Structurally Integrated X-Band Array Development

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ABSTRACT

A long-standing vision of the US Air Force and supporting industry has been to design and incorporate large antennas into military aircraft. However, as the apertures increase in size they typically require larger radomes or "cut-outs" in the primary load bearing structure of the airframe limiting the number and size of the apertures. This directly affects the structural and aerodynamic efficiency of the aircraft thus reducing the endurance. Therefore, the need to develop conformal load bearing antenna structures has become an area of specific interest of development to enhance military mission capability. The payoffs include improved antenna performance/gain through the much larger available antenna area, reduced support cost, lower weight, signature, and drag. Depending on location, the antennas will be required to bear primary or secondary structural loads, and to compensate the radio frequency (RF) beam pattern for structural deformations at high frequency applications. This paper documents work in progress towards the development of a very large structural x-band electronically scanned array (ESA). A building block approach that includes structural and RF array development is presented. The challenge of multidisciplinary integration has been directly addressed by bringing the structural and RF sciences together in order to develop an optimized design that meets functional requirements. At the time of this writing significant structural testing from coupon through large scale structural validation have been complete and is reported. The active array testing will evaluate a three square foot array under deformed conditions in an anechoic chamber, but is pending completion.

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Banks, D.; Berden, M.; Baron, B.; Tenbarge, J. (2006) Structurally Integrated X-Band Array Development. In *Multifunctional Structures / Integration of Sensors and Antennas* (pp. 17-1 – 17-12). Meeting Proceedings RTO-MP-AVT-141, Paper 17. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **01 OCT 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Structurally Integrated X-Band Array Development**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Boeing Company Seattle, Washington**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM202433., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

1.0 INTRODUCTION

This development activity is based on a building block approach to reduce risk; the basic program structure is described in **Figure 1**. The basic concept developed involves the fabrication of primary/secondary sandwich structure using an "egg crate" construction approach with radiating flared dipole elements integrated in the core surfaces to provide horizontal and vertical polarization capability. The building block approach has been used to provide data to quantify electrical/mechanical performance, so trades could be used to develop the most promising configuration. This involved evaluating coupons to understand the electrical performance and the mechanical/electrical durability of the system. Panels have been fabricated to validate the electrical interconnect assembly methodology and the structural performance. This program has directed a significant effort at trades associated with manufacturing tolerances. These results have then been used as inputs to HFSS electromagnetic models to determine the improvement/impact of key manufacturing decisions. Reliability and interconnect integrity have been an upfront design consideration. The RF distribution system and interconnect manufacturing methodology represent a key challenge due to the large number of elements, therefore design/manufacturing considerations and electromagnetic performance models have been concurrently developed to assure that the most effective system is developed. The heat loads associated with a very large X-Band array are a critical design issue for the structural material and the electronics integration. The increased vehicle surface available for apertures using conformal load-bearing antenna structure (CLAS) technology allows for high gain performance with distributed low power electronics that can be air-cooled. The reduced heat load concentration should eliminate the need for complex liquid cooling subsystems. To insure the integrity of the structural system we have directly evaluated the heat load due to the power dissipation and environment through analytical models and by conducting sub-element thermo-mechanical performance testing to ascertain the associated material performance.

