Flight structures fundamental research trends and directions

Victor Giurgiutiu
victor.giurgiutiu@afosr.af.mil
Air Force Office of Scientific Research
Structural Mechanics Program
Arlington, VA
USA

ABSTRACT

The paper presents an overview of the fundamental research performed in the US in the field of flight structures under the sponsorship of the Air Force Office of Scientific Research (AFOSR). After presenting a general overview of AFOSR, the paper focuses on the structural mechanics program. Three large applications areas are considered: (a) future flight structures; (b) structural sustainment; (c) structural dynamics and vibration control. These three broad areas are covered at various levels of complexity and detail. Currently supported topics are presented and major funding and results are discussed. The paper ends with summary and conclusions.

1.0 INTRODUCTION

The Air Force Office of Scientific Research (AFOSR), located in Arlington, Virginia, is the component of the US Air Force Research Laboratory (AFRL) that has the mission to discover, shape, and champion basic research that profoundly impacts the future Air Force (Fig. 1). AFOSR is entrusted with leading and managing the US Air Force's basic research program. The AFOSR research areas are organised and managed in three scientific directorates[(1)]:

(1) Aerospace, Chemical, and Material Sciences

(2) Physics and Electronics

(3) Mathematics, Information, and Life Sciences

Inside each directorate, there are several research programs. For example, the Aerospace, Chemical, and Material Sciences directorate has thirteen research programs; details of these research programs can be found on the public website given in Ref. 1. One of these is the research program in Structural Mechanics.

2.0 FUNDAMENTAL RESEARCH ISSUES IN AFOSR STRUCTURAL MECHANICS PROGRAM

The AFOSR structural mechanics program encourages and sponsors fundamental basic research that will generate understanding, models, analytical tools, numerical codes, and predictive methodologies validated by carefully conductive experiments. The structural mechanics program considers flight structures fundamental research with potential impact in the following applications areas:

1. Future flight structures
2. Structural performance sustainment
3. Structural dynamics and vibration control

The AFOSR sponsors both extramural and intramural fundamental research. The extramural fundamental research takes place in academia and private companies (usually small businesses); the intramural fundamental research takes place in the technical directorates of the Air Force Research Laboratory.

Paper No. 3399. Manuscript received 6 January 2009, accepted 7 May 2009.

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press

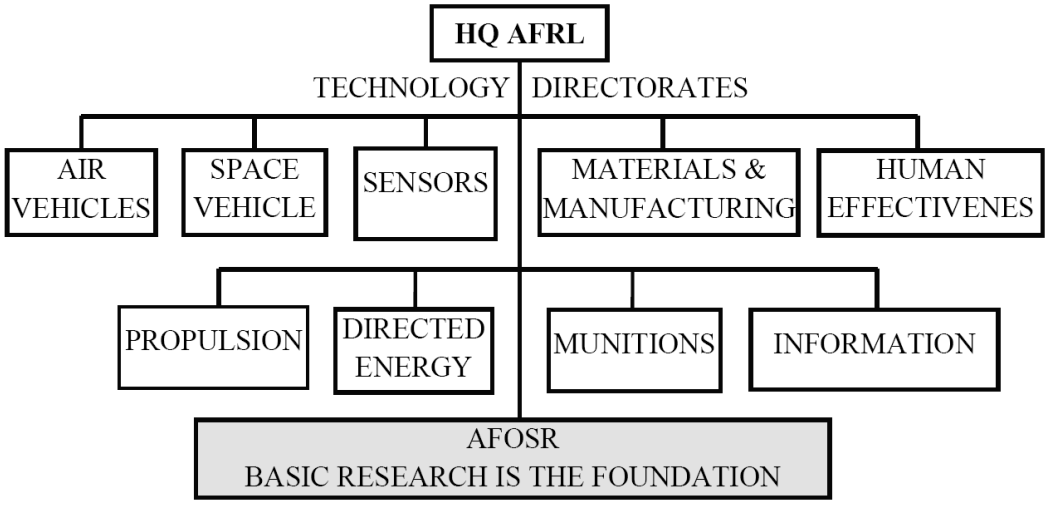


Figure 1. Organisational chart of Air Force Research Laboratory (AFRL) showing that the Air Force Office of Scientific Research (AFOSR) is the sole manager of Air Force basic research.

