INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

ADVANCED APPLICATIONS OF A COMPUTATIONAL DESIGN SYNTHESIS METHOD

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ABSTRACT

From modelling to manufacturing, computers have increasingly become partners in the design process, helping automate many phases once carried out by hand. In the creative phase, computational synthesis methods aim at facilitating designers' task through the automated generation of optimally directed design alternatives. Nevertheless, applications of these techniques are mainly academic and industrial design practice is still far from applying them routinely. This is due to the complex nature of many design tasks and to the difficulty of developing synthesis methods that can be easily adapted to multiple case studies and automated simulation. This work stems from the analysis of implementation issues and obstacles to the widespread use of these tools. The research investigates the possibility to remove these obstacles through the application of a novel technique to complex design tasks. The ability of this technique to scale-up without sacrificing accuracy is demonstrated. The successful results confirm the possibility to use synthesis methods in complex design tasks and spread their commercial and industrial application.

Keywords: computational design methods; generative design; design synthesis methods; design automation; simulation-based design; multi-objective design optimisation.

1 INTRODUCTION

Research in computational generative methods has been introduced with the intent to support designers in the creative phase of the design process (synthesis). These techniques can help finding alternative design solutions and, at the same time, guarantee a better search of the design space in a fast effective way. In the last decades, complexity of optimisation algorithms and their integration with artificial intelligence and machine learning techniques have brought to big advances in the field. Powerful and fast machines have also increased the efficiency with which designs can be generated, allowing growing degrees of complexity for the solutions found. Nevertheless, applications of these techniques are mainly academic, as many open issues remain in this field of research [1]. Synthesis methods, if compared to other computational design tools, keep a peripheral role in the design process and, excluding some sectors, design practice in industrial environments is still far from applying them routinely. The main cause of their limited use is the difficulty of implementing methods for the solution of tasks that require a multidomain knowledge. Another important implementation issue is transferring to synthesis methods the scalability properties that would allow them to handle increasingly difficult tasks. Finally, most of the time synthesis methods are conceived with the purpose of solving a single design task, not allowing their reusability.

This work stems from the analysis of these issues. With the intent to extend their use beyond purely academic applications, here is investigated the possibility of these methods to scale up with applications of industrial complexity. For this purpose, CNS-Burst is the method used: a generative technique previously developed by the authors to test the use of stochastic optimisation algorithms in synthesis tasks [2,3]. The method combines a multicriteria generate-and-test search with an object-oriented, system-based representation, and is able to link automatically to multiphysics simulation for quantitative evaluation of design performances. In previous works, the method has been benchmarked against other methods and successfully applied in different case studies [2,3].

This paper will not present in details CNS-Burst, solely used here for the aforementioned purpose. Neither its validation against other methods will be repeated. References [2, 3] give extended background on CNS-Burst, while Section [3] of this paper will give a general overview of it. What will be reviewed here are considerations on:

- The implementation characteristics of CNS-Burst that make it able to scale-up to complex tasks
- What can be achieved from the application of CNS-Burst in comparison with existing methods whose application was limited to simplistic examples.

What will be proposed here is an exploration of the extendibility and the ability of the method to scale-up to difficult tasks without sacrificing accuracy. This will be done applying the method to complex example of industrial relevance, stretching its boundaries and capabilities to understand how viable can be the integration of computational synthesis in real design practice.

Particular attention has been put in finding the right design field and tasks to serve this purpose. The method is here applied to Microelectromechanical Systems (MEMS) design. MEMS represent the ideal case study for this exploration, due to their design complexity and multi-domain nature. The work confirms the possibility for the method to be applied to complex MEMS applications, removing previous limits on the use of synthesis methods for MEMS development. The case study examined shows how MEMS applications can benefit from computational synthesis techniques. Also, CNS-Burst method introduce itself as an innovative techniques in a field where generative design tools had limited scope so far and design is entirely executed by hand. The results confirm the possibility for computational synthesis to be used in complex scenarios.

2 BACKGROUND

For almost half a century computational design synthesis has been an active research field [1] and today a wide range of problems may be solved through these techniques. Computational generative methods span many fields of engineering. Noticeably, structural and electronic engineering are the fields that benefited most from their advances. The breadth of existing methods is vast and attempts to categorise them have been many. Generative methods can be focused on size, shape and topology optimisation tasks. Some of them are centred on the development of libraries of building components, others on libraries of physical effects that play a role in design functioning. Nevertheless, many of the methods developed, are unable to address multiple design tasks. Often the generated solutions cannot be automatically linked to accurate and appropriate simulation software. And if many of the works found in literature are examples of successful applications, very few of them demonstrated to be solid enough to be commercialised. A detailed literature review of synthesis techniques and their applications can be found in [4] and [5].

