systems. We propose a different approach, not relying on bending of the structure elements. Instead, periodic structure is composed of separate low-CTE units interlocked with high-CTE elements. The principle is illustrated in figure 5: rings of low-expansion material are interspaced with high-expansion bars. However, such a structure is not stretch-dominated and may easily collapse under load.

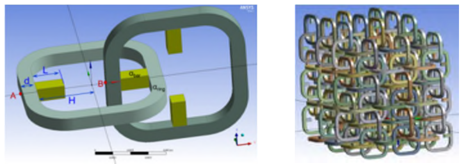

Figure 5. Zero-CTE structure with interlocked rings: schematic (yellow bars have high CTE), periodic extension to 3D

The possible solution is to construct zero-expansion "links" – linear elements that have zero expansion each, and use these links in stretch-dominated lattice structure (as in [4]). Figure 6 shows an example of such a link. Given the total length and bounding limits (so that it will fit in 3D lattice) the link geometry is tuned for maximum compressive stiffness, while maintaining zero CTE. This example uses materials with CTE values (2.5 and 16)$\times10^{-6}$ K^{-1} (Invar 32-5 and AISI 316L). A simple design of the links allows pre-adjusting them for elastic properties and thermal expansion separately. Figure 7 shows a structure composed from such links. Effective CTE is as low as 8×10^{-9} K^{-1}, while effective compressive modulus reached 4.9 GPa with shear modulus ≈ 2.9 GPa – this can be compared with solid plastics, such as nylon etc. Note that this structure is not yet fully optimized. Design of the links and topology of the 3D lattice may be further adjusted.

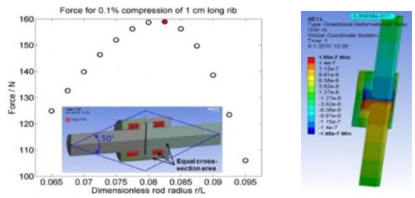

Figure 6. Geometry of expansion-compensated rib (red tube has high CTE), axial displacement (1/4 rib) when heated by 10°C.

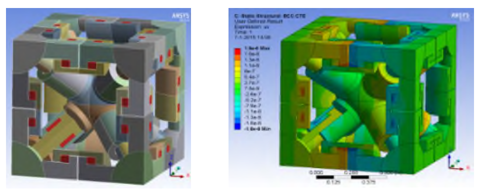

Figure 7. Cubic cell example based on expansion-compensated links. Right: relative X displacement when heated by 1°C.

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