2.1 Future flight structures research issues

Fundamental research issues for *future flight structures* include:

- 'Disruptive' new and revolutionary structural concepts and unprecedented flight configurations
- Reconfigurable adaptive structures with on-demand shape morphing for real-time response to changing missions demands and threat environment
- Hybrid structures of dissimilar materials (metallic, composite, ceramic, etc.) with multi-material joints and/or interfaces under dynamic loads, blast, and extreme environments
- Controlled-flexibility distributed-actuation smart structures for flapping/clapping flight
- Physics-based models to predict quantitatively the materials performance and durability of future flight structures operating at various regimes

2.2 Structural performance sustainment research issues

Fundamental basic research issues for structural performance sustainment include:

- Prediction of the structural flaws distribution and service-induced damage on each aircraft and at fleet level
- Structural analysis that accounts for variability due to materials, processing, fabrication, maintenance actions, changing mission profiles
- On-board health monitoring and embedded nondestructive evaluation (NDE) to
  - (a) track mission effects on the structure
  - (b) provide on-demand structural health bulletins (diagnosis and prognosis)
  - (c) give the commander a state-awareness risk-based approach to mission planning and aircraft maintenance
- Prediction of structural 'hot spots' prone to
  - (a) cyclic plastic deformations
  - (b) local buckling
  - (c) crack growth in high-temperature flight structures, with changing material properties, and accumulating fatigue damage in local regions

2.3 Structural dynamics and vibration control research issues

Fundamental basic research issues for structural dynamics and vibration control include:

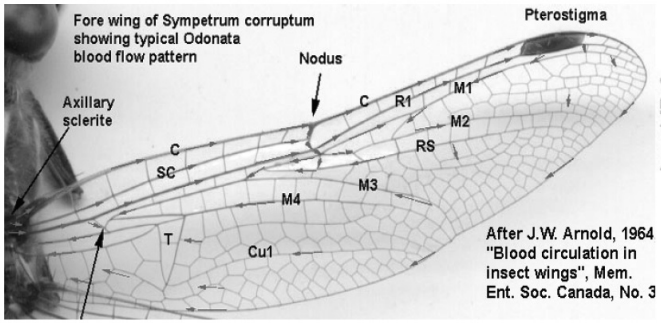
- Control of dynamic response of extremely flexible nonlinear structures
- Control of unsteady energy flow in nonlinear structures during various flight conditions
- Unsteady nonlinear structural dynamics in interaction with air flow, unsteady heating, directed energy, and servo-controls at various Mach and Reynolds numbers
- Nonlinear dynamics and vibration control of thin-wall structures of functionally graded hybrid materials with internal vascular networks under extreme loading conditions.

3.0 SPONSORED RESEARCH IN FUTURE FLIGHT STRUCTURES

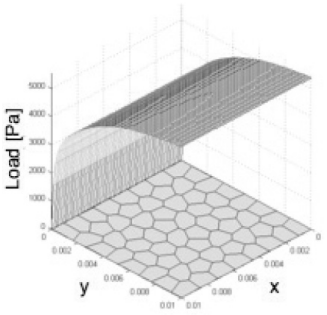
AFOSR is currently sponsoring a number of extramural and intramural fundamental research projects in future flight structures, as follows

- Sanders, Reich and their collaborators at AFRL Air Vehicles Directorate study the scientific development of flexible skins for morphing aircraft[2,3].
- Kobayashi and Butler at University of Hawaii study algorithmic tools for rational discovery and new concepts for future flight structures
- Bejan at Duke University studies the use of constructal theory[4] for thermal management of hot flight structures[5] and self healing composites[6].
- Rahn and Tadigadapa at Penn State University study the development of MEMS-fabricated piezoelectric airframes for nano air vehicles
- Friedmann at University of Michigan studies structural dynamics and vibration response at the micro scale
- Lesieutre and Frecker at Penn State University study the topology optimisation of mechanised morphing aircraft
- Moorhouse and his collaborators at AFRL Air Vehicles Directorate study the exergy-based multidisciplinary design of future flight vehicles[7,8].

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press



(a)



(b)

Figure 2. Algorithmic development of new flight structural concepts:
(a) natural complexity and structural diversity in an insect wing; (b) algorithmically developed cellular structure meeting prescribed objectives.

- Weisshaar at Purdue University is studying the trends and future developments in aerospace structures in order to identify fundamental research needs and issues[9].

In studying the natural complexity and structural diversity of insect wings (Fig. 2(a)) Kobayashi and Butler at University of Hawaii have found that even within same species and family, no two insect wings are the same. In fact, nature allows for deviations in the detailed realisation of the wing's dendritic construction without noticeably affecting its ability to fly. This flexibility in detailed realisation is so much different from our aircraft manufacturing practice in which a given blue-print has to be realised within tight tolerances. The practice of abiding to tight manufacturing tolerance has at least two detrimental effects: (a) expensive manufacturing; (b) susceptibility to significant loss of performance due to small structural deviations, as they may appear in theater operations. In view of this observation, it is imperative that we develop new structural concepts that are less sensitive to small structural deviations while being more affordable and easier to manufacture.

