Synthesis of Path Generation Compliant Mechanism (PGCM) using Local Search Based Multi-objective Genetic Algorithm

State of the Art Seminar

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Overview

- Introduction
- Literature Review
- Proposed Approach
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- Future Work
- References

1. Introduction

1.1 Definition

Compliant mechanisms are flexible structures which generate some desired path and/or transmit force by going elastic deformation (under some applied load) instead of through rigid linkages/joints as in rigid body mechanism.

1.2 Advantages

- Less friction, reduce wear and need of lubrication
- Ease of manufacturing without assembly
- Jointless structure and Monolithic nature
- Reduction in Backlash Error
- Reduction in vibration and noise
- Reduction in weight over rigid body counterparts

1.3 Applications

- Product Design
- Offshore structures
- Smart Structures
- MEMS : Microstructure structure, sensors and actuators

2. Literature Review

- Two approaches of systematic design of Compliant Mechanism
  - Kinematic based approach
  - Continuum Mechanics based approach

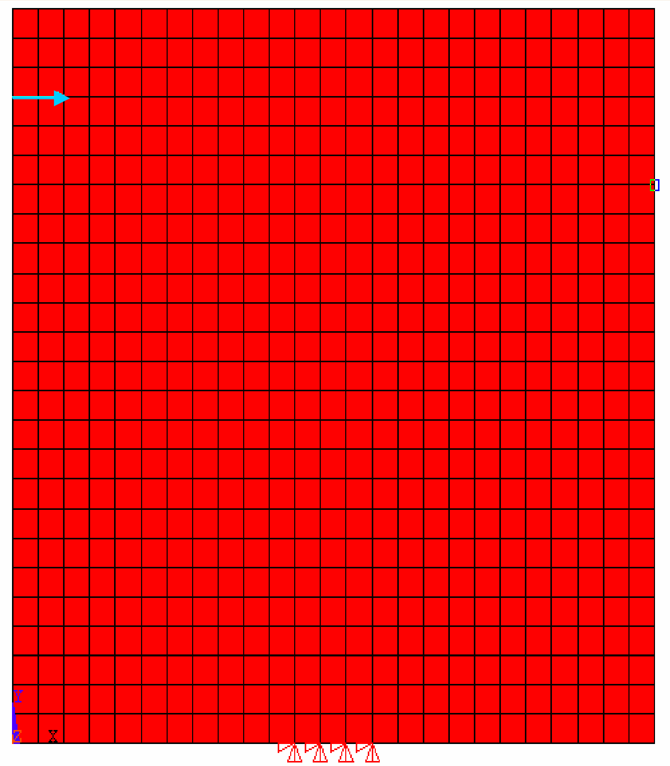
2.1 Kinematic based approach

Midha, Her and Salamon[1992], ,Howell and Midha [1995,1996], Hetrick, Kota [1999]

- Pseudo rigid body models
- Converting hinges into elastic hinges
- Nonlinear behavior
- Limitation: Manufacturing of hinges at micro level

2.2 Continuum Mechanics based approach

- Focuses on the determination of the topology, shape and size of the mechanism
- Popular strategy:
  - ➢ Discretize the allowable design space (FE)
  - ➢ Apply Boundary Conditions
  - ➢ FEM Analysis
  - ➢ Optimization algorithm
    - Determines whether element contains material or void



2.3 Different methodologies in continuum based approaches

- By Homogenization method { Bendsoe, Kikuchi, Nishiwaki, Frecher, Min [1988, 1998] }
  - Material property depends: Size and orientation of the void within the element
  - Multi-objective problem
    - Based on kinematic requirement (Max. of mutual mean compliance between input and output ports)
    - Based on structural requirement (Min. of mutual mean compliance between output region and work-piece)
  - Weighted Sum of objective functions or ratio of objective functions
  - Sensitivity analysis of objective function with respect to design variables using differential calculus.
  - Sequential Linear programming (SLP)

Different methodologies in continuum based approaches (Continued…)

- Material density approach {Yang & Chuang[1994], Kumar & Gossard [1996], Yin &Anathasuresh [2001] }
  - Material Density of each element
- Discrete variable approach using Genetic Algorithm {Chapman, Saitou, Jakiela, Duda [1994, 1996, 2000] }
  - One dimensional (0-1) binary coded bit string chromosome
    - "0" represents no material in the element
    - "1" represents a material in the element
  - Min. of structural compliance subjected to maximum volume
  - Limitation: Check board pattern and floating elements

2.4 Topology optimization of Compliant Mechanism

- Anathasuresh, Kota & KiKuchi [1994]:
  - Maximizing the stiffness (or Minimizing the strain energy)
  - Maximizing the output along desired direction
- Kumar & Gossard [1996]:
  - Shape density function over the structure
  - Assign a threshold value: Below this value refers a hole in the structure
  - Minimizing the compliance subjected to mass of the structure
  - Optimization
    - Sequential Linear Programming (SLP)