2.1 Synthesis Methods for MEMS

Interest in MEMS market has been soaring in the last decades, expediting the development of various devices. However, despite their vast commercial use, MEMS are still designed through complex hand calculation, followed by behavioural analysis that makes use of specialised software tools. A number of CAD iterations involving simple functional simulations are usually attempted during the prototyping phase. As a result, fabrication replaces simulation in the iterative design loop. This is a time consuming and expensive process, since fabricated prototypes often do not meet performance specifications. And although MEMS represent an ideal field for the application of generative methods, high investments in fabrication have not been strong motivators to the development of synthesis tools for MEMS. One of the reasons for this may be due to the design complexity of MEMS resulting in part due to their multi-domain nature. The integration with electronics and the coupling between several physical effects used to control product behaviour requires interdisciplinary knowledge. Other difficulties in MEMS design are related with accurately modelling certain physical phenomena at microscale, such as material losses and damping effects.

In literature, MEMS applications used to test synthesis methods are sometimes been as being simplistic, with no intent of extending these techniques to more complex design tasks. However, some computational design approaches demonstrated to be a successful milestone in the development of commercial tools for MEMS. Among them the investigations carried out by Fedder [6] and Cagan’s research groups [7] actively contributed to the field. The method developed at Berkeley by Zhou et al. is one of the most successful examples of automated design [8, 9]. This work, based on the use Multi-Objective Genetic Algorithms (MOGAs), is a non problem-specific technique that guarantees high robustness and capability to optimise for multiple design objectives. Much attention has also been devoted to the automated synthesis of microcompliant mechanisms [10, 11]. A complete review of synthesis methods for MEMS design can be found in [12].

CNS-Burst has been formulated with the idea of pushing its capabilities beyond the achievements obtained applying existing methods. CNS-Burst has been conceived as a flexible technique adaptable to different design tasks, and able to perform the search for solutions in a more efficient way. For this purpose, in previous works CNS-Burst has also been benchmarked against existing synthesis methods for MEMS design, based both on deterministic optimisation algorithms [11] and genetic algorithms [8]. These test applications showed how the method was able to provide comparable or better solutions to design tasks compared to those found with existing techniques [2]. The method was also tested in a variety of case studies, showing its adaptability to different design tasks. Finally, preliminary applications of both size and topology optimisation tasks applied to MEMS case studies of commercial interest have been previously tested with success [3].

The present work is not only a validation of the method in a case of complex topology optimisation, but represents a step forward in the implementation of synthesis tools. Their potentials are here investigated addressing the following points:

- Definition of complex and realistic design objectives: applications used to test synthesis methods are often simplistic and do not engage commercial interest. In this work the novelty consists in the application of the method to design taks that are of common interest to designers and that show a high degree of complexity and realistic design objectives.
- Direct link to accurate simulation tools that are also able to handle multiphysics analysis.

3 CNS-BURST METHOD: OVERVIEW

CNS-Burst has been developed in recent years and has not been formulated for a specific design domain or task. Given a design task formulated as an optimization task, the computational synthesis technique is based on the automated generation of solutions using a library of parts. These building blocks are combined using a set of rules applied by a simple generate-and-test algorithm. Using the rules, the search algorithm can apply modifications to a generated solution (according to design constraints) or generate solutions from scratch. Any generated solutions are simulated, evaluated, and compared among each other for inclusion in a design archive. Designs that satisfy the Pareto optimality criteria are stored in the archive to evolve a Pareto-optimal front of non-dominated solutions, according to all the solutions seen throughout the optimisation process. A solution is ‘non-dominated’ when, through pair wise comparison, it is superior to any other in the design archive for at least one objective. The Pareto-optimal front develops throughout the search process so that the outcome is a set of Pareto-optimal designs. The main modules of the architecture of CNS-Burst are (Figure 1):

1. A concise and flexible design representation method, used to embody the generated designs in a virtual object. For this purpose, a Connected Node System (CNS) has been employed. The method makes use of basic building blocks, called primitives, and nodes connecting them to build systems and subsystems of primitives. Primitives can be of different types, for example beams or masses. Nodes can be anchored or floating. The embodiment of generated design in a virtual object is essential to perform behavioural analysis of the solution.