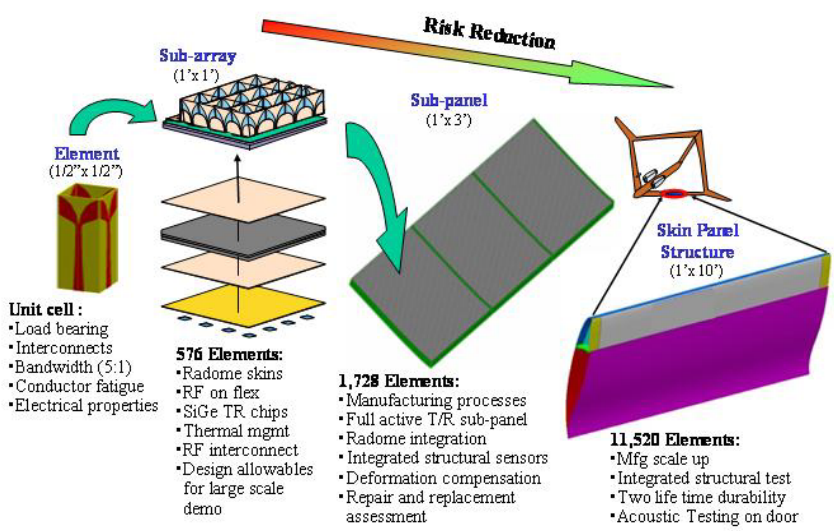

Figure 1: Structural X-Band Array Development

A key attribute of design configuration involves considering the manufacturing build up of tolerance errors over the length of a large array. In order to control tolerance build up the design has evolved as a series of sub arrays. This allows the fabrication to be completed in a controlled manufacturing environment tailored for electronics. The electrical subarrays are then integrated with load bearing radiator core with a high level of precision, since tolerance error build up has been eliminated. Therefore the risks associated with conventional composites fabrication processes have been minimized. Effort has been directed at developing an integrated deformation compensation system; this includes algorithm development and a distributed array of strain sensors. This system will ultimately be used to achieve coherence for beam forming as the structure deforms over the large span of the structural array. The completed large scale demonstration activities of this effort include a twenty square foot large-scale wing primary structure component and a secondary structure panel to demonstrate static and fatigue performance, including typical electrical connections.

2.0 STRUCTURAL DESIGN

Integrated Conformal Load Bearing Antenna Structures (CLAS), also known as Structurized Antenna Arrays, have the potential to enhance the number and nature of sensor functions currently provided by traditional antenna. To date, there exist few designs/low cost manufacturing approaches that combine the precise dimensional tolerances, durable electrical interconnects and light weight materials required to make such load bearing antennas a viable product option. Reductions in parasitic payload weight and increased antenna size integration capability in non-traditional locations (doors, wing skins, fuselage panels, etc.) could greatly improve mission scope and Intelligence Surveillance and Reconnaissance (ISR) effectiveness on space-based, military and commercial variant systems.

This paper will discuss critical component details, manufacturing processes and integration technologies developed as part of an ongoing government contract called, “Structurally Integrated X-band Antenna (SIXA).” In fulfillment of the SIXA program effort, Boeing is teamed with Raytheon to mature this technology and to build a series of sub-array, sub-panel, and large-scale component demonstration articles. At the heart of this technology is the capability to integrate radiator elements into composite honeycomb-like core structure. Although possessing nonmetallic core properties, the SIXA array is constructed in a manner and to a precision as to facilitate mate-up electronic feeds to structural core with radiators. Engineering requirements, interfaces, design criteria, structural arrangement, and test configuration issues will be provided.

Initial design work on SIXA began with development and trades in several key areas: material trades, radome/backplane design, manufacturing trials (figure 2), and development of an electrical interconnect method, durability/repair analysis, and conformability. Upon selection of basic design criteria, flow down of program goals, key performance parameters and requirements a series of coupon trials were performed to solidify a final structural design.

Figure 2: Core Development Approaches

During manufacturing trials, several samples were made that allowed for shear, flatwise tensile, compression and bending test of the three core approaches. Key design features (wall thickness, ply orientation, radius filler size/type, centerline dimensions, and prepreg/adhesive mix) were varied to provide baseline structures data.

Coupon manufacturing began upon completion of core manufacturing trials. Structural subassemblies consisted of all panel components including core, egdeband transition, and laminate sections to be tested in standard mechanical, environment, and impact environments, as seen in figure 3. Analysis was completed to understand basic materials and subassemblies failure modes and measured design values.

