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RTO AGARDograph 160
Flight Test Instrumentation Series – Volume 22

SCI-228

Application of Fiber Optic Instrumentation

(Validation des systèmes d'instrumentation
à fibres optiques)

This AGARDograph has been sponsored by SCI-228, the Flight Test Technology Task Group of the Systems Concepts and Integration Panel (SCI) of RTO.

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AGARDograph Series 160 and 300

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development (AGARD) recognized the need for a comprehensive publication on Flight Test Techniques and the associated instrumentation. Under the direction of the Flight Test Panel (later the Flight Vehicle Integration Panel, or FVP) a Flight Test Manual was published in the years 1954 to 1956. This original manual was prepared as four volumes: 1. Performance, 2. Stability and Control, 3. Instrumentation Catalog, and 4. Instrumentation Systems.

As a result of the advances in the field of flight test instrumentation, the Flight Test Instrumentation Group was formed in 1968 to update Volumes 3 and 4 of the Flight Test Manual by publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, it was decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group (FTTG) was established to carry out this task and to continue the task of producing volumes in the Flight Test Instrumentation Series. The monographs of this new series (with the exception of AG237 which was separately numbered) are being published as individually numbered volumes in AGARDograph 300. In 1993, the Flight Test Techniques Group was transformed into the Flight Test Editorial Committee (FTEC), thereby better reflecting its actual status within AGARD. Fortunately, the work on volumes could continue without being affected by this change.

An Annex at the end of each volume in both the AGARDograph 160 and AGARDograph 300 series lists the volumes that have been published in the Flight Test Instrumentation Series (AG 160) and the Flight Test Techniques Series (AG 300) plus the volumes that were in preparation at that time.

Application of Fiber Optic Instrumentation

(RTO AG-160 Vol. 22 / SCI-228)

Executive Summary

This AGARDograph presents an introduction to fiber optic systems and is intended to provide a basic understanding of the utilization of these systems for aircraft instrumentation. It documents the current state of the art and provides references for users of this technology to track the rapid advances expected in fiber optic technology in the coming years.

Revolutionary advances in fiber optic technology, as applied to flight-test instrumentation, have been achieved over the last decade and are expected to continue at a rapid pace for the foreseeable future. There has been significant maturation in both the manufacturing of fibers and the miniaturization of hardware, which has enabled movement of this technology from controlled laboratory environments to realistic aircraft operations. The ability to closely space sensors on the fibers has improved by orders of magnitude and the capability for continuous sensors is rapidly becoming feasible. Fiber optic systems will revolutionize flight-test instrumentation for all of the NATO members, potentially eliminating strain gages and their associated wiring while collecting more accurate and densely spaced measurements at a significantly reduced system weight. Fiber optic instrumentation provides the ability to capture system-wide stress, strain, and temperature measurements far beyond classic aircraft flight-test instrumentation applications. The technology also enables the determination of many other derived engineering parameters such as structural shape, and applied loads; information that has not been available before with conventional aircraft sensors systems.

This AGARDograph documents the current state of the art for this technology and provides references for users to track the rapid advances expected in fiber optics in the coming years. One application for this technology could be to a wide range of NATO aircraft systems in order to establish a comprehensive set of data for aging aircraft. Other future applications could entail embedding fiber optic systems in composite structures as they are manufactured, allowing extremely light-weight flexible structures to be actively controlled, giving enhanced capability to air, surface, and ground-based NATO systems.

Validation des systèmes d'instrumentation à fibres optiques

(RTO AG-160 Vol. 22 / SCI-228)

Synthèse

Cette AGARDograph présente une introduction aux systèmes à fibres optiques et a pour objet d'expliquer l'utilisation de ces systèmes dans l'instrumentation embarquée. Elle expose l'état actuel de la technique et fournit un cadre de référence pour que les utilisateurs de cette technologie puissent suivre les progrès rapides qui sont attendus dans le domaine des fibres optiques au cours des années à venir.

Durant les dix dernières années, des progrès révolutionnaires ont été accomplis par la technologie des fibres optiques appliquée à l'instrumentation des essais en vol, et ces avancées devraient se poursuivre à un rythme rapide dans un avenir prévisible. Le degré de maturité des procédés de fabrication de fibres et de miniaturisation du matériel a progressé, permettant ainsi à cette technologie de passer du stade des conditions contrôlées en laboratoire au stade des conditions d'opérations aériennes réalistes. La densité d'intégration de capteurs dans les fibres a été accrue de plusieurs ordres de grandeur et les progrès réalisés en termes de faisabilité de capteurs continus sont rapides. Les systèmes à fibres optiques vont révolutionner l'instrumentation des essais en vol dans l'ensemble des pays membres de l'OTAN, entraînant la disparition progressive des jauges extensométriques et des câblages qu'elles nécessitent, tout en autorisant des mesures plus précises à haute densité d'intégration et pour un poids bien moindre. Les instruments à fibres optiques offrent des capacités de mesure de contrainte, d'allongement et de température à l'échelon d'un système bien supérieures aux possibilités des instruments embarqués classiques d'essais en vol. Grâce à cette technologie, il est en outre possible de calculer une multitude d'autres paramètres techniques dérivés, tels que la forme de structures et les charges appliquées, informations qu'il n'était jusqu'à présent pas possible de recueillir avec les systèmes de capteurs embarqués classiques.