2. A generative mechanism to generate alternative designs: the main idea behind the search method presented is to iteratively modify an initial design (represented by a connected-node system) using a library of modification operators that generate new solutions by combining primitives and altering their connectivity and internal geometry.

3. An evaluation mechanism to evaluate design objectives for each generated design: solutions are evaluated according to desired design performance criteria, stated as objectives of the search. This evaluation makes use of results returned by an integrated simulation for quantitative analysis of designs’ behaviour. The evaluation requires that complex analysis is executed through external multiphysics FEM packages embedded in the search code. Analysis tools must be able to perform rapid simulation of the designs’ behaviour and pass to the search code accurate feedback on designs’ performance. Also, design simulation must be performed automatically after each design generation.

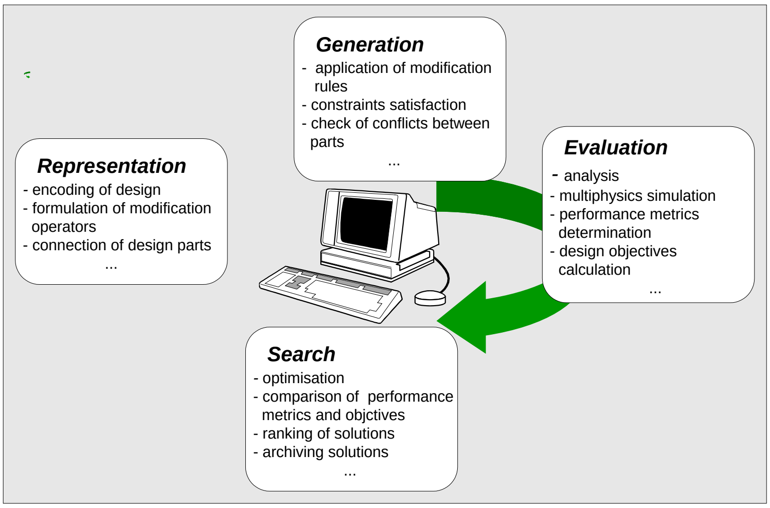


Figure 1. Computational synthesis method architecture: modules interaction.

4. An integrated multicriteria search: this module is the search method used to find feasible and optimised design alternatives. It directs the search using all the modules mentioned above: it applies modifications to existing designs and decides how to apply them, and also evaluates and compares designs. The search module used in this work has been called Burst, as it applies combinations of modification rules in short bursts. Burst is a simple multicriteria generate-and-test algorithm that provides, at the end of the search, a final archive of Pareto-optimal solutions.

All the modules of the architecture of CNS-Burst have been implemented by the authors, except for the ones used for evaluation of designs, which is executed through the use of external off-the-shelf behavioural analysis packages to be integrated in the search.

3.1 New Implementation Solutions Introduced by the Method

This section introduces some considerations on the characteristics of CNS-Burst that makes it a flexible, scalable tool and that differentiate it from other existing methods. The first consideration is that rule based design methods require a rather large degree of flexibility in the exploration engine. Among many different approaches that have been taken in the past to define generative design methods, stochastic optimisation algorithms incorporate probabilistic elements in the algorithm itself (through random variables, random choices, etc.) [13] and have been successfully applied to complex engineering tasks such as structural ones. The main advantage of these methods lies in their randomness that introduces in the search a non-prejudicial element, typical of creative designers in action, and that enables to bring about novel and alternative designs. Generate-and-test implementation is perhaps the most flexible type of stochastic search in this respect, as it offers the advantage of covering the entire design space. The approach does not require problem-specific tuning and is very easy to apply to a wide range of multiobjective searches without modifications.

The second consideration is related to the architecture of synthesis methods and its influence on flexibility and scalability. On this regard, a good implementation solution consists in developing methods with some characteristics that are recognised to have an effect on scalability. These are modularity, regularity and abstraction [14]. Most of the time synthesis methods are conceived without taking into account any of these characteristics. Moreover, they are designed solely to be used in a single design task, not allowing their reusability. CNS-Burst has been entirely implemented in MATLAB. Characteristics of adaptability and flexibility have been considered in the architecture of the method, which is based on a modular programming paradigm [15]. Each of the fundamental components of the method has been implemented as a stand-alone module, independent from the others. This allows for desired changes in each module without affecting the rest of the code, enabling also straightforward inclusion of new domain knowledge and external analysis/simulation packages.