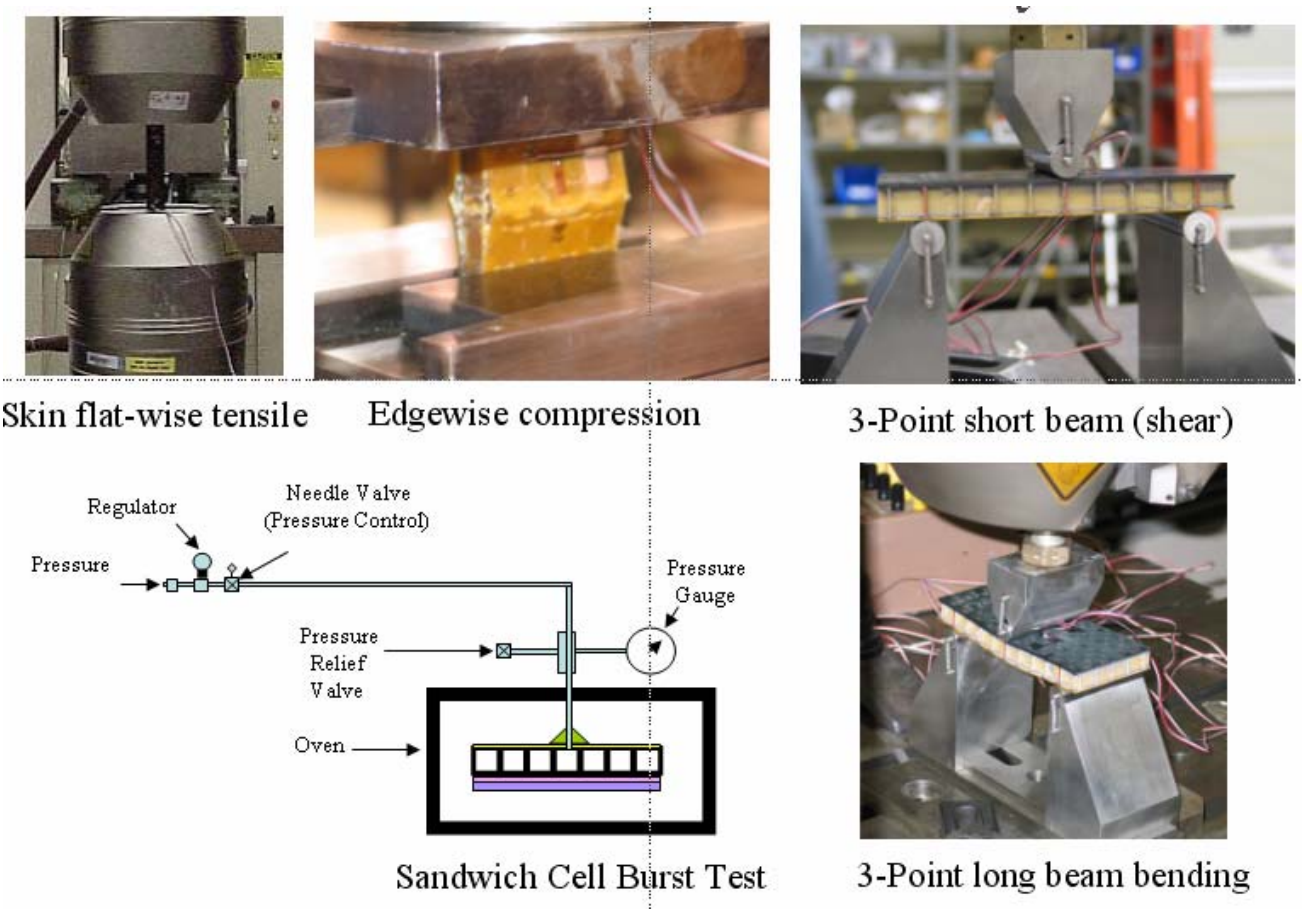

Figure 3: Coupon Testing

The coupon trials were essential to understand not only the core properties but also the integration of the edgeband for panel attachment to structure. Edgeband designs were revised multiple times to drive the failure of the coupon into the core, therefore making future full scale panels as strong as the core.

