



Finite Element Analysis and Modal Characterisation of a Titanium 3D-Printed Single-Axis Accelerometer for High-g Shock Applications Using COMSOL Multiphysics

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Abstract— Inertial sensors are increasingly required to survive severe shock and vibration, which has drawn attention to materials and fabrication routes other than silicon micromachining. This study presents the finite element analysis and modal characterisation of a single-axis accelerometer designed for 3D printing in titanium (Ti) and intended for high-g sensing. The device occupies a $2.5 \times 2.5 \text{ mm}^2$ die footprint, with a central proof-mass carried by folded-beam suspension springs and anchor structures. An eigenfrequency study was performed in COMSOL Multiphysics v6.3 with the Solid Mechanics module, using a free tetrahedral mesh of 6,132 domain elements whose convergence was verified. Six structural modes were extracted between 11.1 and 37.6 kHz. The mode at 12,001 Hz shows predominantly translational motion of the proof-mass along the sensing axis and is identified as the sensing mode; modes 4–6 lie more than an octave above it, whereas modes 1 and 3 lie within about 16% of it. A lumped spring–mass model based on the simulated sensing frequency gives a mechanical sensitivity of about 1.725 nm/g, corresponding to proof-mass displacements of 1.725 μm at 1000 g and 17.25 μm at 10,000 g under the assumption of linear elastic behaviour. The results indicate that the titanium design offers a high resonance frequency suited to high-g measurement, while its material promises greater robustness than brittle silicon. The study provides a simulation-based design framework for additively manufactured metallic inertial sensors and a baseline for their fabrication, experimental validation and optimisation for aerospace, defence and industrial monitoring.

Keywords— MEMS accelerometer, titanium, additive manufacturing, COMSOL Multiphysics, modal analysis, high-g sensing, finite element analysis, inertial sensor

I. INTRODUCTION

MEMS accelerometers measure acceleration, vibration and shock across aerospace, automotive, defence, structural health monitoring and inertial navigation [1]–[3]. Most are made from silicon by photolithographic micromachining, which gives them high sensitivity, low power consumption and excellent repeatability [4]–[6], and they are now ubiquitous in consumer electronics, automotive safety systems, monitoring and navigation. Silicon is, however, a brittle material of low

fracture toughness, and this limits the reliability of silicon devices under the extreme shock and impact loads met in aerospace crash monitoring, ballistics and other high-g measurement [7]–[9].

As more sensing tasks move into such environments, interest has grown in alternative materials and processes. Metals, and titanium in particular, combine high specific strength, good fatigue behaviour and corrosion resistance in a way that silicon does not [10]–[12], which makes titanium attractive for inertial sensors that must operate where silicon devices risk degradation or fracture [13]–[15]. Zega et al. [13] have already demonstrated a uniaxial capacitive accelerometer 3D-printed in Ti6Al4V, showing that the route is practicable.

Advances in metal additive manufacturing (AM) now allow complex three-dimensional metal parts that micromachining could produce only with difficulty, if at all. Direct Metal Laser Sintering (DMLS) uses a high-energy laser to fuse successive layers of metal powder into near-net-shape parts; it can produce features of a few hundred micrometres with layer thicknesses of 20–50 μm , offers great design freedom and avoids many constraints of cleanroom MEMS processing [16]–[18].

Finite element analysis (FEA) allows the structural behaviour, modal characteristics and dynamic response of a sensor to be assessed before it is built, so that geometry, material and boundary conditions can be optimised and development time and cost reduced [19]–[21]. COMSOL Multiphysics provides an integrated environment for such work, including modal and eigenfrequency studies of MEMS-scale structures [22]–[24].

This paper designs and analyses, in COMSOL Multiphysics v6.3, a titanium 3D-printed single-axis accelerometer with a $2.5 \times 2.5 \text{ mm}^2$ die footprint, in which a central proof-mass is suspended by folded-beam springs from fixed anchors. The aims are to characterise the modal response of the device, identify its sensing mode and assess its suitability as a high-g shock sensor, using eigenfrequency analysis, mode-shape visualisation and an analytical spring–mass model. The results provide a basis for the fabrication and experimental



characterisation of metallic inertial sensors for extreme environments.