Topology optimization of Compliant Mechanism (Continued…)

- Sigmund [1997]:
  - Maximizing the mechanical advantage (a ratio between the output and input forces)
  - Subjected to Equilibrium equation of motion, volume, deflection at input port and bounds on element density.
  - Sequential Linear Programming (SLP)
- Larsen, Sigmund & Bouwstra [1997]:
  - Material with Negative Poisson's ratio (Lake's foam)
    - Used in designing of Hydrophones and other sensors
    - Low bulk modulus of NPR materials & sensitive to hydrostatic pressure
  - Minimizing the summation of Mechanical and Geometrical advantages
  - Use Homogenization method for FEM analysis
  - Constraint on volume and bounds on elemental densities
  - Optimization algorithms: Simplex Method

- Frecker, Ananthasuresh, Nishiwaki ,Kikuchi, Kota, Min [1997, 1998]:
  - Maximizing the ratio of mutual potential energy (or output displacement) and strain energy
  - Truss ground structure's constraints
    - Equilibrium equation of motion, volume, and limits on areas of truss members
  - Continuum problem's constraints
    - Equilibrium equation of motion and volume
  - Sequential Linear Programming (SLP)

Topology optimization of Compliant Mechanism (Continued…)

- Kota, Joo, Li, Rodgers, Sniegowski [2001]:
  - Maximizing the ratio of Geometrical Advantage to Strain Energy
  - Subjected to Equilibrium equation of motion, volume and bounds on area.
  - Sequential Linear Programming (SLP)
  - Example: Stroke Amplification mechanism
- Chen, Silva, Kikuchi [2001]:
  - Material Density function
  - Design of Compliant Mechanism: Maximizing the ratio of mutual mean compliance and composite mean compliance function
  - Subjected to Equilibrium equations and volume
  - Design of Flextensional Actuators: Maximizing the ratio of mean transduction and mean compliance
  - Optimization algorithm: Sequential Linear Programming (SPL)

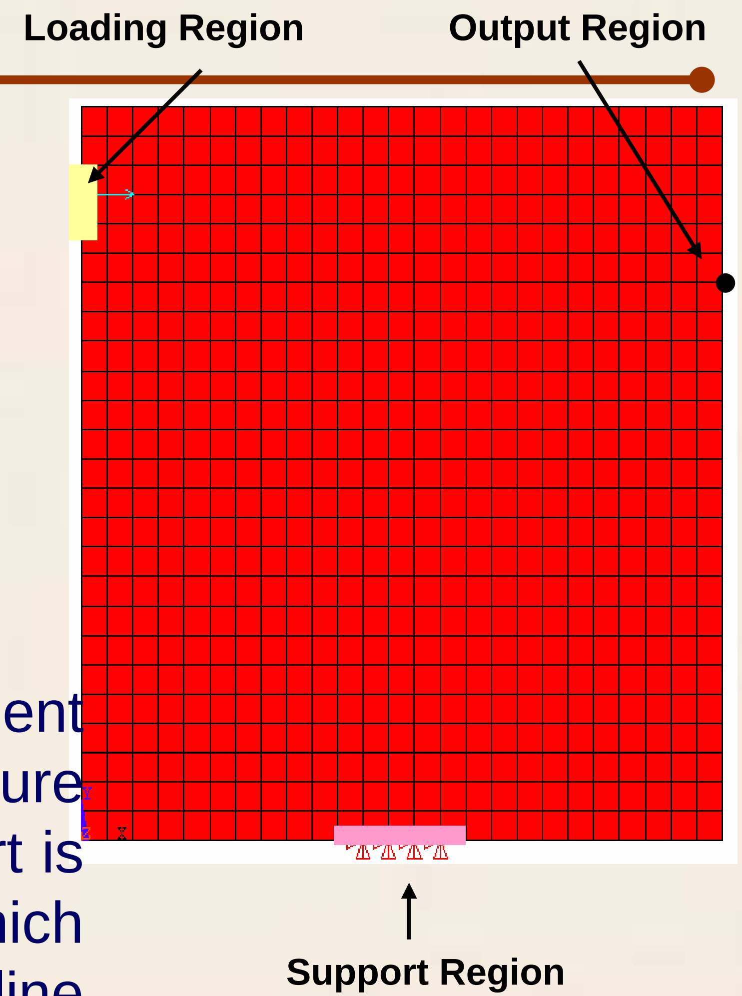
- Yin, Anathasuresh [2001]:
  - ➢ Use continuous peak function for material interpolation (Linear combination of a normal distribution function)
    - Advantage: Multiple material can easily be incorporated
  - ➢ Minimizing the ratio of mutual strain energy under input force to the mutual strain energy under dummy unit force at output subjected to volume constraint.
- Parsons, Canfirld [2002]:
  - ➢ Different objective functions for different complaint structures
    - Maximizing the Mechanical efficiency
    - Maximizing the Geometrical advantage
    - Maximizing the Mechanical advantage
    - Minimizing the maximum compressive load
  - ➢ Optimization tool: Genetic programming (GA)