Upon completion of coupon trials, sub panel development began to scale up the manufacturing and develop more efficient methods of assembly. The primary goal in testing large panels is to provide a test-proven design envelope for typical primary load-bearing applications; and provide comparison data to validate and calibrate existing analysis results. The key consideration for both of these goals is the load which the structure must bear. However, loads depend on the particular vehicle, geometry and environment. A standard industry

approach is therefore to use strain as the surrogate generalized parameter instead of load.

It is informative to review the typical sources of strain history which a local region or fiber that an antenna panel experiences. The first local strain effects occur in the autoclave assembly process, as the various material fabric/tape layers cool down from the glass transition temperature. Due to the significant tool/bag pressures, these tension/compression strains are locked into the structure, and remain at least until the article is removed from the autoclave. Upon removal the structure warps to some extent, the strains are redistributed and the total strain energy decreases somewhat. Specifically, the strains tend to be larger for panels that contain multiple composite materials, due to CTE effects. Of course the overall panel is in stress equilibrium in an integrated volume sense. When the panel is fastened onto a fixture, strains again redistribute and the panel strain energy increases. Part of the strain increments here are due to bending (flattening of the panel) and part are due to the fastening sequence (tightening of outer fasteners in a row before the more inner fasteners tends to lock in axial compressive strains).

An important point is that, as the test article experiences each of these typical sources of strain, it becomes more like an actual panel over the majority of its operational service. We expect load/strain plots to generally become more linear after the residual stresses are shaken out.

In correlating the panel test results with the FEM analysis model, we also focus on the test load and its incremental relationship to the surrogate strain value. Our FEM correlation does not include strain which might have occurred in a previous load condition analysis.

3.0 AIRFRAME INTEGRATION

The results from sub panel testing and correlated FEM data has been used to develop and test large scale component panels for specific airframe applications such as wing and weapons bay door. As noted before, we will focus on strain because it is a surrogate for the load bearing capability (strength and durability) which we need to demonstrate. The designer of the antenna/vehicle is interested in whether our panel can carry the required loads. These loads are represented by the surrogate increment of strain in a given test. We can take no credit for, and receive no penalty from, any strain which might have occurred prior to the start of the load condition. Such prior strains may be of academic interest, but would only confuse verification and reporting of tested strain-increment (load) capability.

At this point, the SIXA program has developed an accurate understanding of the mechanical properties of the panel, but has not been applied to a specific airframe. Due to this development being independent of a program and platform, large scale panels are designed using simple spectrums mixed with known data from Boeing airframes. The SIXA load-bearing first-use application is not yet well defined, and longer-term applications are not confined to a single vehicle or location on a vehicle. A simple spectrum serves as a better general design basis, because it is more easily compared with particular application requirements.

4.0 STRUCTURE TO RF INTERCONNECT

Boeing and its partners have developed a novel packaging approach for the RF electronics required to operate the SIXA array. This concept revolves around the integration of all of the primary and secondary electronic subcomponents into a durable building block. Other than the primary RF requirements these electronic sub-assemblies are required to survive the extreme thermal and mechanical cycling experienced during the

components life time.

One of the most challenging aspects of this unique integrating approach is the creation of the large number of structuralized RF signal line interconnections. The sheer number of connections required made this a daunting task on its own without the additional structural and electrical requirements. Due to the high level of integration of load bearing elements and electrical components a unique set of requirements are imposed on these interconnects. In terms of electrical (RF) functionality, interconnects need to have properties including low loss and matching impedance. Structurally, interconnects are expected to perform under high strain environments under a range of temperature without insignificant impact on the overall RF performance of the antenna. This includes the ability to survive low cycle mechanical and structural fatigue. Other factors considered in the development of these interconnects was scalability, process compatibility and cost.