Cette AGARDograph expose l'état actuel de la technique et fournit un cadre de référence pour que les utilisateurs de cette technologie puissent suivre les progrès rapides qui sont attendus dans le domaine des fibres optiques au cours des années à venir. Cette technologie pourrait, notamment, être appliquée à un large éventail de systèmes d'aéronefs de l'OTAN dans le but de constituer un ensemble détaillé de données pour des aéronefs vieillissants. D'autres applications futures pourraient consister à intégrer des systèmes à fibres optiques dans des structures composites en cours de fabrication, autorisant ainsi le contrôle actif de structures flexibles ultra légères et améliorant les capacités des systèmes OTAN aériens, de surface et terrestres.

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The authors gratefully acknowledge the support provided by our many colleagues at NASA Dryden Flight Research Center and across the agency who have provided seemingly endless opportunities to validate fiber optic sensing technology on a wide variety of aerospace vehicles and large-scale test articles. We are greatly indebted to the highly-qualified technical staff in the Flight Loads Laboratory at NASA Dryden for their expertise in conducting the large-scale structural test operations. These tests were essential to validate many of the new theories and measurement approaches documented in this report. We are especially grateful for the encouragement, strong support and technical leadership provided by our senior management for allowing us the opportunity to help mature this technology for NASA applications. Special thanks go to Mr. Patrick Stoliker for the many years of technical guidance he provided as Director for Research, as well as his unflinching support as Deputy Center Director to publish the technical results in this report.

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List of Acronyms and Symbols

A/D	Analog to Digital
ATR	Air Transport Rack
c	half depth of uniform beam (distance from neutral surface to bottom or top surface), in.
CCM	Composite Crew Module
cPCI	compact Peripheral Component Interconnect
COPV	Composite Over-wrapped Pressure Vessel
COTS	Commercial-Off-The-Shelf
CPU	Central Processing Unit
DUT	Device Under Test
E	Young modulus, lb/in^2
EFPI	Extrinsic Fabry Perôt Interferometer
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
FBG	Fiber Bragg Grating
FEA	Finite Element Analysis
FLL	Flight Loads Laboratory
FOSS	Fiber Optic Smart Structure
I	moment of inertia, in^4
I_R	reflected intensity of light
k	wave number
L	optical path length difference
n_0	core index of refraction
n	effective index of refraction
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering Safety Center
O/E	Optical to Electrical
OFDR	Optical Frequency Domain Reflectometry
p_e	strain-optic coefficient
P	applied load, lb
R	spectrum of ith grating
S	Section modulus, I/c, in^3
T	Temperature, °F
UAV	Uninhabited Aerial Vehicle

α	coefficient of thermal expansion
α_n	thermal optic coefficient
α_{sub}	thermal optic coefficient substrate
α_Λ	coefficient of thermal expansion of fiber
ε	strain, µin/in
ε_{app}	apparent strain, µin/in
ε_{ind}	indicated strain, µin/in
ε_{true}	true strain, µin/in
δ	multidimensional differential operator
Δ	one dimensional change in scalar value
Δl	distance between two adjacent strain-sensing stations, in
λ	light wavelength, nm
λ_B	Bragg reflected wavelength, nm
Λ	periodity of grating planes
ξ	temperature coefficient of resistivity

Preface

Dr. W. Lance Richards has a Ph.D. in mechanical engineering from the University of Wales, Swansea, UK. He has 30 years experience with NASA conducting research, development, and implementation of advanced sensors and instrumentation, with specific application to aerospace vehicle technology. He has authored more than 75 reports and is a co-recipient of U.S. patents for developing highly accurate and efficient data-driven methods for real-time, on-board determination of structural shape and externally-applied loads for aerospace vehicles.

Allen R. Parker Jr. received a Master of Engineering degree in the area of microelectronics from Texas A&M University. Mr. Parker is currently working as a researcher at NASA's Dryden Flight Research Center focusing in the area of advanced sensor development with major emphasis on using fiber Bragg gratings to measure various physical parameters. He has played a major part in the development of algorithms and systems, which has made possible the practical application of this "game changing" sensing technology. With this technology, Mr. Parker continues to support projects inside as well as outside NASA, covering industries from medical to aerospace to space.

Dr. William L. Ko has a Ph.D. degree in aeronautics from California Institute of Technology. He formulated the internationally recognized Blatz-Ko Constitutive Law for hyperelastic materials. He also formulated aging theories for flight structure service life predictions. Lately, he developed displacement theories for converting surface strains into out-of-plane deflection for deformed shape predictions of aerospace structures.

Anthony Piazza has over 25 years experience in the field of structural instrumentation and test; specializing in strain measurements using both electrical and optical based sensors/systems. He also possesses unique proficiency in the development, attachment, evaluation, and characterization of extreme sensors applicable to hot-structures testing and hostile environments.

Dr. Patrick Hon Man Chan has a Ph.D. in Interdisciplinary Material Science and Engineering from University of California, Irvine. He is a fiber optics researcher at NASA Dryden, working to mature various aspects of current fiber optics sensing system technology for wide-spread deployment. Dr. Chan has published numerous journal papers related to fiber technology, and is currently working on all-fiber laser source as well as conducting research on shape-sensing fiber technology.

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14. Abstract

Fiber optic sensing technology has emerged in recent years offering tremendous advantages over conventional aircraft instrumentation systems. The advantages of fiber optic sensors over their conventional counterparts are well established; they are lighter, smaller, and can provide enormous numbers of measurements at a fraction of the total sensor weight. After a brief overview of conventional and fiber-optic sensing technology, this paper presents an overview of the research that has been conducted at NASA Dryden Flight Research Center in recent years to advance this promising new technology. Research and development areas include system and algorithm development, sensor characterization and attachment, and real-time experimentally-derived parameter monitoring for ground- and flight-based applications. The vision of fiber optic smart structure technology is presented and its potential benefits to aerospace vehicles throughout the lifecycle, from preliminary design to final retirement, are presented.

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