2.5 Limitations

- Single objective analysis.
- Linear FE models are used for synthesis of Compliant Mechanism.
- Transforming a discrete problem into a continuous one.
- Using classical optimization techniques.
- Prescribing a threshold value for variables.
- Arbitrary interpretation : Lead to non-optimum designs

2.6 Path Generation Compliant Mechanism

- Three important regions:
  - ➢Prescribed Boundary conditions
  - ➢Output port is moving along a desired trajectory or path



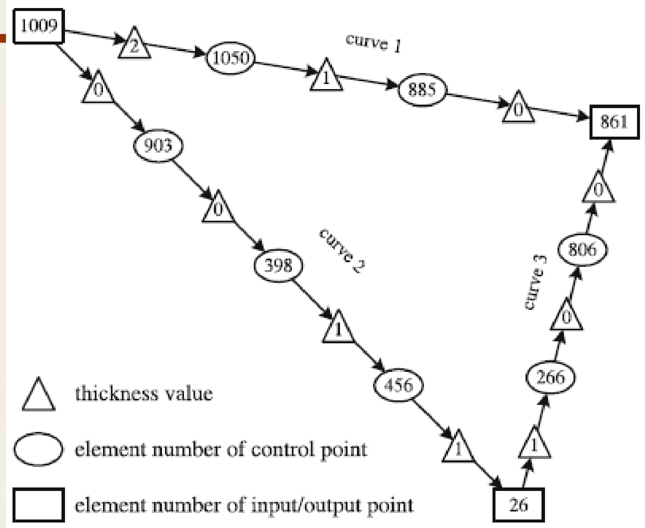
- When an input force or displacement boundary condition is prescribed, structure deforms elastically such that another part is displaced along some desired path which may be a curvilinear or straight line trajectory

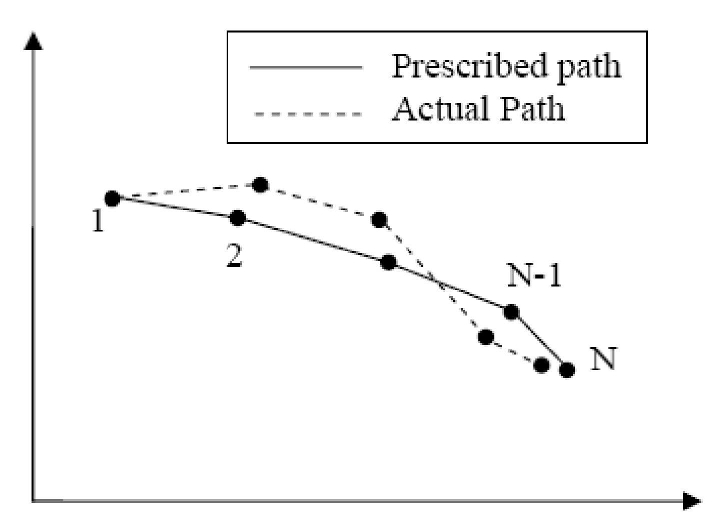
Path Generation Compliant Mechanism (Continued…)

- Tai, Akhtar, Cui, Ray, Chee [2000, 2002, 2005]:
  - Chromosome string
  - Morphological Technique
  - Geometrical Nonlinear model (Abaqus software)
  - Objective functions

$$d_{avg} = \frac{1}{N} \sum d_i$$

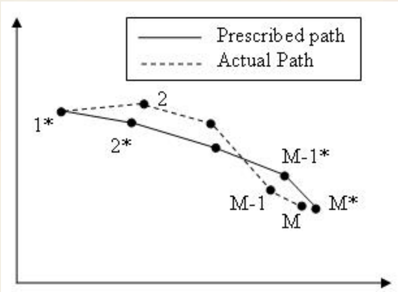
  - Constraint: Input force should be less than the prescribed values
  - Evolutionary algorithm (GA)





Path Generation Compliant Mechanism (Continued…)

- Pederson, Buhl, Sigmund [2000, 2001]: Topology synthesis of large displacement compliance mechanism
  - Geometrical Nonlinear model
  - Topology optimization problem:
    - Max. of output displacement
    - Constraints: Input displacement, elemental volume, material density
  - Path generation mechanism problem $\Phi = \sum_{m=1}^{M} \left[u_{out,m} - u^{*}_{out,m} \right]^2$
    - Min the summation of error
    - Constraint : Input reaction force at each precision point, elemental volume, material density
  - Sensitivity Analysis: Adjoint method
  - Optimization problem
    - Method of moving asymptotes