II. SENSOR DESIGN AND MATERIAL PROPERTIES

A. Mechanical Architecture

The accelerometer has three structural elements: a central proof-mass, folded-beam suspension springs, and anchor structures integrated into a square substrate frame (Fig. 1). The proof-mass is the inertial element, displaced along the sensing direction when the device is accelerated. The folded springs supply the restoring force for its motion; folding increases their compliance within the available footprint while limiting cross-axis sensitivity. The anchors connect the suspension to the supporting substrate and are treated as rigidly fixed boundaries in the FEA.

Within the $2.5 \text{ mm} \times 2.5 \text{ mm}$ die, four folded-beam springs are arranged symmetrically around the proof-mass. Symmetry balances the stiffness, suppresses unwanted rotation, stabilises the dynamic behaviour and makes the fundamental translational sensing mode easier to identify. The centrally placed proof-mass is mechanically decoupled from the substrate by the springs, so that it can follow the external acceleration while the suspension carries its weight. The side view in Fig. 1(b) shows the sensing direction and the operating principle under external shock.

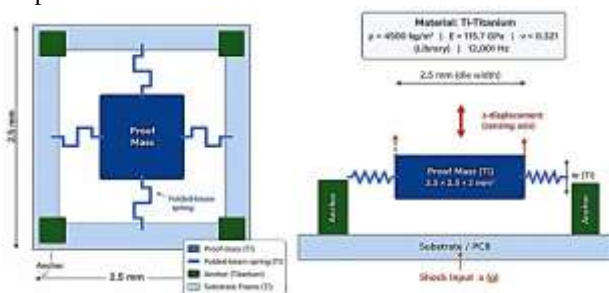


Fig. 1. Engineering schematic of the 3D metal-printed titanium accelerometer: (a) top view showing proof-mass, folded-beam springs, anchors and substrate frame; (b) side-view cross-section showing the sensing direction and operating principle.

The three-dimensional geometry was built in COMSOL Multiphysics v6.3 from parametric work planes, extrusions and Boolean unions to form a single monolithic titanium structure with six computational domains: the proof-mass, spring elements, anchor regions and supporting frame. The resulting CAD model is shown in Fig. 2.

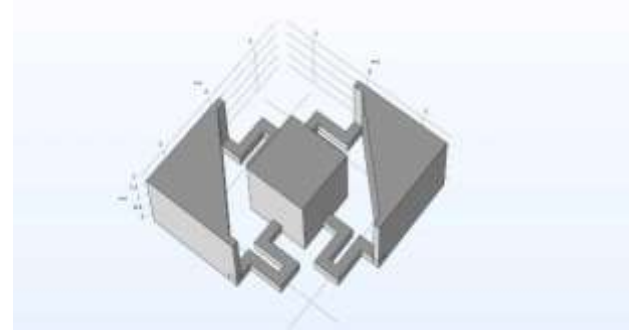


Fig. 2. COMSOL geometry of the titanium accelerometer showing the proof-mass, folded-beam springs and anchor structures.

B. Material Properties

Titanium was chosen for its combination of specific strength, stiffness, corrosion resistance, fatigue resistance and fracture toughness. It is far more resistant to shock-induced damage than silicon, which suits it to high-g sensing under impact, vibration and harsh conditions.

The material properties were taken unchanged from the COMSOL material library (Ti – Titanium, mat1) and applied uniformly to all domains (Table I). Density, Young's modulus and Poisson's ratio govern the dynamic response and resonance; the thermal and electrical properties are listed for completeness and for later multiphysics studies.

TABLE I. Ti – TITANIUM PROPERTIES (COMSOL LIBRARY, MAT1)

Property	Symbol	Value	Unit
Density	ρ	4500	kg/m^3
Young's modulus	E	115.7×10^9	Pa
Poisson's ratio	ν	0.321	—
Electrical conductivity	σ	2.6×10^6	S/m
Coeff. of thermal expansion	α	8.6×10^{-6}	1/K
Heat capacity (const. P)	C_p	522	J/(kg·K)
Thermal conductivity	k_{th}	21.9	W/(m·K)

This combination of properties is favourable. The high stiffness-to-density ratio places the resonances in the kilohertz range while keeping the structure robust; the low density relative to most engineering metals limits the inertial load on the springs, and the high elastic modulus gives the stiffness needed for high-frequency operation. Titanium's fracture toughness and fatigue resistance should also allow the device to withstand repeated shocks in harsh environments. Combined with the geometric freedom of AM, these properties make titanium a promising basis for stiff, robust inertial sensors in aerospace, defence, structural monitoring and other high-g applications.



