AIRFRAME STRUCTURES TECHNOLOGY FOR FUTURE SYSTEMS

Joseph M. Manter[1] and Donald B. Paul[2]
Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA

Keywords: *Structures Technology, Certification by Analysis, Active Flow Control, Multifunctional Structures, Simulation-Based Prototyping, Affordable Composite Structures, Extreme Environment Structures*

Abstract

An overview of future structures technology for military air vehicles is given. The overview is prefaced by a discussion of the factors influencing structures research today. The key to meeting affordability and rapid technology insertion is identified as simulation-based prototyping, including certification by analysis. Other enabling structures technology candidates for future systems are discussed, including multi-functional structures, extreme environment structures, affordable composite structures and active flow control for structures applications.

1 Introduction: Factors Influencing Structures Technology Research

The design emphasis for military air vehicles has changed in recent years from a primary focus on aircraft performance, lethality, and survivability to the current focus of affordability (see Fig. 1). While affordability is now the center of attention, requirements still exist to retain the previously emphasized attributes.

Systems requirements for military aircraft will also change dramatically in the twenty-first century. The United States and many allies share the vision of global reach and force projection requirements brought on by the regional conflicts that are predicted for the foreseeable future. To meet those threats, tomorrow's air vehicles may look significantly different from today's fighter, bomber, reconnaissance and support aircraft [1].

This combination of changes in systems and design requirements will give rise to new design processes for air vehicles and some of the most pronounced changes will be in structures technology. Novel structures technologies will be considered early in the design phase, as will sister technologies from aerodynamics, propulsion, flight control, materials and subsystems [2]. Life cycle cost will be an overriding design variable. Airframe structures will be called on to answer many system requirements and the enabling technologies will be certification by analysis, active flow control, multifunctional structures, simulation-based prototyping, affordable composite structures, and extreme environment structures

2 Certification of Structures by Analysis

The first implementation of certification of structures by analysis may be in structural sustainment because small, near term payoffs are expected there first. The need for more structural qualification tests is expected to increase as maintainers turn to material substitution and design replacement for minor and major subcomponents to solve chronic aging aircraft problems. Certification by analysis, however, has the potential for much wider applications, and is considered in the military to be an integral part of simulation based acquisition research.

---

[1] Chief, Structures Division, Air Vehicles

[2] Chief Scientist, Air Vehicles; Fellow, Royal Aeronautical Society

For new aircraft, full-scale airframe static, durability and damage tolerance tests are expensive procedures required by the military. These tests are becoming ever more expensive due to increased labor costs, more complex designs, and more sophisticated test equipment costs required to reduce program risk. These factors will continue to accelerate certification costs as will new design concepts such as aeroelastic tailoring, extreme environment structures, multi-functional structures and relying on probabilistic design requirements for transient loads.

Increased computational power will enable structural qualification simulations to use sophisticated finite element codes to model structural response and computational fluid dynamics codes to better model static and dynamic aerodynamic inputs [2]. Additionally, codes could simulate thermal, acoustic and flight control inputs for a more faithful representation of these design development tests.

While absolute replacement of these traditional tests is probably tens of years away and even longer in terms of customer acceptance, incremental payoffs will be seen much sooner. These payoffs will most likely be seen in the reduction of the building block tests, from coupon to component, required today.

3 Active Flow Control

Active flow control is the local predictable, schedulable, or on-demand altering of the local flow around an air vehicle to gain a desired outcome. Active flow control, requiring the expenditure of energy [3], can be affected by the use of micro-electromechanical motors, zero-mass flow synthetic jets or fluidic injection from engine air bleed or some other mass flow source. Early applications of active flow control will be vehicle flight control, inlet distortion control, control of boundary layer transition or separation, the mixing of primary and secondary exhaust flows or the control of the local flow within open air vehicle cavities.

Destructive acoustic levels prevalent within open weapons bays result in substantial damage to internal structures and internally carried weapons and subsystems. Today’s modern air vehicles configured with weapons bays often use passive devices to attenuate that acoustic energy and alter the airflow to enable a safe separation of stores. These passive devices, however, are optimized for a unique store configuration and flight condition and their effectiveness is compromised at off-design conditions. A more robust design capable of effective operation for a wide variety of store configurations and flight conditions will use active flow control coupled with a closed loop control system (see Fig. 2).