The development cycle for these interconnect began with an initial evaluation of numerous conventional and non-conventional methods for creating electrical interconnects. During this first phase of development interconnects were evaluated based upon ease of integration into the baseline process, cost (labor and materials), scale-ability, repeatability and yield. This initial down select process was followed by several rounds of coupon testing. Test coupons were subject to a range of structural, thermal and electrical testing. Additional selection criteria considered during this testing phase included yield and compatibility with overall process flow. After several iterations a process was selected which best met all the electrical, structural and thermal requirements.

Following this initial test phase the down selected process and resulting interconnect architecture was included in the manufacturing of a large structural test article. This exercise was used to evaluate the scalability of the baseline interconnect. Additional structural and electrical testing of this large test article revealed several limitations of the baseline process. As a result a second round of coupon testing was performed to address the scale-ability issues. This second round of coupon testing reviled a dynamic relationship between the interconnect process and subsequent processes used in the fabrication of the overall SIXA array structure.

Minor modifications to baseline manufacturing processes were required to increase interconnect yield and address the scalability issues. The result was a high yield, scalable interconnect which satisfies all electrical, thermal and structural requirements of the SIXA antenna.

5.0 LARGE SCALE STRUCTURAL EVALUATION

When the large scale testing effort of this program was initiated it was decided that the x-band array aperture design must be configured into a load bearing structural skin panel, sized to match substructure arrangements, and conformal to the OML of the notional host vehicle platform such as “Sensorcraft”, in an area where its field of regard is compatible with mission objectives. This required that the panel be attached to a supporting structural durability test fixture in the same way as it would be installed on the host air vehicle platform. The structural durability test fixture was capable of applying static limit and ultimate loads, as well as repeated strains and deflections to the X-Band Array panel for fatigue performance validation. The applied strains/load conditions were established to be representative of those encountered during two lifetimes of normal air vehicle flight and ground operations. This includes the primary GAG (Ground/Air/Ground) loading spectrum, to which the air vehicle would be subjected during a typical mission, or variety of missions. The key structural considerations for design and test of the array panel were: a) strain spectrum level, due to combined

torsion and bending loads; b) the number of flight cycles; and c) environmental conditions from -60°F to 160°F; and d) primary structural loads requiring that the panel incorporate a graphite epoxy back skin.

5.1 Large Scale Wing Component Testing

Various loading configurations were considered for the design of the combined load wing box structure to evaluate the SIXA structural technology; it was decided to design this test article so that it could be loaded in a 4-point bending configuration. This provided a means of establishing well behaved load distribution and boundary conditions. The loading configuration is shown below in 4.