III. FINITE ELEMENT ANALYSIS METHODOLOGY

A. Physics and Boundary Conditions

The accelerometer was modelled with the Solid Mechanics module of COMSOL Multiphysics v6.3, treating Ti – Titanium as homogeneous, isotropic and linearly elastic. A small-deformation formulation was used, which is appropriate for modal analysis when vibration amplitudes are much smaller than the characteristic dimensions of the structure.

The principal objective was to obtain the natural frequencies and mode shapes. An eigenfrequency study was therefore used to extract the lowest structural modes, which govern the dynamic response; the solver returns natural frequencies and deformation shapes without any applied load.

Fixed constraints on the anchor regions represent attachment to a rigid substrate, setting their translations and rotations to zero to reproduce ideal clamping. All other surfaces were left free, so that the proof-mass and springs could deform in each mode. This arrangement matches the intended physical configuration, in which the anchors are bonded to the substrate and the proof-mass and springs respond to external acceleration, and so gives a suitable representation of the modal behaviour of the sensor structure.

B. Mesh Generation and Convergence

Because solution accuracy depends strongly on mesh quality and density, the geometry was discretised with COMSOL's free tetrahedral mesher, which handles complex 3D shapes and slender suspension members well. An automatically generated mesh was refined locally around the spring features, where displacement gradients are high. Narrow-face regions associated with the folded beams, identified during meshing, were then optimised to improve element quality and capture local deformation. The final mesh (Fig. 3) contains 6,132 domain elements, 2,550 boundary elements and 624 edge elements.

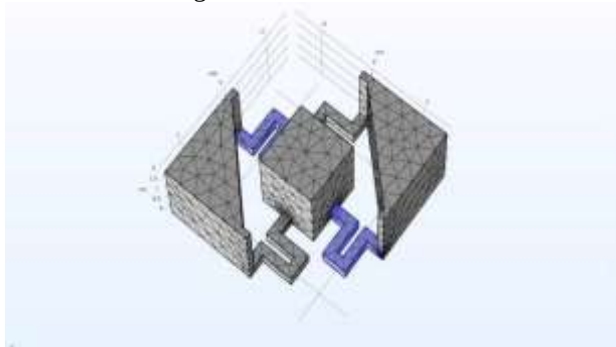


Fig. 3. Free tetrahedral finite element mesh (6,132 domain, 2,550 boundary and 624 edge elements), refined around the suspension springs.

Mesh convergence was checked by increasing the number of elements and monitoring the primary eigenfrequency. Beyond about 6,000 elements the change in frequency became negligible, and refining to about 9,000 elements altered it by less than 0.3%, confirming a mesh-independent solution. The

final model had about 31,581 degrees of freedom and solved for the eigenfrequencies in about 4 s.

IV. RESULTS

A. Eigenfrequency Spectrum

Table II lists the six lowest natural frequencies and the normalised z-direction participation factors, and Fig. 4 displays the spectrum. The first three modes lie between 11 and 14 kHz and involve flexure and translation of the proof-mass and springs; modes 4–6 lie between 27 and 38 kHz.

TABLE II. EIGENFREQUENCIES AND NORMALISED Z-DIRECTION PARTICIPATION FACTORS

Mode	Freq. (Hz)	Z-particip.	Dominant motion
1	11,083	-0.003736	Flexural rocking
2	12,001	+0.002341	Primary sensing mode
3	13,959	-0.002481	Lateral-torsional coupling
4	27,505	+0.003131	Torsional mode
5	31,348	-0.001972	Mixed torsional-flexural
6	37,561	+0.002690	Higher-order spring mode

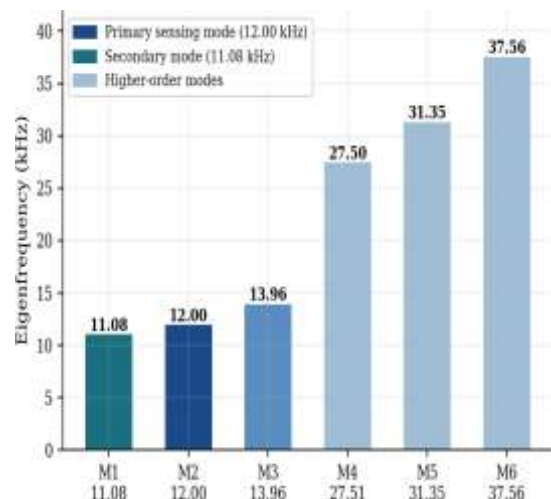


Fig. 4. Eigenfrequency spectrum of the six extracted modes.