Figure 2(b) shows an insect wing-like dendritic structure developed through and algorithmic approach: map L-systems that developed from an embryonic map ω through cellular division rule p created an initial dendritic structure. Structural mechanics was used to balance the osmotic pressure and cell elasticity through cell dynamics. An FEM analysis was used to calculate a fitness function (here, the tip displacement). Finally, a genetic algorithm was applied to evolve the map ω and rules *p* in order to improve the fitness function while maintaining the same overall weight.

4.0 SPONSORED RESEARCH IN STRUCTURAL PERFORMANCE SUSTAINMENT

AFOSR is currently sponsoring a number of extramural and intramural fundamental research projects in structural performance sustainment. These projects could be grouped in three main research threads:

1. micromechanics modelling for structural state awareness
2. novel structural sensing concepts for structural state awareness
3. uncertainty and stochastic prognosis for structural performance sustainment

The projects sponsored under these threads in the structural performance sustainment research thrust will be discussed separately. The scientific scope of the structural performance sustainment research thrust is to attain a structural state awareness through diagnosis at both structural and material levels. Subsequently, one has to perform predictive modelling at the material level combined with predictive modelling at the structural level in order to achieve overall structural prognosis.

4.1 Micromechanics modelling for structural state awareness

The currently sponsored research projects in micromechanics modelling for structural state awareness include the following efforts:

- Cai at Stanford University is modelling nonlinear ultrasonics via ParaDiS large scale dislocation dynamics simulation
- Neu and McDowell at Georgia Tech are studying the fretting fatigue in Ti and superalloys via crystal plasticity FEM modelling with tessallation and simulated annealing[10].
- Ghosh at Ohio State University is studying the fatigue of titanium alloys via crystal plasticity finite element modelling (FEM) with image-based microstructure, CAD reconstruction/mesh generation, statistically equivalent microstructure builder, and multi time scale acceleration[11].
- Larsen and John and their collaborators at AFRL Materials and Manufacturing Directorate are performing the crystal-plasticity modelling and analysis of actual microstructure including defects
- Dawson and Miller at Cornell University are studying crystal-level fatigue initiation via in-situ X-ray scattering and crystal plasticity FEM[12].
- Ghosh at Ohio State University is modelling composites fatigue via multi-scale analysis; starting with damage modelling at the fiber-matrix level, he applies a homogenisation procedure to raise to the continuum damage mechanics level and then to be able to predict crack growth at the composite structure level[13].
- Laursen and Dolbow at Duke University are developing numerical strategies for handling interfaces in FEM analysis without the need for finite elements boundaries to follow the physical interfaces. This approach eliminates the need for remeshing as new interfaces develop.

4.2 NOVEL SENSING CONCEPTS FOR STRUCTURAL STATE AWARENESS

The currently sponsored research projects in novel sensing concepts for structural state awareness include the following efforts:

- Wireless sensing:
  - Syntronics, Inc in collaboration with Ohio State University is studying passive wireless strain gages based on the surface acoustic wave (SAW) principle
  - Huang at University of Texas in Arlington is studying the use of patch-antenna principles for wireless sensing of strain and detection of cracks