A closed loop active flow control design has been demonstrated in a wind tunnel test and shown effective in reducing the acoustic levels within open weapons bays. The test simulated both baseline and closed loop control of the weapons bay for various Mach numbers, mass flows and flow injection frequencies. The test demonstrated the feasibility of the closed loop system, reducing some tones by 20 decibels and a noticeable reduction in the overall sound pressure level [4]. More applied and advanced demonstration research will enable air vehicles of the future to operate weapons bays with existing and novel stores over larger operating envelopes with greatly reduced acoustic environments.

4 Multifunctional Structures

Multifunctional structures include concepts that extend airframe functionality to perform tasks beyond load reaction. Potential benefits exist to increase survivability, lethality, aerodynamic efficiency and thermal efficiency. At the same time, this new technology may also reduce manufacturing cost, while maintaining or improving reliability, supportability and repairability. Candidate technologies include:

- Conformal load bearing antennas
- Integral heat exchangers
- Flight control actuators
- Embedded sensors
- Embedded power systems

Multifunctional structures may contain actuators and sensors that will allow them to alter actuators' mechanical state (position or velocity) and or mechanical characteristics (stiffness or damping). Benefits of such structures include aeroelastic control, load alleviation, and elimination of detrimental dynamic oscillations at reduced structural weight while simultaneously achieving a structural integrity equivalent to present safety requirements. Such designs (see fig. 3) will open the vehicle design space to significantly reduce takeoff gross weight [5].

Multifunctional structures are in an early stage of development, but already benefits can be foreseen in reduced life cycle cost and reduced direct operating cost through improvements in both performance and maintainability. Active/adaptive structures, structure health monitoring and structure/avionics integration are three areas presently being pursued. There is a potential to reduce inspections on both new and repaired airframes thereby reducing maintenance costs.

Eventually, multifunctional structures are expected to develop to the point where they can facilitate on-demand and in-situ monitoring of structural health. Once they become reliable enough, costly airframe tear down inspections need only be performed when there is a fault indication.

A multifunctional airframe that integrates antenna functions into the loadbearing structure offers many significant benefits. Elimination of structural cutouts will save weight and lower manufacturing costs. The larger inherent platform area can enhance current or enable additional antenna functionality. The cleaner design will reduce radar cross section and air vehicle drag. Finally, the elimination of blade antennae will reduce the damage susceptibility inherent in blade antennae [6].

5 Simulation Based Prototyping

Solid modeling coupled with feature-based design software and advanced visualization technology is already enabling the designer to change design variables and evaluate the effect of these changes on the response characteristics of the structure, in real time. It has become commonplace to display stress contours, deformations and vibration mode shapes in computerized color graphical depictions, for highlighting critical areas.

The Air Force Automated Structural Optimization System (ASTROS) is an example of a tool that has been developed for facilitating Integrated Product Design. ASTROS provides a mechanism for effective communication across different disciplines, including aerodynamics, flight controls and electrodynamics. In the future, there will be a system of design tools that will facilitate virtual prototyping and enable simulation of advanced technologies and configurations before physical flight.

Alternative configurations can be explored relative to their ease of manufacture and cost. With the capability to "immerse" the designer, the pilot, or the maintainer in the design, customer familiarity with the product can begin before it is produced [7]. Concepts currently under study in the Air Force Research Laboratory's Multi-Disciplinary Center are illustrated in Fig. 4.

By linking these advanced, high fidelity engineering models to battlefield and campaign analysis simulations, the true payoffs of structures and other technologies can be evaluated in a virtual wartime scenario (see Fig. 5).

6 Affordable Composite Structures

Advanced composite structures can facilitate a high degree of subsystem integration, as their mechanical, thermal and electromagnetic properties are tailorable and amenable to embedded sensors, actuators and subsystems.

Composites are becoming cost effective in subelement areas where they have not been in the past. Rapid progress in textile subelements fabricated by Resin Film Infusion (RFI) and Resin Transfer Molding (RTM) of braided and woven preforms is being made. Fuselage frames and cut out reinforcements are near term applications. Since textile composites provide integral reinforcement in the "Z" direction, significant improvements in intralaminar and interlaminar strength can be obtained to react and transfer out-of-plane space loads. These advantages should offset the disadvantages of lower stiffness and compression strength for braided and woven composites vs. laminates.