The final and probably most relevant consideration is the importance of multiphysics analysis integration in the method. Design of complex devices requires accurate multiphysics simulation and post-processing. Particular attention has been put in the choice of a complete analysis tools that could guarantee not only accurate but also complete evaluation of solutions. The aspect that differentiates the use of analysis and simulation tool, compared to other attempts in literature, is the direct and automated link to COTS simulation and evaluation packages. This integration has been conducted via API. The capability to be linked to multiphysics simulation tools is again an advantage created by the modular structure of the method, allowing any analysis software to be easily plugged into the search code. The external package used in this work is COMSOL, a general multiphysics FEM simulation package, able to perform both linear and non-linear analysis. A more extended description of the method and its modules can be found in [15].

4 AN EXAMPLE OF COMPLEX APPLICATION: SYNTHESIS OF MICRORESONATORS

A resonator is a device with a vibratory natural response, actuated by the application of an electrically generated force. Resonators can be considered as second order mass-spring-damper mechanical systems consisting of a central resonant mass suspended by spring structures. Mechanically resonant structures are used widely in communication systems, in area of timing and frequency control. Due to their compact size, microelectromechanical resonators have opened new possibilities for single-chip and low-power wireless communication systems [16].

The development of new sensors to be fabricated by silicon micromachining techniques requires many prototypes to be tested. Automated generation of designs can be employed in order to reduce the design time necessary to obtain the high number of prototypes required for experimentation. For this reasons, microresonators have fast become the micro-device most often investigated using generative methods. Important works are those of Fedder [7] and Zhou [9] on meandering resonators, although the case studies examined were not taking into account some design parameters that are considered of industrial relevance. The interest in automating microresonators design rests in the many challenges presented by their design. Among them, the need of designing structures that vibrate according to preferred modes and directions. Other challenges are represented by energetic considerations expressed by the dissipation of energy in the structure for given vibration mode. These characteristics are represented by conflicting performance parameters, making designers' task particularly complex. The energetic and vibrational considerations taken into account in the application of CNS-Burst that follows can be considered an innovation in MEMS computational synthesis development.

4.1 Design Task: Sandwich Microresonators

Sandwich resonators were first proposed as a new resonator topology in 2005 and have since then raised industry's interest[17]. An example of sandwich resonator is shown in Figure 2. Sandwich resonators are called this way because the resonant structure is sandwiched between two electrode beams. A typical structure is a regular one, where the sandwiched beams are arrayed in parallel in the vertical direction (Figure 2). The resonator is anchored at two edges of a central beam that runs through the length of the structure. The introduction of this new type of silicon resonator comes from the necessity to address some technical challenges, one of which is concerned with the value of the equivalent motional resistance Rm. This key parameter determines the signal to noise ratio and power dissipation of a reference oscillator incorporating the microresonator as a timing element [17]. The topology of the resonator and the coupling of mechanical and electrical domains have a strong influence on Rm. Sandwich resonators, compared to other resonant structures, were seen to better meet the requirement of minimal motional resistance for the same operating frequency. The sandwich structure is also advantageous for designers that perform design calculations by hand. The geometry is simple and the behaviour of deformed beams is predictable. The primary frequency mode of interest is the bulk in-plane one, which involves in-phase longitudinal extension associated with the array beams. This mode can be driven using an electrostatic parallel-plate excitation mechanism where two electrodes are arranged parallel to the exterior beams (shaded blue in Figure 2). More complex geometries for sandwich resonators would be difficult to examine, especially because of their unknown out-of-plane modes and complex detection of frequency modes of interest. For this reason, innovative structures remain largely unexplored, although accurate and efficient, leaving unexplored the possibility to reach more accurate resonant frequencies. The case study presented here is very complex even for expert designers. In recent years the case has been developed at industrial level by a major European electronic company and, considering its complexity, has never been used as a case study in any computational synthesis work on MEMS. The design of these devices has been so far executed by hand analysis. Figure 4 shows an optical micrograph of a sandwich resonator.

4.2 Key Design Objectives

The goal for this case study is to generate a structure that resonates in the desired mode and for a desired range of frequencies. Figure 3 shows the design area $A=H\text{x}L$ sandwiched between the electrode beams, where new topologies can be synthesised as an alternative to the typical arrayed ones. The design area A is fixed and so are its boundaries. This task leaves sufficient flexibility to allow for the creation of any truss-like structure. A theoretical model for sandwich resonator behaviour has been developed and validated by Yan et al. [18]. In this model the sandwich resonator is considered as an array of subsystems constituted by single longitudinal beam resonators. The analytical model was found to be a reasonable approximation towards estimating the resonant frequency and results obtained through the application of CNS-Burst has been compared to hand analysis results based on this approximation. For this case study, the design objectives taken into consideration are the bulk frequency and the motional resistance, as well as the quality factor. The aim is to design resonators vibrating in a desired frequency range. Resonant frequency f is in the order of magnitude of several *MHz*. The quality factor Q is a measure of the energy dissipated per cycle in the resonator. For the model considered here, it is assumed that anchor loss mechanisms are the dominant component of the quality factor. For sandwich resonators, the Q can be as high as 13,000 in vacuum. The method used here to automate the calculation of Q is based on energetic consideration [19]. Starting from the assumption that the energy lost per cycle due to anchor loss is proportional to the total strain energy present in the anchor, Q can be expressed as follows:

$$Q = \alpha \frac{E_{total}}{E_{anchor}} \qquad (1)$$

where E_{total} represents the total strain energy of the entire structure (resonant parts plus anchors) for a certain mode shape and E_{anchor} is the strain energy present in the anchors for the same mode. The strain energy in any given part of the structure is calculated using the COMSOL-MEMS analysis package. The parameter α is determined through measurements of Q obtained through experimental results [19]. Results presented show that Q in the order of 10^4 are achievable. The automated calculation of Q represents an advantage in using CNS-Burst for designers, especially considering that Q calculation is never straightforward. As for the motional resistance, it has been mentioned above that Rm is the parameter that justifies the recent interest in sandwich resonators. The motional resistance of sandwich resonators can be analytically calculated as [18]:

$$\frac{R_{m-longitudinal}}{R_{m-sandwich}} = \frac{\dfrac{\pi\sqrt{E\rho}\,g^4}{8\varepsilon_0 Q V_{DC} T}\,\dfrac{1}{W_e^2}}{\dfrac{\pi\sqrt{E\rho}\,g^4}{8\varepsilon_0 Q V_{DC} T}\,\dfrac{W_e}{nW_a^2}} = \frac{nW_a^2}{W_e^2} \qquad (2)$$

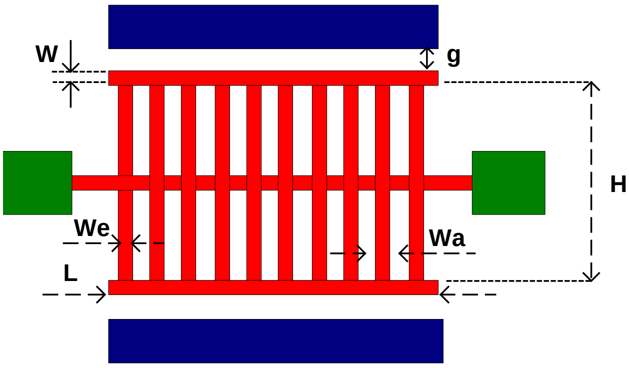


Figure 2. Sandwich resonator

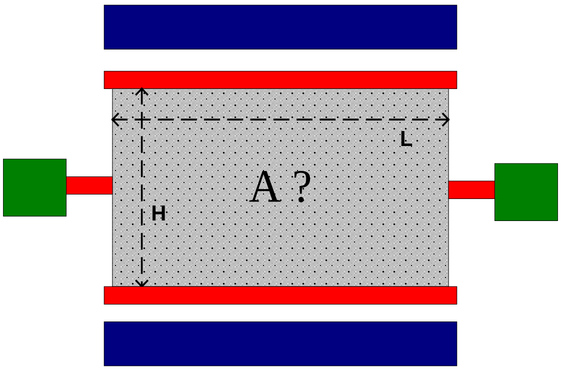
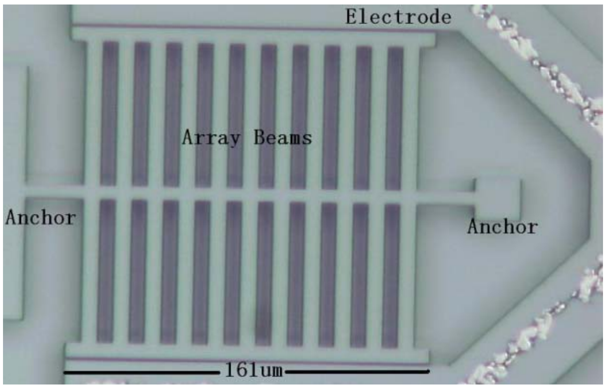


Figure 3. Sandwich resonator: the topology optimisation task.

(In green: anchors; in blue: electrodes; in red; resonant structure).