Path Generation Compliant Mechanism (Continued…)

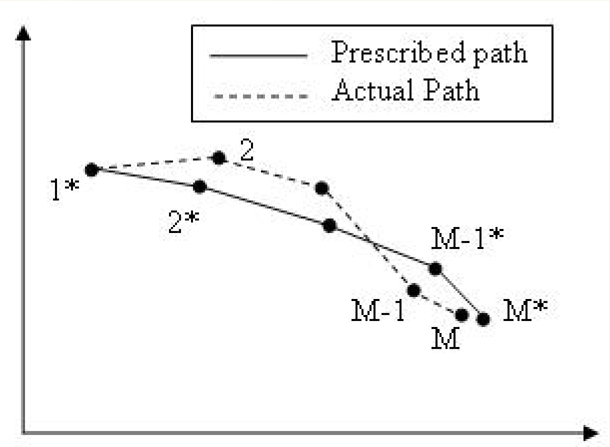
- Saxena and Anathasuresh [2001]:
  - Maximizing the Geometrical Advantage
  - Using Geometrical Nonlinear FE model
  - Frame elements : For implementing general approach and capturing bending modes
  - For sensitivity analysis:
    - Direct Differentiation Method
    - Adjoint Variable Method
  - Optimization Problem
    - Sequential Quadratic Programming (SQL)

Path Generation Compliant Mechanism (Continued…)

- Saxena [2005]: Genetic algorithms used for synthesis of path generation complaint mechanism.
  - Objective functions

$$Minimize: \left(u_{out,m} - u^{*}_{out,m}\right).\left(u_{out,m} - u^{*}_{out,m}\right)$$

$$for\ m = 1, \ldots, M$$



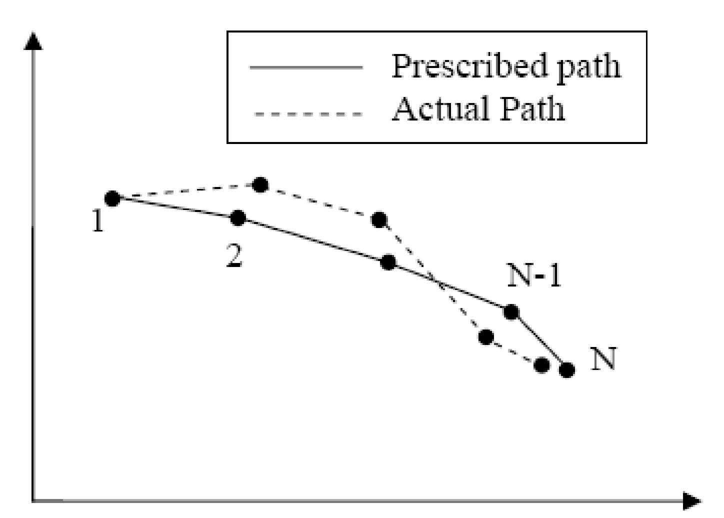
  - Geometric Nonlinear FE model
  - Optimization problem
    - NSGA-II algorithm

Path Generation Compliant Mechanism (Continued…)

- Saxena [2005]:
  - Large displacement complaint mechanism with multiple materials and multiple output ports
  - Variable: Elastic modulus of each element
  - Barrier assignment approach: Multiple materials
  - Objective function for a single output port:
    - Ratio of output displacement and strain energy
  - For multiple output ports, the same number of ratio objectives may be considered.
  - Minimize Volume of continuum
  - Optimization using NSGA-II

3. Proposed Approach

- Two Conflicting objective problem
  - ➢Minimization of weight
  - ➢Minimization of input energy
- Constraints
  - ➢ Maximum 10 % deviation at each precision point



Proposed Approach (Continued…)

- 4 node rectangular element (2 dof per node)
- Discretized structure: Representation scheme Fig
- Connectivity through repairing
- Geometrical nonlinear FE model (with the help of ANSYS)
- A parallel multi-objective GA
  - Parallelization

search power of an evolutionary algorithm α number of function evaluations

- A spring of constant stiffness at the output point

- Optimization using NSGA-II
  - Obtain a number of trade-off solutions
- Clustering { Zitzler [1999] }
  - Pick a few representative trade-off solutions
- Local Search{ Goel [2001], Chaudhuri [2002] }
  - Improve the quality of GA solutions
  - Helps in reducing the computational time

$$F(x) = \sum_{j=1}^{M} \frac{\bar{w}_j \left(f_j{}^{(x)}{}_{\max} - f_j{}^{(x)} \right)}{\left(f_j{}^{(x)}{}_{\max} - f_j{}^{(x)}{}_{\min} \right)} \qquad \bar{w} = \frac{\left(f_j^{\max} - f_j^{(x)} \right) / \left(f_j^{\max} - f_j^{\min} \right)}{\sum_k^M \left(f_k^{\max} - f_k^{(x)} \right) / \left(f_k^{\max} - f_k^{\min} \right)}$$