Mode 2, at 12,001 Hz, is identified as the sensing mode because its mode shape is dominated by translation of the proof-mass along the sensing direction, and its non-zero z-participation factor confirms a z-directed contribution. The participation factors of modes 1, 3, 4 and 6 are, however, of similar or larger magnitude, so the choice of sensing mode rests on the mode shapes rather than on the participation factors alone.

Modal separation differs above and below the sensing mode. Modes 4–6 lie more than an octave above it (27,505 Hz is 2.29 times 12,001 Hz), so interference from them is unlikely. Modes 1 and 3, by contrast, lie only about 8% below and 16% above it. Since mode 1 also has a z-directed component, its



proximity is the main constraint on clean single-mode operation and is a priority for design refinement.

B. Mode Shapes

Mode shapes were examined to characterise the deformation associated with each frequency. Fig. 5 shows the mode at about 11.1 kHz, in which the proof-mass rocks and the springs flex; the displacement field is partly rotational, which makes this mode unsuitable for primary sensing.

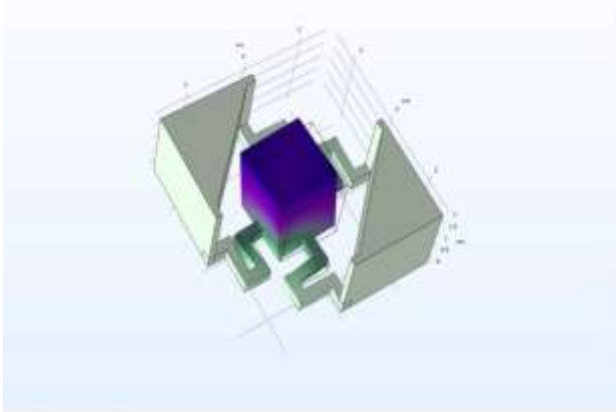


Fig. 5. Mode shape at approximately 11.1 kHz, showing flexural rocking of the proof-mass and suspension springs.

Fig. 6 shows the 12,001 Hz mode. Here the proof-mass moves mainly by translation along the sensing direction, as required of the sensing mode. The deformation is highly symmetric, indicating a well-balanced suspension stiffness, and the anchors remain essentially stationary, as the boundary conditions require.

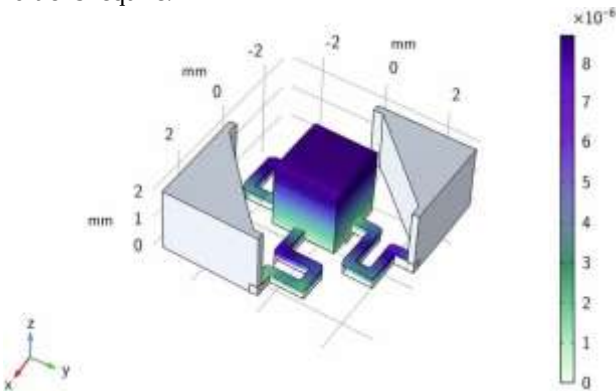


Fig. 6. Sensing mode at 12,001 Hz, showing symmetric translation of the proof-mass and deformation of the folded-beam springs.

The displacement contours in Figs. 5 and 6 are normalised modal displacements returned by the eigenfrequency solver. They describe the shape of deformation, not the physical amplitude during operation, which depends on the excitation and on damping and must be obtained from transient or frequency-response analysis.