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press

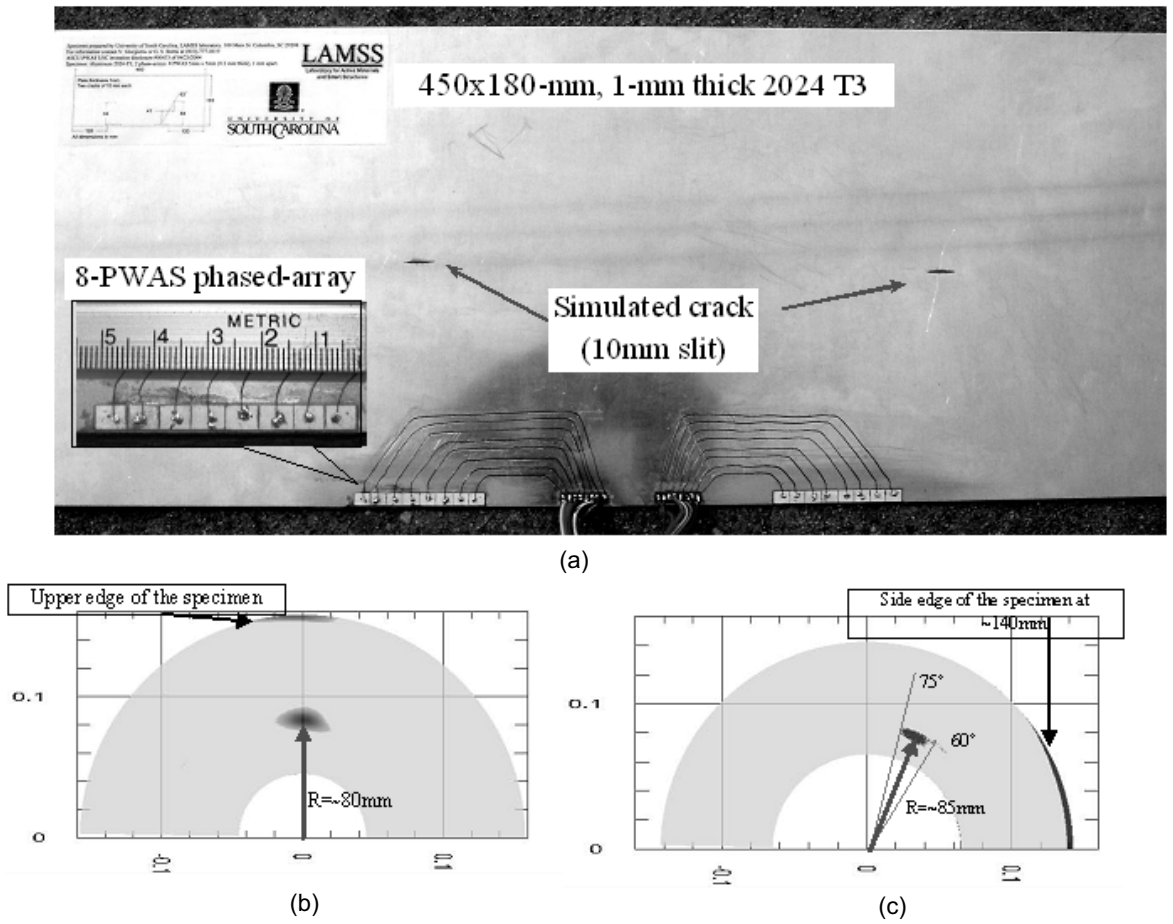


Figure 3. Crack-detection in a flat plate using a piezoelectric wafer active sensors (PWAS) phased array: (a) test schematic; (b) broad side crack imaging; (c) off side crack imaging

- Cesnik at University of Michigan is studying a new type of embedded ultrasonic transducers[14].
- Dunn and Maute at University of Colorado are studying an acoustic 'transistor' strain sensor
- Millennium Dynamics, Inc in collaboration with Georgia Tech are developing a multi-scale damage detection methodology[15].
- Zagrai at New Mexico Tech is studying in-situ sensing of acoustic nonlinearities
- Wang at University of Michigan in collaboration with Tang at University of Connecticut are studying damage detection in periodic structures (bladed disks, space antennas, etc.) by piezo-enhanced vibration localisation
- Bergman and Vakakis at University of Illinois at Urbana-Champaign are studying the use of nonlinear dynamics for sensing structural damage
- Todd and Lanza di Scalea at University of California at San Diego are studying methods for adhesive bond monitoring using extraction of coherent guided waves from diffuse fields[16] and chaotic ultrasonic waves[17].
- Peters and Zikry at North Carolina State University are studying intelligent multi-scale sensing for damage identification and mitigation in woven composite for aerospace structural applications[18].
- Kudu at University of Arizona is studying the modelling of ultrasonic and terahertz radiation in defective tiles for condition monitoring of thermal protection systems[19].

4.3 Uncertainty analysis and stochastic prognosis for structural performance sustainment

The currently sponsored research projects in uncertainty and stochastic prognosis for structural performance sustainment include the following efforts:

- Haftka at University of Florida in collaboration with Yuan at North Carolina State University are studying the probability-based integration of structural health monitoring into the aging aircraft sustainment program[20,21].
- Larsen, John, and their collaborators at AFRL Materials and Manufacturing Directorate are studying the implications of fatigue data variability on life prediction. In particular they have identified some very interesting aspects related to bimodal distributions of fatigue life data[22].
- Derriso at AFRL Air Vehicles Directorate is studying the quantification of structural uncertainty in health monitoring
- Hajela and Dvorak at Rensselaer Polytechnic Institute are performing uncertainty-based multi-scale modelling of damage-tolerant composites
- Knopp, Aldrin, and Jata at AFRL NDE branch in Materials and Manufacturing Directorate are studying the modeled-assisted prediction of NDE probability of detection[23].
- Michaels, Jacobs, Qu, and Ruzzene at Georgia Tech are studying a multi-scale structural health monitoring approach for damage detection, diagnosis, and prognosis in aerospace structures[24].
- Chang at Stanford University is studying the SHM-based characterisation of the failure properties of hybrid composites