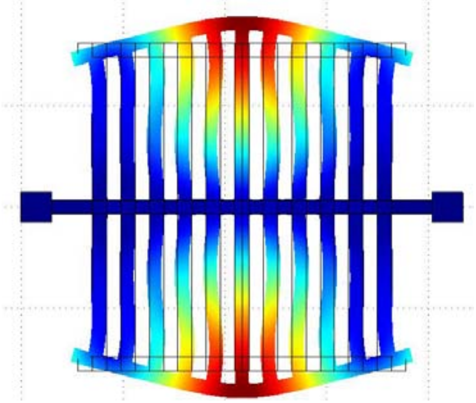


Figure 4. Optical micrograph of the resonator with outer colourelectrodes electrically shorted together [Yan, 2007].

Figure 5. Sandwich bulk mode shape (in colour mode shape resonant mode).

where W_a and W_e are the width of the array beams and the width of the additional exterior layer (i.e. double the half distance between axes of two consecutive beams, Figure 2), n is the number of beam members of the sandwich, E is the Young's Modulus, ρ is the material density, ε_0 is the dielectric constant, Q is the quality factor, V_{DC} in the operational DC voltage, T the thickness of the structure, g the gap between resonator and electrode. For the same range of operational frequencies (order of *MHz*), the R_m of a sandwich resonator value is usually in the order of magnitude of $K\Omega$. $\mathrm{R_m}$ is calculated using (2) in the case of regular sandwich resonator structures as the one showed in Figure 4, where the parameters used for the calculation are easily detectable from the geometry of the structure. For complex geometries as the one found applying computational synthesis, more considerations have to be taken into account, making the application of CNS-Burst not trivial.

Automated search of sandwich-bulk modes

The objective of this case study is to find a resonator with the required resonant frequency and resonant mode. The resonant mode in question is the sandwich-bulk mode, as the structure vibrates in plane in the direction traversal to the axis of the resonator (Figure 5). The search of the bulk mode resonator has been automated through a new module that first finds the right resonant mode for the generated design, then verifies that the resonant frequency corresponding to that mode is in the desired range. The search exploits energetic and displacement considerations based on quarter-symmetry of the design, and consists in examining pairs of symmetric electrode beams by extracting the values of a displacements matrix of their sections. As mentioned before, this verification process can be quite lengthy if executed by hand. The computational routine calculations introduced here, although showing a high degree of complexity in its implementation, proved to be reliable as well as representing an advantageous tool for designers to analyse resonant frequencies and modes of many solutions in a short amount of time. Further details of the search algorithm can be found in [15].

4.3 Results of a Standard Search with Three Design Objectives

This section reports the optimisation model used for the application of CNS-Burst to the sandwich resonator topology optimisation task. The design objectives considered are:

- A target operational frequency f_o of *25 MHz* (a constraint-satisfaction problem formulated as a soft constraint)
- A minimal motional resistance R_m (formulated as a minimisation problem)
- A maximum quality factor Q (formulated as a minimisation problem).

The optimisation model for this design task is:

$$\min\left\{|\Delta f|, R_m, \frac{1}{Q}\right\}, \tag{3}$$

$$\text{S.t.} \quad 0 \le x_j \le 161\mu m, 0 \le y_j \le 155\mu m$$

Design Constraints (see Table 1)

where $\Delta f = (f_0 - f)$, i is the number of beams used to form the structure, j is the number of nodes, (x_j, y_j) are the coordinates of a node. The minimum width (w_i) of the beam elements equal to 1µm is due to fabrication constraints. The three design objectives have a complex computational representation and have never been defined in such details in any other work on MEMS synthesis.

Table 1: Design constraints for the beam primitive.

Specific to beam primitives	**Conflicts with other beam primitives**	**Node connectivity**
• Maximum length = 161µm ▪ Maximum width = 40 µm ▪ Minimum length = 5 µm ▪ Minimum width = 1 µm ▪ Thickness = 20 µm ▪ Number of instances N≤10	• No overlap allowed ▪ Minimum separations between any two of non-connected beams = 1µm ▪ Angle between the beams θ ≥ 15°	▪ Can share normal (floating or irremovable) nodes with maximum 10 other beams ▪ If connected to anchor type node, cannot share that node with any other primitive.