The potential payoff of applying textile technology to sandwich structures will allow elimination of the skin-to-core adhesive bond problems. Since there is an integral link between upper and lower face sheets there is no debonding. Impact damage is minimized since through the thickness fiber serve to block delamination growth and thereby localize damage.

Another approach to improving the out-of-plane properties of laminated composite structure is Z-pinning technology. Z-pinning has been developed by the Aztex Corporation in cooperation with AFRL, United States Navy Air War Center and the airframe companies.

The technology introduces reinforcing pins through the thickness. The pins provide increases in pull-off loads and offer a mechanical interlocking capability to inhibit crack propagation and provide a fail-safe linkage if a crack initiates.

The USAF and US Navy are supporting programs to characterize the structural and cost benefits of this technology. Specific focus has been directed at understanding how the technology can be used to modify failure criteria in composites, enhance ballistic survivability, and reduce cost through the elimination of fasteners.

Non-autoclave processes such as Electron-Beam curing offer great potential for lowering composite structure processing costs. Cationic epoxy resin composite parts can be non-autoclave cured in minutes. In the electron beam process, the electron’s kinetic energy is deposited directly in the material volume rather than by surface heating and thermal diffusion. Both aircraft and space vehicle structures are being produced by this method of processing. Examples are a 14-inch diameter 3-foot long integral fuel tank for the US Army’s Longfog tactical missile by Oak Ridge National Laboratory and an Aerospatiale filament wound rocket motor case. The latter program did not employ resins or processing techniques required to produce structures with the properties and quality required of airframes. It did demonstrate the feasibility to produce structures limited in size only by the facilities required for shielding E-beams. At its present stage in development, E-beam processing technology is far from mature and has to be characterized as high risk but with high potential to reduce processing costs.

Composite airframe applications will continue to grow at the steady pace of the past. A major increase in the use of composites will be in the automobile industry and civil infrastructure. Because of the magnitude of these applications, lower cost composite materials will become available for aerospace use. Also, the emphasis on lower cost airframes will encourage use of innovative design that exploits low cost manufacturing techniques and up front system arrangements that allow optimum load paths. The combination of these two developments will fundamentally shift the airframe cost vs. weight curve [7].

7 Extreme Environment Structures

One of the most demanding new structures research areas is extreme environment structures. The extreme environment relative to military applications is the combined regime of high acoustic and thermal loads (see Fig. 6) in conjunction with the mechanical loads experienced by a vehicle in flight. Unfortunately, the combined environment loading is usually several times more severe than the summation of each individual load [8]. Even today’s most common extreme environment situation, the closely coupled propulsion/ airframe designs characterized by exhaust washed structures, requires research to reduce maintenance costs. Tomorrow’s extreme environment encounters also will be experienced by air vehicles operating in the hypersonic speed regime and space access vehicles capable of aircraft-like operations.

To meet these challenges, both the military and civilian communities are vigorously pursuing research in next generation thermal protection systems, high temperature structures and integrated environmental control systems [9]. Some promising techniques are mechanically attached blanket thermal protection systems for initial application to the leeward side of a transatmospheric vehicle. The long-term solution to reducing mass fractions for space access vehicles involves reduction on the reliance of parasitic thermal protection systems and exploitation of high temperature materials [8]. Basic research is underway to characterize high temperature ceramic matrix composite design criteria [10].

Because analytical models today are inadequate to define the acoustic loads and its interaction with the structures, the Air Force Research Laboratory (AFRL) will continue to rely on experimental facilities to develop new structural design concepts and the analytical tools to mitigate the reliance on the experimental facilities.

A cornerstone of tomorrow's research in extreme environment structures will be AFRL's new $17.5 million Consolidated Aerospace Structures Research Laboratory (CASRL). Scheduled to begin construction in November of 2000, the CASRL will merge and improve the capabilities of AFRL's Combined Environment Acoustic Chamber and its Structural Mechanics Facility to yield a world class facility required to meet USAF research needs for its space access and future strike vehicles (see Fig. 7). Slated for completion in fall 2002, the CASRL will be able to simulate, for a 10-foot by 10-foot article, a combined environment of a 174 dB overall sound pressure level (for a 50-500 hertz flat spectrum) acoustic load, a 70 BTU/ft^2-sec thermal load and a representative mechanical load.