- Local based search
  - Select a representative solution and calculate weighted sum of the scaled fitness
  - Check all elements having material
  - Mutate a bit one by one around all 9 positions
  - FEM analysis after bit wise mutation
  - Calculate weighted sum of the scaled fitness of new string
  - Compare weighted sum of the scaled fitness of new and old string

- Criteria:
  - In case of mutating "0" bit to "1"

Weighted sum of scaled fitness of new string < Weighted sum of scaled fitness of old string with satisfying all constraint

  - In case of mutating "1" bit to "0"

Weighted sum of scaled fitness of new string $\leq$ Weighted sum of scaled fitness of old string with satisfying all constraint

  - Else reject the new change and restore all values
- Termination criteria of local search
  - If there is no bit change and
  - If there is no change in values of weighted sum of scaled fitness

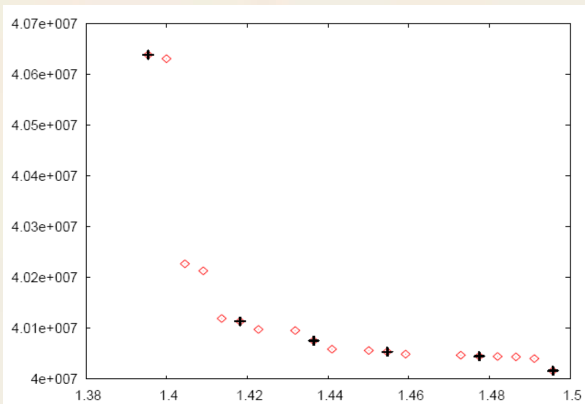
4. Case Studies

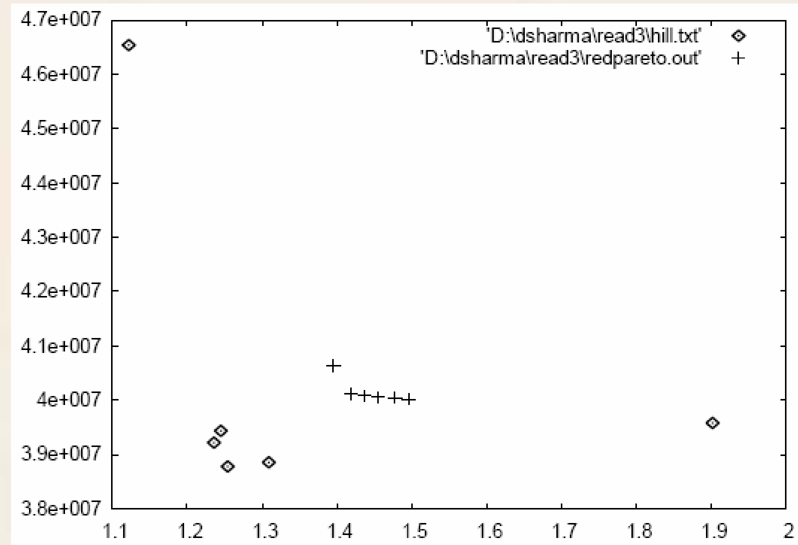
- Two case
  - Straight Line Trajectory
  - Curvilinear Trajectory
- Same Design Specification for both cases
  - 50mm by 50mm
  - 25 by 25 elements (4 node rectangular element)
- Material : Nylon (3.3 GPa and Poisson ratio of 0.4)
- Applied force: 5 N in five steps (1N in each sub-step)

- Prescribed Trajectory
  - Divide into 5 precision points
- A spring of constant stiffness (0.4KN/m)
- NSGA-II
  - Generation: 200
  - Population size: 192
  - Crossover probability : 0.95
  - Mutation probability : 1/ String length
- Six representative solutions have been chosen from Pareto-optimal front {End clustering}
- Local search is employed.