The boundary limits of the design area $A=H\mathrm{x}L$ (Figure 3) are formulated as a constraint for the position of the nodes (x_j, y_j) to be in the design area. The design variables are the width of the beam primitives (w_i) forming the design, the connectivity of the beam primitives, the position of the nodes, as well as the number of beams used (i). Length and width of the electrode beams, height of the resonator, DC voltage, capacitive gap and thickness of the resonators are considered parameters and kept constant in the calculations ($W = 14\mu m$, $L = 161\mu m$, $H = 155\mu m$, $V_{DC} = 80\ V$, $g = 1\mu m$ and $T = 20\mu m$ respectively). The initial design (Figure 2) used to start the search is the one designed and experimentally tested by Yan [17] using traditional calculation methods. This design has a typical regular structure formed by eleven parallel beams, resonant frequency close to the objective target ($f_0 = 24.38\ MHz$), motional resistance around $R_m = 800\ K\Omega$, and quality factor $Q=12{,}980$ circa. The initial design reproduced with the CNS design representation showed a complex geometry, being only a quarter of its topology formed by twenty-five beam primitives and twenty-one nodes. Figure 7 shows an archive of solutions obtained from five optimisation runs at *5000* iterations each.

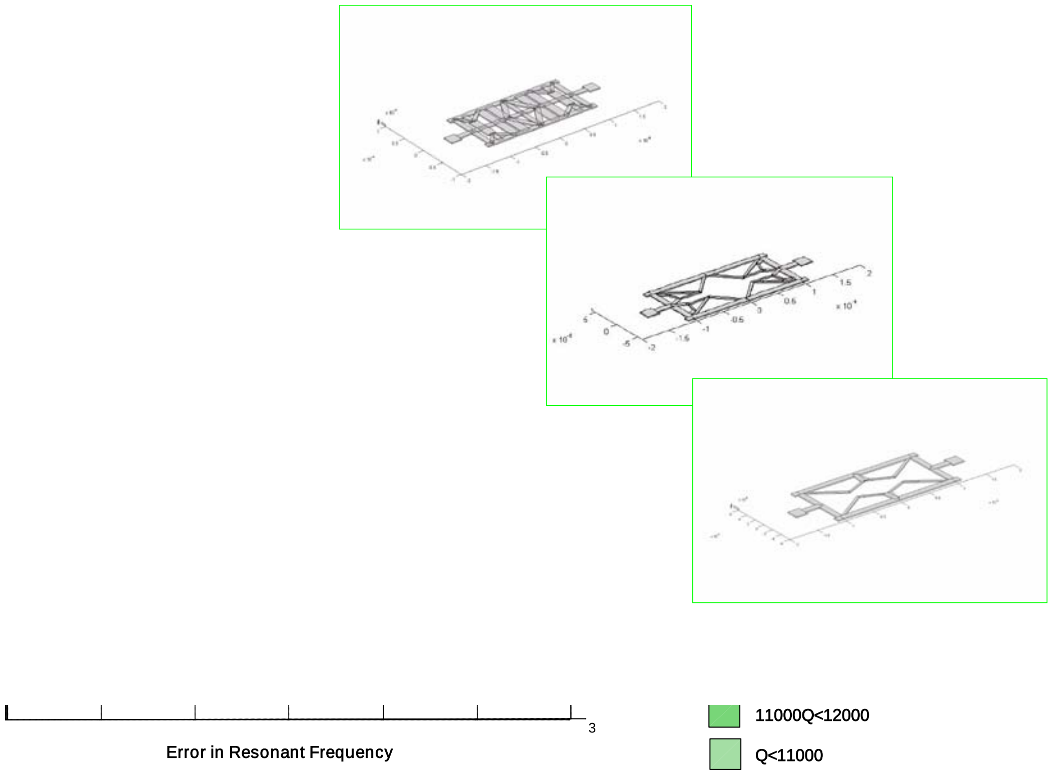


Figure 7. Archive of Solutions that resulted from five optimisation runs at 5000 iteration each (Objectives values for Designs 1-3 specified in Table 2).

Each run, resulting in an archive of non-dominated solutions distributed on a Pareto front, is overlaid on the same axes. The three coordinates of the plot represent the objectives of the search (the error in resonant frequency, the motional resistance and the quality factor: in the x, y and z direction respectively. An x-y view of the plot is given, being the values of the third coordinate z represented in different shades of green). The design archive presents a variety of solutions to the task, also illustrating performance trade-offs. The results show that *27%* of the solutions kept in the design archives have an error in resonant frequency $\Delta f < 1\%$, and that 69% of the solutions have motional resistance R_m smaller than the initial design. Design 1-3 in Figure 7 show some interesting solutions obtained. Design 3 shows a $\Delta f = 0.055\%$ of the target frequency. For design 2, $R_m=455K\Omega$ (decrement of *43%* from the initial value of R_m). A comparison of these designs with the initial design obtained with hand analysis is shown in Table 2. This preliminary search performed using a simple generate-and-test algorithm produced solutions comparable with the initial design, if not better, for even two of the design objectives. As this industrial case has only been examined through hand analysis, this comparison shows that no better solution for this design tasks can be achieved than using the method here proposed. The solutions generated showed improved performance, as well as some interesting and innovative topologies. Figure 8 presents some of the original structures obtained in the search. The commercial package used for analysis and simulation of design solutions here is the COMSOL-MEMS Module. Five searches at *5000* iterations each were run using an Athlon XP *2.8GHz*, *2GB* RAM machine, for a total time of *1h/100* iterations circa.