8 Summary

Research in airframe structures technology will be vital in meeting the military's determined emphasis on affordability. New visions of global reach and force protection have already resulted in changes in the research direction of the United States military and many of its allies. The key to meeting these challenges affordably is simulation-based prototyping, including certification by analysis. Other enabling structures technology breakthroughs will come from multi-functional structures, extreme environment structures, affordable composite structures and the exploitation of active flow control.

9 References

[1] USAF Scientific Advisory Board (SAB) Panel, New World Vistas. *Air and Space Power for the 21st Century*, Aircraft & Propulsion and Materials Volumes, SAB Summer Study, 1995.

[2] Sensburg, Otto, Draft *Terms of Reference for Qualification of Structures by Analysis*, NATO RTA Applied Vehicle Technology Panel Meeting, May 2000.

[3] Gad-el-Hak, Mohamed, *Applied Mechanics Reviews*, Vol. 49, pp 365-379, 1996.

[4] Shaw, L.L., and Northcraft, S. *Closed Loop Active Control for Cavity Acoustics*. AIAA-99-1902, Proceedings of 5th AIAA/CEAS Aeroacoustics Conference and Exhibits, Bellvue, Washington, May 1999.

[5] Pendleton, E., Bessette, D., Field, P., Miller, G., and Griffin, K. *Active Aeroelastic Wing Flight Research Program: Technical Program & Model Analytrical Development*. Paper 98-1972, Proceedings of the 39th AIAA Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, 20-23 April 1998.

[6] Lockyer, A. J., *Design and Development of a Conformal Load-Bearing Smart-Skin Antenna: Overview of the AFRL Smart Skin Structures Technology Demonstration (S3TD)*, SPIE Smart Structures and Materials, Vol. 3674, Paper Number 3674-46, "Industrial and Commercial Applications of Smart Structures Technologies," pp. 410-424, Newport Beach, CA, March 1-4, 1999.

[7] Paul, D., et. al., *The Evolution of U.S. Military Aircraft Structures Technology*, submitted to AIAA Journal of Aircraft, Oct 1999.

[8] Paul, D., et. al., *Structures Technology for Future Aerospace Systems*, Paper AIAA 98-1869, 39th SDM AIAA, Long Beach, California, April 1998.

[9] Pratt, D.M., Brown, J., and Hallinan, K. P., *Thermocapillary Effects on the Stability of a Heated, Curved Meniscus*, Journal of Heat Transfer, Vol. 120, pp. 220-226, 1998.

[10] Wolfe, H., Camden, M., Byrd, L., Paul, D., Simmons, L., Kim, R., *Failure Criteria Development for Dynamic High-Cycle Fatigue of Ceramic Matrix Composites*, AIAA Journal of Aircraft, Volume 37, Number 2, Pages 319-324, March-April 2000.

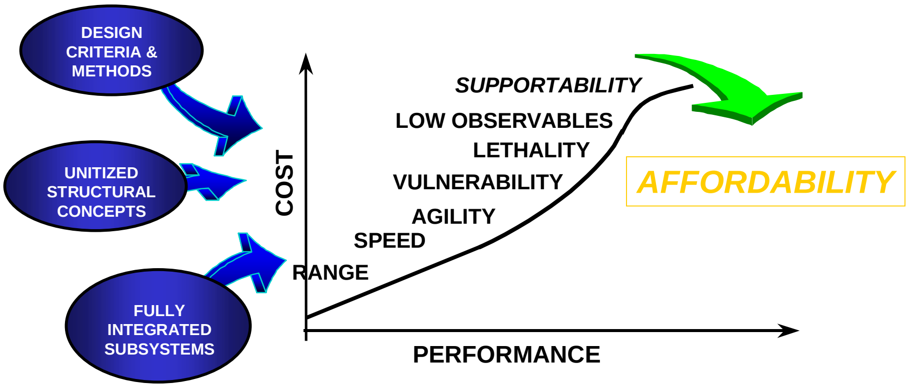


Fig. 1 A dominate feature of future military air vehicles will be affordability.