Case Studies (Continued…)

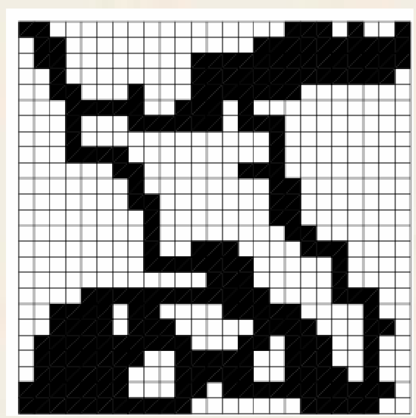
- Straight line trajectory

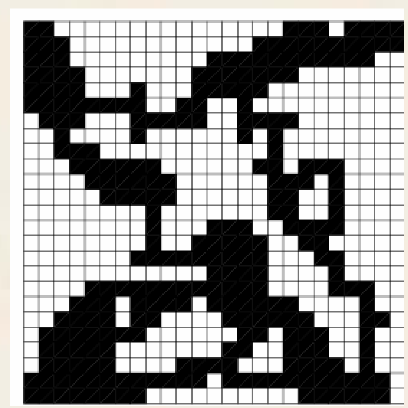


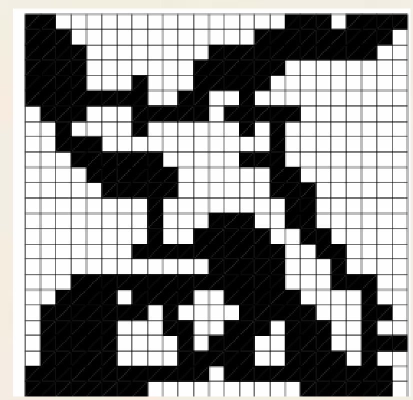


- Deflection

15 % in X-dir.





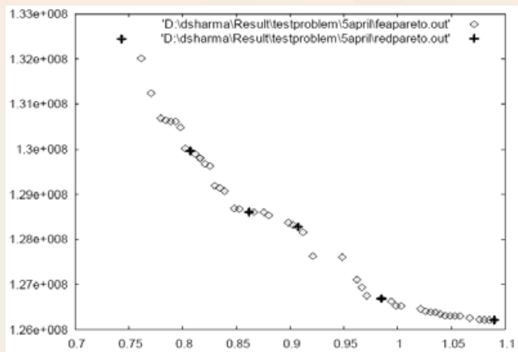


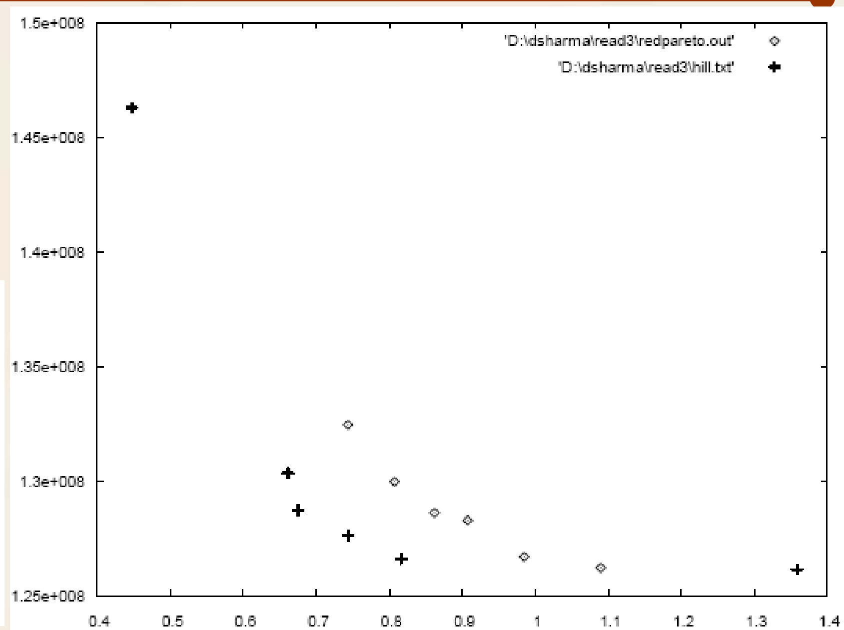
Case Studies (Continued…)

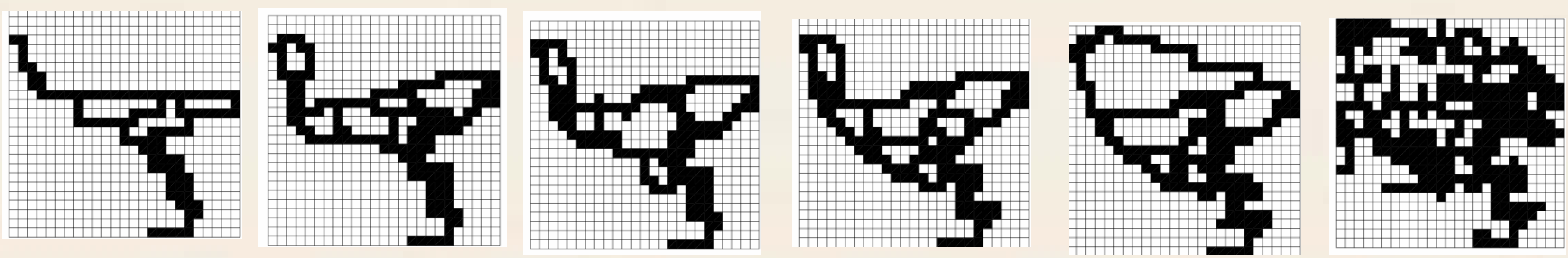
- Curvilinear Trajectory
- Deflection: 29% in X