Table 2. Comparison of Solutions.

	Δf	**R (KΩ)**	**1/Q**
Solution1	3.178	679	$7.24\text{x}10^{-5}$
Solution 2	4.645	455	$6.63\text{x}10^{-5}$
Solution 3	0.22	889	$6.63\text{x}10^{-5}$
Hand Analysis (Initial Design)	0.62	800	$7.68\text{x}10^{-5}$

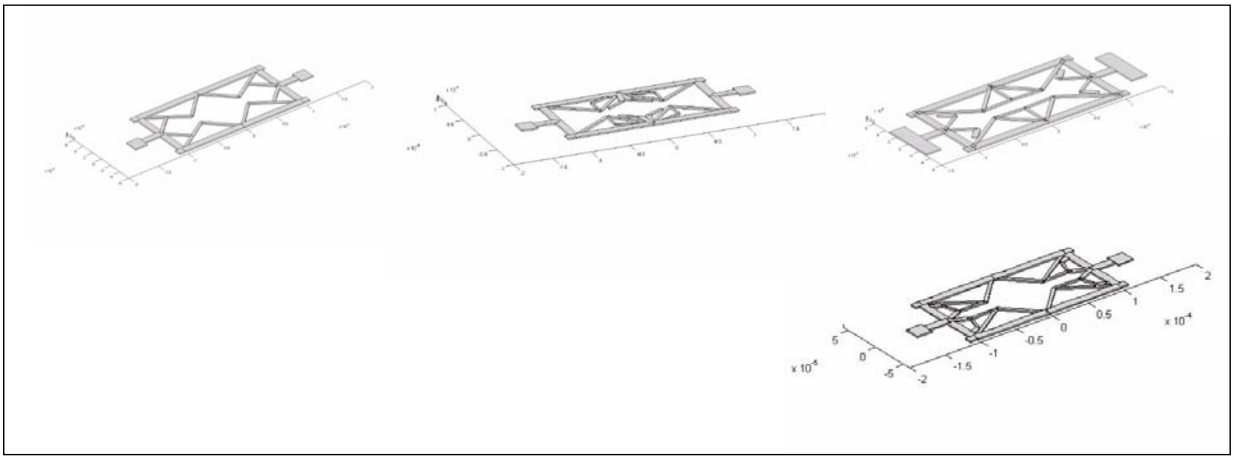


Figure 8. Variety of Sandwich resonator topologies obtained with CNS-Burst.

5 CONCLUSIONS AND FUTURE APPLICATIONS OF SYNTHESIS METHODS

Stemming from the analysis of weaknesses in the development and use of synthesis methods, this research has brought forward the need for multidomain generative tools that are able to scale up with the complexity of designs. For this purpose, a novel method was tested in a challenging application. The successful results showed its capability to incorporate sufficiently accurate modelling and simulation software, and to be scalable in complex tasks that are of practical interest to designers. In particular, comparisons with hand analysis results have shown that complexity of design objectives does not necessarily imply lack of accuracy and precision in the results. Early stage designs obtained are ready to be analysed for fabrication issues and finally manufactured. In many cases, designs solutions obtained with CNS-Burst rivalled those obtained by hand or were at least comparable in terms of one design objective, confirming the effectiveness of the method. Although the advantage, compared to design by hand, is that the technique was able to compensate computational efforts with a drastic cut of the design time. Topology design cases may in fact require a considerable amount of computational time, which is a potential obstacle to the development and use of generative methods in complex design tasks. The results obtained showed that a trade-off between computational time and successful outcome of the search is possible in automated synthesis. Successful results obtained with CNS-Burst demonstrated that not only the method is worth further investigation. This novel use of the computer in design practice can also help designers achieving the most beneficial design alternatives even in complex tasks, possibly providing innovative design solutions (as demonstrated by the new topologies of sandwich resonators obtained).

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