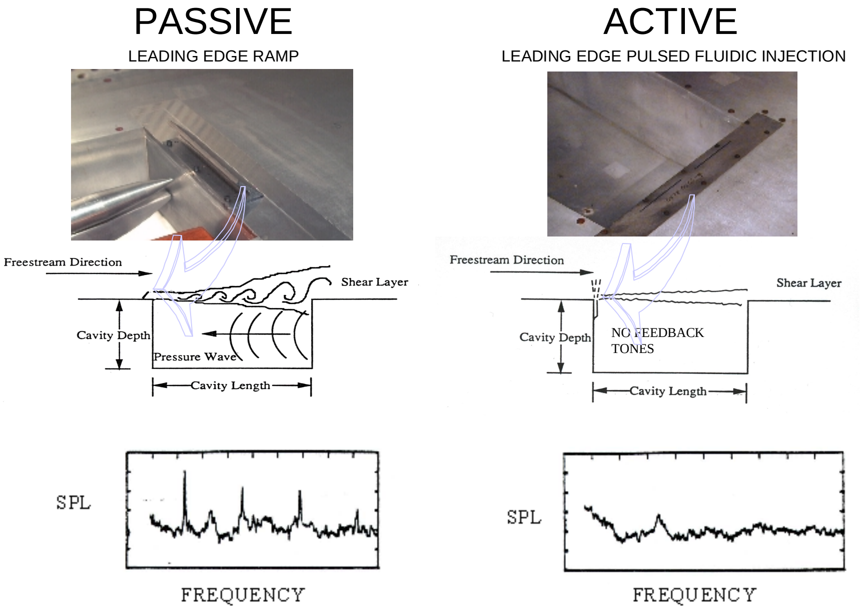


Fig. 2 Active flow control will significantly reduce acoustic levels within weapons bays.

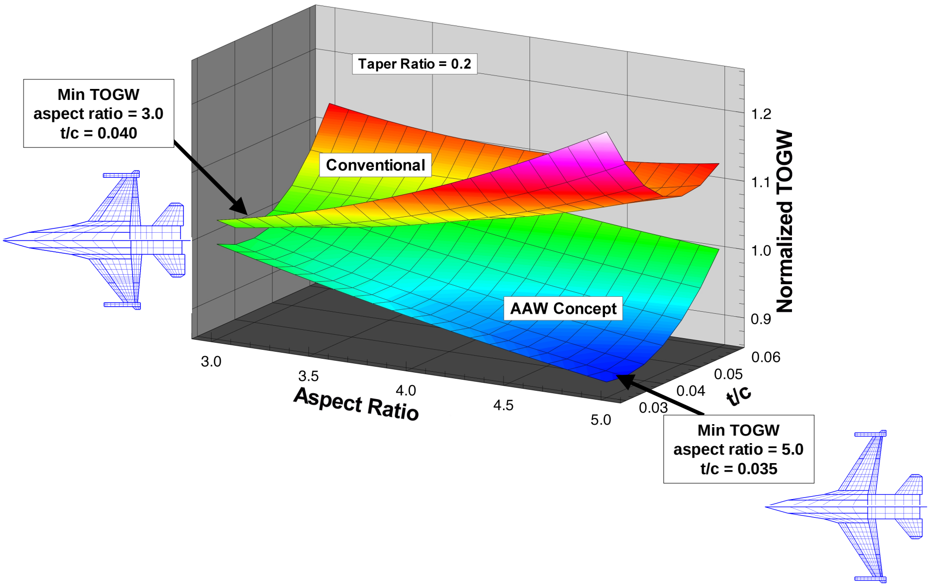


Fig. 3 An active aeroelastic wing will open the air vehicle design space.

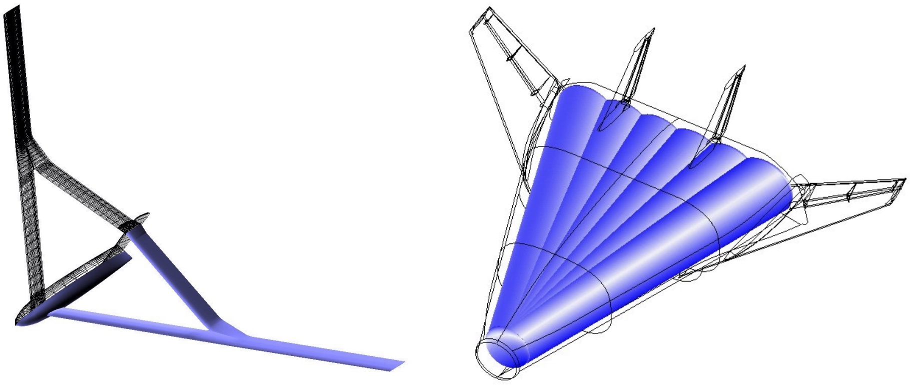


Fig. 4 Advanced concepts studied in development of simulation-based research and development