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press

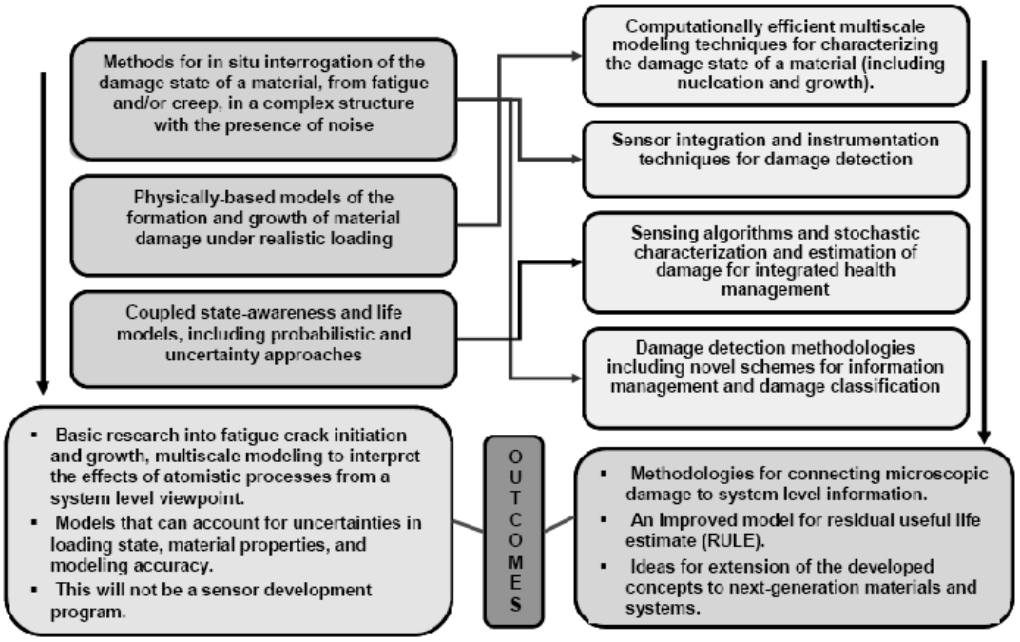


Figure 4. Schematic representation of the interactions within the SHM MURI.

As an example, the author will discuss here the project on fundamental studies in embedded ultrasonic NDE which he performed under AFOSR sponsorship before taking on the current duties of AFOSR program manager. This research project was aimed at studying the interaction between piezoelectric wafer active sensors (PWAS) and the Lamb waves in the structure. The project pursues analytical modelling, numerical simulation, and experimental validation. Several significant results have been obtained:

(a) Selective tuning of Lamb wave modes with in-situ PWAS transducers[25].

(b) In-situ imaging of crack growth with PWAS phased arrays using our embedded ultrasonics structural radar (EUSR) concept[26,27]. (shown in Fig. 3)

(c) Monitoring of in-situ durability and survivability of PWAS transducers installed on coupon specimens representative of structural parts[28].

Closed form solutions were developed to predict how the Lamb waves are excited by a surface mounted PWAS transducer[25]. These solutions have been developed using space-domain Fourier transform of the Lamb-waves differential equations and of the shear excitation given by the PWAS transducer. These closed form solutions were thoroughly verified by experiments.

4.4 Multidisciplinary approach to structural health monitoring and prognosis

A multidisciplinary university research initiative (MURI) program is currently taking place at Arizona State University in collaboration with Virginia Tech, Johns Hopkins University, and University of Southern California.

This MURI program is named 'A Multidisciplinary Approach to Structural Health Monitoring and Prognosis of Metallic Aerospace Systems'. The SHM MURI approach is to use damage diagnosis and prognosis methodologies following a hierarchical framework of physics-based modelling, sensing, information extraction, and processing in order to integrate scales from microstructure to structural levels. The SHM MURI effort is being undertaken by a multidisciplinary research team with specific expertise in material, structural, mechanical, electrical, and systems engineering and with extensive experience in interdisciplinary collaborative research projects.

The SHM MURI team includes:

- Aditi Chattopahdhyay (team leader), Antonia Papandreou-Suppappola, Pedro Peralta at Arizona State University
- Dan Inman at Virginia Tech
- Roger Ghanem at University of Southern California
- James Spicer at Johns Hopkins University

A schematic representation of the interactions within the SHM MURI is given in Fig. 4. Recent publications include Refs 29-32.