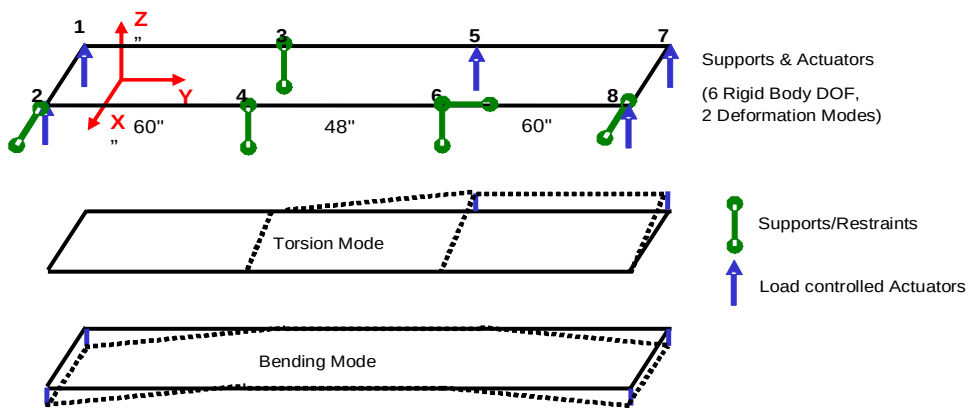

Figure 4 Bending and Torsion Modes

The SIXA panel is integrated into an aluminium wing box. The panel (top center of wing box) is connected by splice ribs to curved graphite panels on each end. The curved ends of the SIXA panel (tension/compression loaded) each have two rows shear-head fasteners. The straight sides of the panel (shear loaded) each have one row of fasteners. The bottom skin of the wing box is formed by three flat aluminium panels, spliced at the same rib locations as the top. The fasteners for the graphite and aluminium panels are similar to those for the SIXA panel. The wing box is designed for plastic yielding in the destruct case, in order to ensure that enough load can be applied to the SIXA panel. Four trunnions and eight corresponding actuators/supports allow a combination of bending and torsion loads to be applied to the wing box, putting the SIXA panel into tension/compression and shear. The configuration of the loading frame (without the environmental control chamber) is shown in Figure .

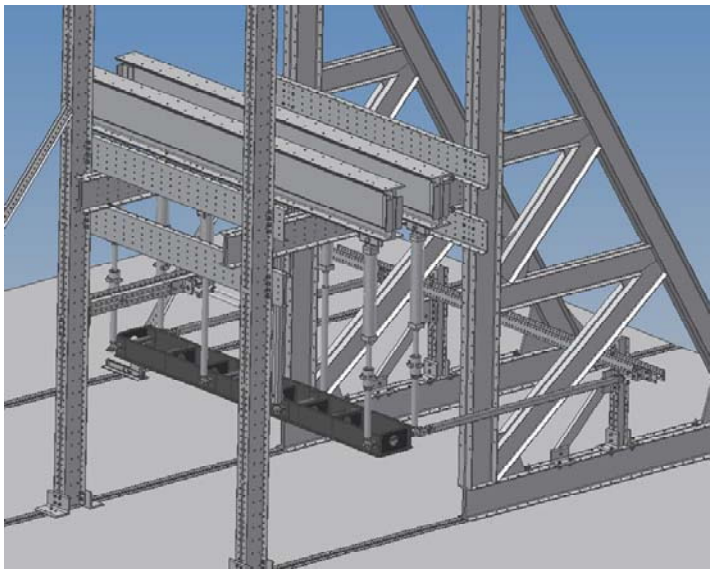

Figure 5 Loading Apparatus

The testing first involved subjecting the SIXA panel to a series of low velocity impact events at varying levels. Secondly, the component was taken through a series of design limit load conditions, including tension/compression panel bending, torsion and combined loads. These tests were achieved without any indication of failure. The low velocity impact sites did not grow and no failure or onset of failure was identified in any of the test data or after comparing to baseline ultrasonic non-destructive investigation maps that were developed. After completing these design limit tests, fatigue tests were then performed. The fatigue conditions involved completing two lifetimes of the defined loading spectrum. This spectrum involved room temperature cycling, cold at -60°F and then hot at 160°F. Again, all data was reviewed and it was determined that the structure had not undergone any observable degradation nor had the electrical interconnects from the subarray to the integrated radiators. Therefore, it was decided to run the box through an equivalent of 4 additional loading spectrums that were slightly modified to account for gust loads. While this approach to test may not be orthodox for certification, it was recognized that this was a research article and we were intent to learn as much as possible. After the completion of these final test cycles all data was again reviewed and it was determined that the structure had not undergone any degradation. This was considered a terrific accomplishment and validated the "robustness" of the design configuration. The final test involved taking the component skin to ultimate compression failure. Failure occurred at 5700 μ-strain in a true compression failure, as opposed to buckling.

5.2 DEFORMATION COMPENSATION

Boeing has developed a unique strain-based structural deformation compensation approach for predicting structural displacements. For structurally integrated arrays, there is a need for a measurement system that does not interfere with the operation of the antenna, which provides real-time feedback and at many locations

about the structure, and that does not add to the overall complexity system. Previous systems for measuring the "flatness" of planar structures have relied on metrology devices that measure the distance from a common source to pre-determined points on the structure, typically through laser reflection from a surface mounted target or by some form of photogrammetry. These systems can be very accurate but they do rely upon line-of-sight measurements and a potentially limited number of measurement locations. The application of surface mounted and/or structurally embedded high-resolution strain sensing devices for predicting structural deformations provides a low-cost, minimum weight, non-intrusive structural monitoring system for determining the shape of the antenna. Figure 6 illustrates the strain-based deformation compensation approach.