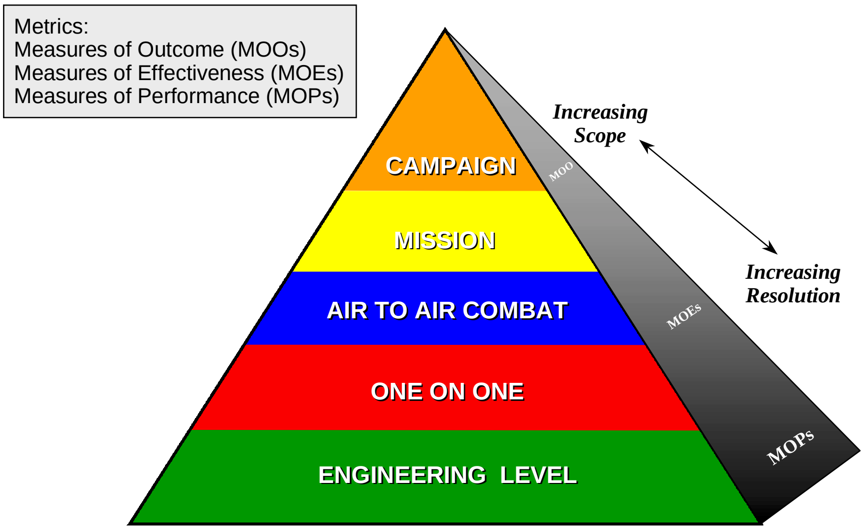


Fig. 5 The hierarchy of simulations in simulation-based prototyping (courtesy of ASC/ENM.)

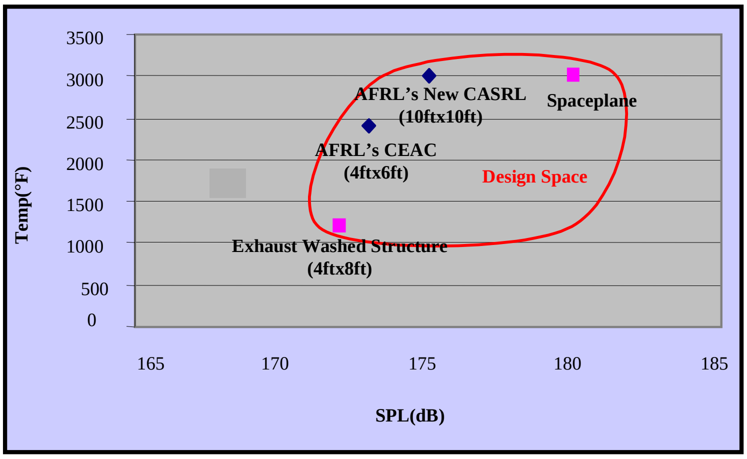
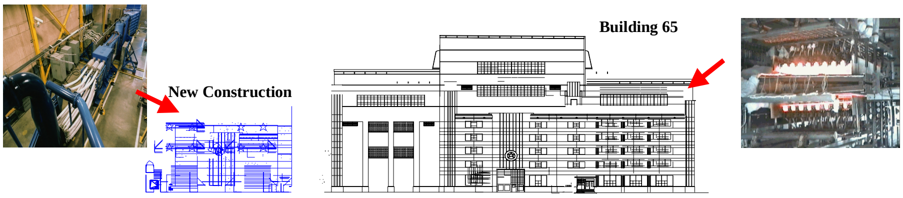


Fig. 6 Combined extreme environments for exhaust washed structures and space access configurations.



Consolidated Aerospace Structures Research Lab

Simultaneously Validate:
- Sound (174 dB)
- Temp (3000°F)
- Mechanical Load
- Size: 10ft x 10ft

NEW COMBINED ENVIRONMENT CAPABILITY

Fig. 7 AFRL's new Consolidated Aerospace Structures Research Laboratory will simulate combined extreme acoustic, thermal and mechanical loads.