5.0 SPONSORED RESEARCH IN STRUCTURAL DYNAMICS AND VIBRATION CONTROL

The currently sponsored research projects in structural dynamics and vibration control include the following efforts:

- Mignolet at Arizona State University is studying reduced-order modelling of nonlinear transient thermo-elastodynamics of functionally graded panels under intense acoustic excitation
- Lagoudas and his colleagues at Texas A&M University is studying solid-state damping via nonlinear shape memory alloys
- Keer at Northwestern University is studying robust damping via particulate mechanics[33].
- Mukherjee at Michigan State University is studying nonlinear vibration control through on-off constraints and actuators[34].
- Inman at Virginia Tech is studying structural dynamics control for adaptive optics[35].
- Masri at University of Southern California is studying the propagation of uncertainties in nonlinear dynamics systems through computationally-efficient reduced-order models[36].
- Robertson at AFRL Space Vehicles Directorate is studying the structural dynamics and vibration control of rapid satellite systems
- Kammer at University of Wisconsin is studying rapid identification of dynamic systems with nonlinearities

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press

- Beran and his colleagues at AFRL Air Vehicles Directorate is studying model-assisted stores clearance for aeroelastic limit cycle oscillation using reduced order models[37].
- Dowell at Duke University is studying the modelling and understanding of aeroelastic limit cycle oscillations
- Cizmas at Texas A&M University is studying the prediction of nonlinear aeroelastic response[38].
- ZONA Technologies Inc is studying the aero-servo-thermo-propulso-elasticity (ASTPE) for hypersonic vehicles[39].
- Bergman at University of Illinois at Urbana Champaign and Strganac at Texas A&M University have developed a new approach for suppressing aeroelastic instability through broadband passive energy sinks[40,41].
- NextGen Aeronautics Inc in collaboration with University of Illinois and Texas A&M University are studying the identification and management of aeroelastic limit-cycle oscillations through nonlinear energy sinks
- Balachandran at University of Maryland is studying computational tools for nonlinear simulation of super maneuverable flapping wing aeroelasticity with focus on fluid interaction[42].
- Beran and his colleagues at AFRL Air Vehicles Directorates is studying the analysis and design of micro air vehicles (MAV)

6.0 SUMMARY AND CONCLUSIONS

This paper has presented an overview of the current fundamental research work sponsored by the US Air Force Office of Scientific Research in the area of structural mechanics. Three large applications areas are considered:

(a) future flight structures

(b) structural performance sustainment

(c) structural dynamics and vibration control.

These three broad application areas are covered at various levels of complexity and detail. The paper has also presented some fundamental research issues that are currently being considered in these three application areas. This list is not exhaustive and is subject to continuous updating. As we move our mental focus further into the future, it becomes apparent that a few generic issues are still insufficiently addressed and need more investment of creativity and ingenuity. Among these, the author would like to list just a few personal views:

- *Disruptive' new and revolutionary structural concepts and unprecedented flight configurations* that are substantially different from what we are flying today are needed. The large investment in structural materials that happen in the last few decades has produced unprecedented material formulations; however, there has not been a similar revolutionary development in flight structures concepts which are, more or less, the same as were pioneered in the 1940s and 1950s.
- *Robust optimisation leading to affordable flight structures* is needed. Current structural optimisation algorithms have produced configurations that too sensitive to slight deviations from an 'optimum' blue print. In contrast, nature allows for variations in the detailed structural realisation that would satisfy the 'duty cycle'; because it relies on structural growth algorithms that use the genetic information to satisfy functional performance requirements. Our current design optimisation and blueprint based fabrication is no-robust (cusp like) and very sensitive to slight variations, thus leading to expensive manufacturing and unaffordable new-systems cost; nature's approach is robust and highly efficient. Ergo, a fundamental shift in our design optimisation perspective is needed to achieve again affordable flight structures.
- *Structural performance sustainment science interwoven with structural design and prognosis* is needed. Lager strides have been achieved in developing permanently attached sensory concepts that can produce on-demand structural diagnostics on par to conventional nondestructive evaluation results. Characterisation and predictive modelling of structural materials (metallic as well as composite) has achieved significant developments. However, structural prognosis capabilities that efficiently utilise the diagnosis information are still lacking and need to be developed interwoven with structural design and structural health monitoring systems.
- *In structural dynamics and vibration control*, the analysis of nonlinear structures during various flight conditions in interaction with air flow, unsteady heating, directed energy, and servo-controls at various Mach and Reynolds numbers is strongly needed.

It is apparent that fundamental research in structural mechanics should be a sustained continuous effort that will enable new and revolutionary flight structures to satisfy an ever changing operational environment.