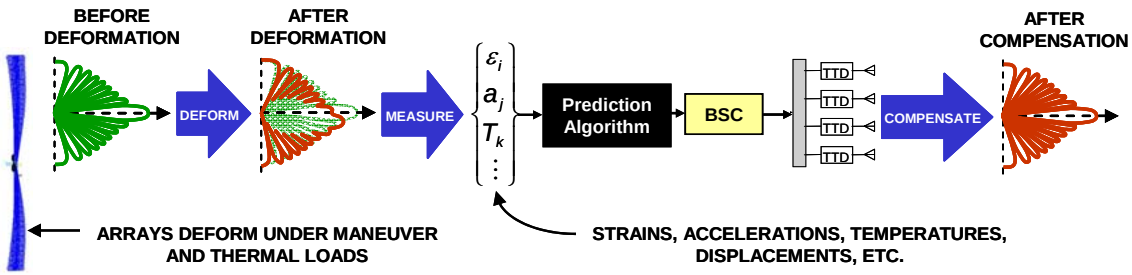

Figure 6 Boeing strain-based deformation compensation approach

One of the key features of strain-based deformation compensation is the prediction algorithm used to interpret measured strain patterns into structural deformation patterns. The prediction algorithm must be accurate, robust, and adaptable. Techniques for predicting displacement from strain information range from linear structural mechanics formulations[1] to nonlinear heuristic formulations based on empirically gathered data. One of the limiting factors with purely structural mechanics based techniques is that they are fundamentally linear in development. In practice, nonlinear effects will limit the accuracy of linear based techniques. Using heuristic models provides a methodology that can robustly account for nonlinear behavior as well as adapt to system changes over time.

1 Bogert, P.B., Haugse, E.D. and Hehrki, R.E., "Structural Shape Identification from Experimental Strains Using a Modal Transformation Technique," 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, Apr. 7-10, 2003, AIAA-2003-1626.

7.0 SUMMARY

The SIXA program has demonstrated and validated the structural viability of the x-band primary structure. The structural testing has used a building block approach to develop a design configuration that will meet RF requirements and survive the anticipated service environments. The testing has shown that the design is actually more robust than anticipated even though the sandwich core is weight comparable to conventional HRP core, indicating that an opportunity may exist to reduce weight even more in the future. However, the data developed is the result of a prototyping manufacturing methodology, therefore significant work will need to be accomplished in the future to assure a low cost manufacturing process is developed and can be transitioned. Validation of the RF array design in the anechoic chamber is scheduled for early in calendar year 2007.

SYMPOSIA DISCUSSION – PAPER NO: 17

Author's Name: D. Banks

Question (H. Schippers):
Do you also consider deformation compensation due to vibrations? Can you compensate in real time?

Author's Response:
All deformations must be considered, vibration is usually a lower order term versus aero driven deformation of wings. Doors may have more vibrations when opened that closed.

Question (G. Günther):
Where in the "building block approach" of integrated sensors/actuators into primary structures are aspects of repairs to be RF-systems evaluated/demonstrated?

Author's Response:
We have demonstrated by impact tests the repair of primary structure of array elements. For RF systems we have assumed a repair approach, and we will demonstrate part of this approach over the next 4 month.

Question (J. Thomas):
How does the current design approach (antenna embedded in sandwich core) influence vehicle performance to what might be other "unifunctional" design approaches? For example, differences in: weight, cost, vehicle and antenna performance, etc.

Author's Response:
Current design approach is based on a sensor critical vehicle which is an ISR aircraft. Structural integration is baseline. Other systems have other design drivers, but for a large ISR platform in which the Large Array is an add on, weight savings of more than 5x have been shown. Cost is a program issue.