V. ANALYTICAL MODEL AND SENSITIVITY

A. Mechanical Sensitivity

For loading well below resonance, the accelerometer can be represented as a lumped single-degree-of-freedom spring-mass system, in which an effective proof-mass m is suspended by the folded springs of equivalent stiffness k . The undamped natural frequency is

$$f_n = (1/2\pi) \sqrt{k/m} \quad (1)$$

and, when the acceleration a varies slowly compared with f_n , the static displacement of the proof-mass is

$$x = ma/k \quad (2)$$

Substituting $k/m = 4\pi^2 f_n^2$ from (1) gives

$$x = a / (4\pi^2 f_n^2) \quad (3)$$

so the mechanical sensitivity, the displacement per unit acceleration, is

$$S = x/a = 1 / (4\pi^2 f_n^2) \quad (4)$$

With the simulated sensing frequency $f_n = 12,001$ Hz, $S = 1/[4\pi^2(12,001)^2] = 1.758 \times 10^{-10}$ m/(m/s²). Taking $g = 9.81$ m/s², this is $S = 1.725 \times 10^{-9}$ m/g ≈ 1.725 nm/g. Equivalently, the sensing mode implies a stiffness-to-mass ratio of $k/m \approx 5.69 \times 10^9$ s⁻². Table III gives the resulting proof-mass displacements.

TABLE III. PREDICTED PROOF-MASS DISPLACEMENT

Applied acceleration	Predicted displacement
1 g	1.725 nm
10 g	17.25 nm
100 g	172.5 nm
1000 g	1.725 μ m
5000 g	8.625 μ m
10,000 g	17.25 μ m

Within the assumed linear elastic range, displacement is proportional to acceleration (Fig. 7). Between 1000 and 10,000 g the predicted displacement rises from about 1.7 to 17.3 μ m, a range compatible with capacitive readout across micrometre-scale electrode gaps.

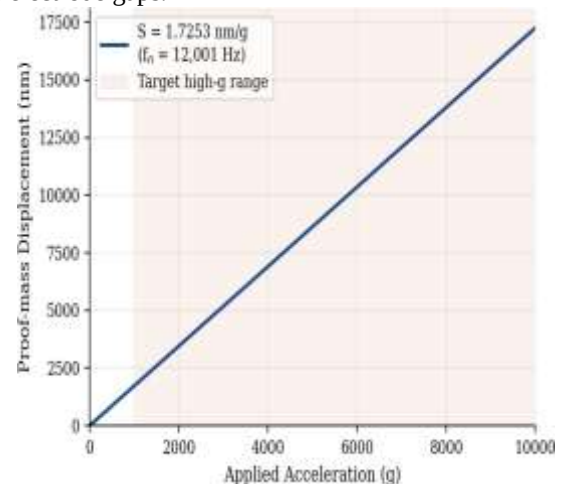


Fig. 7. Analytical proof-mass displacement versus applied acceleration, from the spring-mass model with $f_n = 12,001$ Hz.



B. Consistency of the Numerical and Analytical Models

The finite element results were checked against classical spring-mass behaviour. In the analytical model the natural frequency is set by the equivalent stiffness and effective mass, but the geometric complexity of the folded beams and the distributed mass of the springs make an exact closed-form expression difficult to obtain. The analytical model is therefore used here to interpret the simulated frequency, converting it into a sensitivity, rather than to predict that frequency independently. Within this role it confirms the expected relation between stiffness, mass and resonance, and the simulated frequency of 12,001 Hz lies in the range reported for miniature metallic and high-frequency inertial sensors of similar size.

Because the finite element model includes the boundary conditions, the distributed mass and the full 3D geometry, whereas the analytical model is a simplification, the FEA is taken as the primary source of the resonance prediction and the analytical model as supporting evidence. An independent analytical estimate of k from beam theory and of m from the proof-mass volume would turn this consistency check into a genuine verification and is recommended for future work.

VI. DISCUSSION

The sensing mode at 12,001 Hz allows the device to follow fast transients in shock and vibration with little dynamic distortion. Since the usable bandwidth of such sensors is commonly taken as about one-third of the natural frequency, the design offers an operating bandwidth of roughly 4 kHz, enough to cover the dominant frequency content of many aerospace, structural-monitoring and impact events. The rocking mode at 11.1 kHz, however, lies below the sensing mode, and if it is excited by the input it, rather than the sensing mode, will set the practical upper limit of the bandwidth.

The sensing mode is predominantly translational, and its symmetric displacement field confirms the balanced stiffness of the folded-beam suspension, whereas the neighbouring modes involve flexural and torsional deformation. The large gap to modes 4–6 limits interference from higher-order modes; increasing the separation from modes 1 and 3, for instance by raising the rotational stiffness of the suspension relative to its translational stiffness, would further improve operational stability.