REFERENCES

1. Air Force Office of Scientific Research public website http://www.wpafb.af.mil/AFRL/afosr/
2. MOORHOUSE, D.J. SANDERS, B. VON SPAKOVSKY, M. and BUTT, J. Benefits and design challenges of adaptive structures for morphing aircraft, Royal Aeronautical Society, *Aeronaut J*, 2006, **110**, (1105), pp 157-162.
3. INOYAMA, D., SANDERS, B. and JOO, J. Topology synthesis of distributed actuation systems for morphing wing structures, *J Aircr*, 2007, **44**, (4), pp 1205–1213.
4. BEJAN, A. and LORENTE, S. *Design with Constructal Theory*, Wiley, Hoboken, USA, 2008.
5. KIM, S., LORENTE, S. and BEJAN, A. Vascularized materials with heating from one side and coolant forced from the other side, *Int J Heat Mass Transfer*, 2007, **50**, pp 3498-3506.
6. BEJAN, A., LORENTE, S. and WANG, K.-M. Networks of channels for self-healing composite materials, *J Appl Phys*, 2006, **100**, 033528.
7. PERIANNAN, V., VON SPAKOVSKY, M. and MOORHOUSE, D. A study of various energy- and exergy-based optimisation metrics for the design of high performance aircraft systems, Royal Aeronautical Society, *Aeronaut J*, August 2008, **112**, (1134), pp 449-458.
8. RIGGINS, D., TAYLOR, T., TERHUNE, L. and MOORHOUSE, D. Methods for the design of energy-efficient high-speed aerospace vehicles, Royal Aeronautical Society, *Aeronaut J*, May 2007, **111**, (1119) pp 297-309.
9. WEISSHAAR, T. New aircraft systems concepts-towards new horizons in aeroelasticity, NATO Research Technology Organization Research Symposium, RTO-MP-AVT-152, Loen, Norway, 3-8 May 2008.
10. MAYEUR, J.R., MCDOWELL, D.L. and NEU, R.W. Crystal plasticity simulations of fretting of Ti-6Al-4V in partial slip regime considering effects of texture, *Computational Materials Science*, **41**, (3), pp 356-365.
11. GROEBER, M.J., GHOSH, S., UCHIC, M.D. and DIMIDUK, D. A framework for automated analysis and representation of 3d polycrystalline microstructures, Part 1: Statistical characterization, Acta Materialia, April 2008, **56**, (6), pp 1257-1273.
12. MILLER, M.P., PARK, J.-S., DAWSON, P.R. and HAN, T.-S. Measuring and modelling distributions of stress state in deforming polycrystals, Acta Materialia, **56**, 2008, pp 3927-3939. (www.sciencedirect.com).
13. JAIN, J. and GHOSH, S. A 3D continuum damage mechanics model from micromechanical analysis of fiber reinforced composites with interfacial damage, *ASME J Applied Mechanics*, May 2008, **75**, (3), 031011.
14. SALAS, K.I., CESNIK, C.E.S. and RAGHAVAN, A. Modelling of wedge-shaped anisotropic piezocomposite transducer for guided wave-based structural health monitoring, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23 – 26 April 2007, Honolulu, Hawaii, USA, paper # AIAA 2007-1723 ppler vibrometer, 48th AIAA/ASME/ASCE/AHS/ASC Structures,