  27% in Y

Output







5. Conclusions

- Posed Multi-objective problem shows a conflicting nature of both objectives for PGCM synthesis.
- NSGA-II algorithm is coupled with geometrical nonlinear finite element model and showing a trade off between the two objectives.
- The proposed local search based MOGA approach is efficient to find optimal topologies of PGCM.
- PGCM problems are computationally intensive. Parallel implementation of the algorithm makes the entire process fast.

- Knee solutions after local search
- Knee solutions are showing almost same values of objective functions but have different designs due to the presence of some stiffeners.

6. Future Work

- Include some other conflicting objective functions
- Further refining the meshing.
- Morphing technique.
- Constraint on stress.
- Varying boundary conditions (in fixed range) for robust designing.
- Manufacturing aspect in the synthesis of PGCM.
- Some experimental studies

7. References

1. Howell, L., and Midha, A., 1995“ A Method for the Design of Compliant Mechanism with Small-Length Flexural Pivots,” ASME J. Mech. Des., 116, pp. 280-290.
2. Ananthasuresh, G. K., and Kota, S., 1995, “Designing Compliant Mechanism,” Mech. Engg.(Am. Soc. Mech. Engg.) 117, (11), Nov., pp 93-96.
3. Ananthasuresh, G. K., 2003, “Optimal Synthesis Methods for MEMS,” Kluwer Academic Publishers.
4. Midha, A., Her, I., Salamon, B.A., 1992 ” A Methodology for Complaint Mechanism Design: Part I-Introduction and Large Displacement Analysis,” In DE-vol. 44-2, Advance in Design Automation-vol.2ASME:New York, 29-38.
5. Her, I., Midha, A., Salamon, B.A., 1992 “ A Methodology for Complaint Mechanism Design: Part II-Introduction and Large Displacement Analysis,” In DE-vol. 44-2, Advance in Design Automation-vol.2ASME:New York, 39-45.

References (Continued…)

6. Howell, L.L., Midha, A., 1996, " A Loop-Closure Theiry for the Analysis and Synthesis of Compliant Mechanism,'" ASME J. Mech. Des., 118, pp. 121-125.
7. Hetrick, J.A., Kota, S., 1999 "An Energy Formulation for Parametric Size and Shape Optimization of Complaint Mechanism," Journal of Mech. Des., 121, pp 229-234.
8. Bendsoe, M.P., 1998 "Generating Optimal in Structral Design using a Homogenization Method," Comp. Methods in Appl. Mechanics and Engg., 71, pp 197-224.
9. Yang, R.J., Chuang, C.H., 1994 " Optimal Topology Design Using Linear Programming," Comput. Struct., 52, pp. 265-275.
10. Chapman, C.D., Saitou, K., Jakiela, M.J., 1994, " Genetic Algorithms an Approach to Configuration and Topology Design," ASME J. Mech. Des., 116, pp. 1005-1012.
11. Chapman, C.D., Jakiela, M.J., 1996, " Genetic Algorithm Based Structural Topology Design with Compliance and Topology Simplification considerations," ASME J. Mech. Des., 118, pp. 89-98.

References (Continued…)

12. Jakiela, M.J., Chapman, C.D., Duda, J., Adewuya, A., Saitou, K., 2000, "Continuum Structural Topology Design Design with Genetic Algorithms," Comput. Methods Appl. Mech. Engg., pp. 339-356.
13. Ananthasuresh, G.K., Kota, S., Kikuchi, N., 1994, "Strategies for Systematic Synthesis of Compliant Mechanisms, " Proceedings of the 1994 ASME winter Annual Meeting, Nov., Chicago, IL, pp. 677-686.
14. Kumar, A.V., Gossard, D.C., 1996, "Synthesis of Optimal Shape and Topology of Structures," ASME, J. Mech. Des., 118, pp. 68-74.
15. Sigmund, O., 1997, "On the Design of Compliant Mechanisms Using Topology Optimization," Mech. Struct. Mach. 25, pp. 493–524.
16. Larsen, U. D., Sigmund, O., Bouwstra, S., 1997, "Design and Fabrication of Compliant Micromechanisms and Structures with Negative Poisson's Ratio," J. Microelectromech. Syst., 6, pp. 99–106.
17. Frecker, M. I., Ananthasuresh, G. K., Nishiwaki, S., Kikuchi, N., and Kota, S., 1997, "Topological Synthesis of Compliant Mechanisms Using Multi-Criteria Optimization," ASME J. Mech. Des., 119, pp. 238–245.
18. Nishiwali, S., Frecker, M. I, Min, S., Kikuchi, N., 1998, "Topology optimization of Compliant Mechanism using the Homogenization Method," Int. J. Numer. Meth. Engng., 42, pp. 535-559.