The predicted sensitivity of about 1.725 nm/g is lower than that of many low-g consumer accelerometers, but it is the counterpart of the high resonance frequency that high-g measurement requires, an instance of the familiar trade-off between sensitivity and bandwidth in inertial sensor design. Displacements of 1.725 μm at 1000 g and 17.25 μm at 10,000 g show that measurable structural responses can be obtained at extreme acceleration levels.

Titanium offers several advantages over silicon in harsh environments: high fracture toughness, fatigue resistance and corrosion resistance support repeated shock loading and long service, and AM permits three-dimensional shapes that

conventional micromachining would struggle to produce. These are properties of the material; the strength of the present structure under shock has not yet been analysed.

The study is limited to eigenfrequency analysis and analytical sensitivity estimation. Modal analysis describes resonance and deformation but does not predict the transient response to a shock. Static structural, harmonic-response and transient shock simulations, together with experiments, are needed to establish the full performance of the sensor, and the effects of fabrication, including residual stress, geometric tolerances and surface roughness, on resonance and sensing performance should be quantified. Within these limits, the results indicate that the titanium accelerometer has dynamic characteristics suited to high-g applications and provide a sound basis for fabrication and experimental characterisation.

VII. CONCLUSION

This paper has presented the finite element analysis and modal characterisation, in COMSOL Multiphysics v6.3, of a 3D-printed single-axis titanium accelerometer whose central proof-mass, folded-beam springs and fixed anchors occupy a $2.5 \times 2.5 \text{ mm}^2$ footprint, with the aim of assessing its dynamic response and suitability for high-g sensing. Six structural modes were identified. The sensing mode, a translation of the proof-mass along the sensing axis, occurs at 12,001 Hz; its mode shape is symmetric and the anchors remain isolated, indicating a balanced suspension. Higher-order modes lie more than an octave above it, while two adjacent modes at 11.1 and 14.0 kHz call for further design attention. The discretisation, with 6,132 domain elements, was shown to be mesh-independent at modest computational cost.

The spring-mass model gives a mechanical sensitivity of about 1.725 nm/g, with a linear response reaching 1.725 μm at 1000 g and 17.25 μm at 10,000 g, so the device should produce measurable responses over a wide high-g range. Combining titanium's inherent robustness with additive manufacturing is a promising route to mechanically robust inertial sensors, and the modal results reported here provide a baseline for that work.

VIII. FUTURE SCOPE

Several steps are needed to establish complete device performance. Static structural analysis under prescribed acceleration loads should be used to determine stress distribution, structural integrity and the maximum survivable acceleration, and transient and harmonic-response analyses should characterise behaviour under realistic shock pulses, impacts and vibration, giving fuller information on bandwidth, damping and dynamic response.

The influence of AM on performance also needs detailed study: residual stress, surface roughness, dimensional tolerances, porosity and anisotropy introduced by metal printing may shift the resonances and degrade sensing accuracy, and should be built into future numerical models. The proof-mass dimensions, spring geometry and anchor configuration can be optimised to raise sensitivity while



preserving an adequate resonance frequency and strength, and practical readout schemes, whether capacitive, piezoresistive or piezoelectric, should be explored through coupled multiphysics simulation.

Finally, prototypes must be fabricated by metal AM and subjected to vibration, shock and displacement testing, so that the numerical predictions can be compared directly with measurement and the models refined. This work will support the development of reliable titanium accelerometers for aerospace, defence, industrial monitoring and other harsh environments.

IX. NOMENCLATURE

TABLE IV. SYMBOLS AND ABBREVIATIONS

Symbol	Meaning
f_n	Natural frequency (Hz)
k	Equivalent spring stiffness
m	Effective proof-mass
x	Proof-mass displacement
a	Applied acceleration
S	Mechanical sensitivity
g	Gravitational acceleration (9.81 m/s ²)
E	Young's modulus
ρ	Density
ν	Poisson's ratio
σ	Electrical conductivity
α	Coefficient of thermal expansion
C_p	Specific heat capacity
k_{th}	Thermal conductivity
AM	Additive manufacturing
CAD	Computer-aided design
DMLS	Direct metal laser sintering
DOF	Degrees of freedom
FEA / FEM	Finite element analysis / method
MEMS	Micro-electro-mechanical systems

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