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press

Structural Dynamics, and Materials Conference, 23 – 26 April 2007, Honolulu, Hawaii, USA, paper # AIAA 2007-1727.
16. SABRA, K., SRIVASTAVA, A., LANZA DI SCALEA, F., BARTOLI, I., RIZZO, P. and CONTI, S. Structural health monitoring by extraction of coherent guided waves from diffuse fields, *J Acoustical Society of America*, 2008, **123**, (1), EL8-EL13.
17. FASEL, T., KENNEL, M.B. TODD, M.D., E.H. CLAYTON, STABB, M. and PARK, G. Damage state evaluation of experimental and simulated bolted joints using chaotic ultrasonic waves, *J Smart Structures and Systems*, 2008 (in review).
18. PEARSON, J., ZIKRY, M.A., PRABHUGOUD M. and PETERS K. Global-local assessment of low-velocity impact damage in woven composites, *J Composite Materials*, 2007, **41**, pp 2759-2783.
19. BANERJEE, S. and KUNDU, T. Elastic wave field computation in multi-layered non-planar solid structures: A mesh-free semi-analytical approach, *J Acoustical Society of America*, 2008, (3), pp 1371-1382.
20. RAMU, P., KIM, N.H. and HAFTKA, R.T. Inverse measure-based tail modelling approach for structural reliability estimation, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23 – 26 April 2007, Honolulu, Hawaii, USA, paper # AIAA 2007-1947.
21. ACAR, E., AN, J., HAFTKA, R.T., KIM, N.-H., IFJU, P. J. and JOHNSON, T. F. Options for using data to update failure stress, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23 – 26 April 2007, Honolulu, Hawaii, USA, paper # AIAA 2007-1971.
22. JHA, S.K. CATON, M.J. and LARSEN, J.M. (2006) A new paradigm of fatigue variability behavior and implications for life prediction, Materials Science and Engineering, Series A, doi:10.1016/j.msea.2006.10.171.
23. KNOPP, J.S., ALDRIN, J.C. and JATA, K. Computational methods in eddy current crack detection at fastener sites in multi-layer structures, Nondestructive Testing and Evaluation, 2008, pp 1–18.
24. MICHAELS, J.E. Detection, localization, and characterization of damage in plates with in situ arrays of spatially distributed ultrasonic sensors, *Smart Materials and Structures*, **17**, 2008, article 035035 (15pp).
25. GIURGIUTIU, V. Tuned lamb-wave excitation and detection with piezo-electric wafer active sensors for structural health monitoring, *J Intelligent Material Systems and Structures*, *Sage Pub*., April 2005, **16**, (4), pp 291-306.
26. GIURGIUTIU, V., BAO, J. and ZAGRAI, A.N. (2006) Structural health monitoring system utilizing guided Lamb waves embedded ultrasonic structural radar¸ U.S. Patent Office #6,996,480 of 7 February , 2006.
27. GIURGIUTIU, V., YU, L., KENDALL, J. and JENKINS, C. In situ imaging of crack growth with piezoelectric wafer active sensors, *AIAA J*, November 2007, **45**, (11), pp 2758-2769.
28. GIURGIUTIU, V., LIN, B. and DOANE, J. Durability and survivability of piezoelectric wafer active sensors mounted on aluminum structures for aerospace vehicle health monitoring Aeromat-2005, Integrated Systems Health Monitoring Session, 6-9 June 2005, Orlando, FL, USA.
29. CHATTOPADHYAY, A., DAS, S. and COELHO, C.K. Damage Diagnosis using a Kernel-based Method, *Insight – Non-Destructive testing and Condition Monitoring*, 2007, **49**, (8), pp 451-458.
30. PERALTA, P., CHOI, S.H. and GEE, J. Experimental quantification of the plastic blunting process for stage II fatigue crack growth in one-phase metallic materials, *Int J Plasticity*, **23**, 2007, pp 1763-1795.
31. SPICER, J.B. Nonlinear effects on impurity segregation in edge dislocation strain fields, *scripta Materialia*, **59**, 2008, pp 377–380.
32. DAS, S., GHANEM, R. and SPALL, J.C. Asymptotic sampling distribution for polynomial chaos representation of data: A maximum entropy and Fisher information approach, *SIAM J Scientific Computing*, **30**, (5), 2008, pp 2207-2234.
33. BAI, X.M., SHAH, B., KEER, L.M., WANG, Q.J. and SNURR, R.Q. Particle dynamics simulations of a piston-based particle damper, Powder Technology, 2008, in press.
34. DIAZ, A.R. and MUKHERJEE, R. Optimal joint placement and modal disparity in control of flexible structures, *Structural and Multidisciplinary Optimization*, July 2008, **86**, (13-14), pp 1456-1462.
35. TARAZAGA, P.A., INMAN, D.J. and WILKIE, W.K. Control of a space rigidizable inflatable boom using macro-fiber composite actuators, *J Vibration and Control*, 2007, **13**, (7), pp 935-950.
36. MASRI, S.F., GHANEM, R., ARRATE, F. and CAFFREY, J. Stochastic nonparametric models of hysteretic oscillators, *AIAA J*, October 2006, **44**, (10), pp 2319-2330.
37. LUCIA, D.J., BERAN, P.S. and SILVA, W.A. Reduced-order modelling: new approaches for computational physics, *Progress in Aerospace Sciences*, 2004, **40**, pp 51-117, www.elsevier.com/locate/paerosci
38. CIZMAS, P.G.A. and GARGOLOFF, J.I. Mesh generation and deformation algorithm for aeroelasticity simulations, *J Aircr*, 2008, **45**, (3), May-June 2008, pp 1062- 1066.
39. STARKEY, R.P., LIU, D.D., BALDELLI, D.H., CHANG, R. and CHEN, P.C., Rapid conceptual design and analysis of a hypersonic air-breathing missile, AIAA-2008-2590.
40. LEE, Y.S., VAKAKIS, A.F., BERGMAN, L.A., MCFARLAND, D.M. and KERSCHEN, G. Suppression of aeroelastic instability by means of broadband passive targeted energy transfers, Part I: Theory. *AIAA J*, 2007, **45**, (3), pp 693-711.
41. LEE, Y.S., KERSCHEN, G, MCFARLAND, D.M., HILL, W.J., NICHKAWDE, C., STRGANAC, T.W., BERGMAN, L.A. and VAKAKIS, A.F. Suppression of aeroelastic instability by means of broadband passive targeted energy transfers, Part II: experiments, *AIAA J*, 2007, **45**, (12), pp 2391-2400.
42. VANELLA, M., FITZGERALD, T., PREIDIKMAN, S., BALARAS, E. and BALACHANDRAN, B. Influence of flexibility on the aerodynamic performance of a hovering wing (in press).

https://doi.org/10.1017/S0001924000003018 Published online by Cambridge University Press