References (Continued…)

19. Saxena, A., Anathasuresh, G.K., 2000, " On an optimal Design of Compliant Topologies," Struct. Multidisc Optim, 19, pp. 36-49.
20. Kota, S., Joo, J., Li, Z., Rodgers, S.T., Sniegowski, J., 2001, " Design of Complaint Mechanisms: Applications to MEMS," Analog Integrated circuits ans Signal Processing, 29, pp. 7-15.
21. Chen, B.C., Silva, E.C.N., Kikuchi, N., 2001, "Advances in computational design and optimization with applications to MEMS," Int. J. Numer. Meth. Engng, 52, pp. 23-62.
22. Yin, L., Anathasuresh, G.K., 2001 "Topology optimization of Compliant mechanisms with Multiple Material using a peak function material interpolation scheme," Struct Multidisc Optim, 23, pp. 49-62.
23. Parsons, R., Canfirld, S.L., 2002, "Developing genetic programming techniques for the design of compliant mechanisms," Struct Multidisc Optim, 24, pp. 78-86.
24. Tai,.K., Akhtar,S., 2005 "Structural Topological optimization using a GA with a morphological geometrical representation scheme," Struct Multidisc Optim, 30, pp. 113-127.

References (Continued…)

25. Tai, K., Cui, G.Y., Ray, T., 2000, “Design Synthesis of Path Generation Complaint Mechanisms by Evolutionary Optimization of Topology and Shape,” Proceedings of DETC’00, ASME Design Engg. Technical Conferences, Sept. 10-13, 2000, Baltimore, Maryland, USA.
26. Tai, K., Chee, T.H., 2000, “Design Synthesis of Path Generation Complaint Mechanisms by Evolutionary Optimization of Morphological Representations of Topology,” ASME J. Mech. Des., 122, pp. 560-566.
27. 26 Tai, K., Cui, G.Y., Ray, T., 2002, “Design Synthesis of Path Generation Complaint Mechanisms by Evolutionary Optimization of Topology and Shape,” Proceedings of DETC’00, ASME J. Mech. Des., 124, pp. 492-500.
28. Buhl, T., Pedersen, C.B.W., Sigmund, O., 2001 “Stiffness design of Geometrically Nonlinear Structures using Topology optimization,“ Struct Multidisc Optim, 19, pp. 93-104.
29. Pedersen, C.B.W., Buhl, T., Sigmund, O., 2001, “Topology Synthesis of Large-Displacement Compliant Mechanisms,” Int. J. Numer. Meth. Engng, 50, pp. 2683-2705.
30. Saxena, A., and Ananthasuresh, G. K., 2001, "Topology Synthesis of Compliant Mechanisms for Nonlinear Force-Deflection and Curved Path Specifications," ASME J. Mech. Des., 123, pp. 33–42.

References (Continued…)

31. Saxena, A., 2005, “ Synthesis of Compliant Mechanisms for Path Generation using Genetic Algoithm,” ASME J. Mech. Des., 127, pp. 745-752.
32. Deb, K., Agrawal, S., Pratap, A., Meyarivan, T., 2000, "A Fast Elitist Non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II," in *Proceedings of the Parallel Problem Solving from Nature VI Conference*, 16–20 September, Paris, France, pp. 849–858.
33. Changkong, V., Haimes, Y.Y., 1982 “Multiobjective Decision making theory and Methodology”.
34. Zitzler, E., 1999, “Evolutionary Algorithms for Multiobjective Optimization: Methods and Applications, Ph.D. Thesis, Zurich, Switzerland: Swiss Federal Institute of Technology (ETH).
35. Goel, T., 2001, “Optimal Shape Design of Mechanical Components for single and multi-objectives using genetic algorithms,” M.Tech. Thesis, IIT Kanpur.
36. Chaudhuri, S., 2002, “ Optimal Shape Design of Mechanical Components using Local Search Based Multi-objective Genetic Algorithm,” M.Tech. Thesis, IIT Kanpur.
37. Deb, K., 2001, “Multi-objective Optimization using Evolutionary Algorithms”, John Wiley & Sons (ASIA) Pte Ltd. Singapore
38. Saxena, A., 2005“ Topology design of large displacement compliant mechanisms with multiple materials and multiple output ports.,” Struct Multidisc Optim, 30, pp. 477-490.

Thanking You