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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

Note: There is an Addendum to this publication containing the PowerPoint presentations.

RTO MEETING PROCEEDINGS 51

Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles

(Technologies des systèmes à commandes actives pour l'amélioration des performances opérationnelles des aéronefs militaires, des véhicules terrestres et des véhicules maritimes)

Papers presented at the Symposium of the RTO Applied Vehicle Technology Panel (AVT) held in Braunschweig, Germany, 8-11 May 2000.

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles

(RTO MP-051 / AVT-048)

Executive Summary

The performance demands of future vehicles and engines are becoming increasingly challenging with the trends to high manoeuvrability, lower specific fuel consumption, higher power-to-weight ratios and lower life-cycle cost. Conventional design including passive control has brought vehicle technology to its present high level and in many cases has reached the limits. Active control technology is aimed at enhancing system behaviour by controlling dynamics of processes such as: vibrations, structural deformation, combustion, flow instabilities, noise, etc. It is becoming one of the most important aspects of vehicle design and operation, having in some cases potential of retrofit as well. Tools of a new quality offer improvements in the behaviour of overall systems as well as in sub-domains. To be mentioned are computer technology, sensors and actuators, micro-mechanic technology (MEMS), smart materials, supported by innovative manufacturing technologies, and the improved insight into process laws. Smaller, more efficient, more powerful, and more integrated, solutions are becoming possible. The potential exceeds by far that which can be achieved nowadays by careful system design and the use of passive components, and while the application is possible and of advantage in all kinds of vehicles, land, air, and sea, civil as well as military, the most interesting overall advances have been made so far in air vehicles and in some specific areas in propulsion generally.

The engine including the inlet and exhaust, and the engine subsystems have their control systems in addition to the flight control system of the overall aircraft. The Symposium concentrated specifically on the compressor and the combustors of the gas turbine. Active control in these areas has been proven to be feasible in laboratory as well as in full scale engines, and there is a high potential of early application in particular in land vehicle engines aiming at lower emission levels of noise as well as toxicants. Active control stabilisation of flows permits for example higher pressure ratios which in the end can translate into smaller engines. Another consequence which in view of the better performance possible is often overlooked is the reduction on overall life cycle cost, savings in maintenance and damage due to better control and diagnostics offsetting the higher initial investment.

In fluid dynamics it is now possible to control boundary layer and vortex-flow over vehicles or inside engines. Control of flight attitude by influencing boundary layers and vortices has been proven as being possible, avoiding the use of - energy and weight consuming - control surfaces, and may find their first wide spread application in uninhabited and small or micro vehicles. Flutter and buffet can be avoided, as well as unnecessary high loads in manoeuvres. The application in active lift devices in particular for air vehicles such as STOVL fighters and the utilisation of active control in vectoring nozzles are other areas in which active control has proven its importance. Fluid dynamics application in the water vehicle environment were not treated and are usually strictly confidential. Missile application could as well only be mentioned once.

Last not least there is a high potential in structural applications. Two major roads are the introduction of flexible structures - a concept known from the beginning of aeronautics and now being again made possible by the availability of sufficiently fast and powerful actuators and computers, not to forget the control laws. This can be used for vehicle attitude control as well as for compensating unwanted vibrations in structures instead of making them rigid at a high weight penalty. Besides individual actuators for which the Micro Electro-Mechanical Systems offer an extremely interesting future the

so-called smart materials can be employed. Both areas are only at the beginning of their development, in mechanisms as well as in theory.

Some lessons drawn from this Symposium are: there is an urgent need for further development in fast and reliable actuators, and in sensors, both able to function reliably in adverse environments, in particular in high temperatures and under high vibration loads. Obviously the development of theory and control laws has to keep pace. The most important message for RTO and AVT is probably the observation that there is development being done for vehicles of all four environments, that there are similarities and analogies over all vehicle classes, and that the potential for mutual benefit needs to be probed by initiating Technical Activities aimed at this task.

Technologies des systèmes à commandes actives pour l'amélioration des performances opérationnelles des aéronefs militaires, des véhicules terrestres et des véhicules maritimes

(RTO MP-051 / AVT-048)

Synthèse

Les spécifications de performances des futurs moteurs et véhicules relèvent de plus en plus du défi permanent, l'accent étant mis sur la grande manoeuvrabilité, des consommations spécifiques réduites, de plus grand rapports poussée-poids et des coûts globaux de possession plus modestes. Les techniques de conception classiques, intégrant des commandes passives, qui ont porté la technologie des véhicules à son haut niveau actuel, commencent à atteindre leurs limites. La technologie des commandes actives a pour objectif d'améliorer la réponse du système en contrôlant les phénomènes dynamiques, tels que les instabilités de flux, les vibrations, les déformations structurales, la combustion, le bruit, etc. Elles sont en passe de devenir l'un des aspects les plus importants de la conception et l'exploitation des véhicules, offrant en plus, dans certains cas, des possibilités de remise à niveau. Des outils d'une qualité jamais atteinte permettent d'améliorer le comportement global des systèmes et des sous-systèmes. Il s'agit de matériaux intelligents, de technologies informatiques, de capteurs et de servocommandes, et de la micromécanique (MEMS), soutenus par des technologies de fabrication novatrices et par une meilleure compréhension des lois régissant les processus. Désormais, des solutions plus efficaces, plus étendues et plus intégrées sont envisageables. Les possibilités dépassent de loin ce qui est faisable aujourd'hui par le biais de la mise en oeuvre de composants passifs et de la conception soignée des systèmes, et bien que la mise en oeuvre de ces technologies soit réalisable et profitable pour tous véhicules civils et militaires terrestres, aériens et maritimes, c'est dans le domaine des véhicules aériens et dans certains domaines de la propulsion en général qu'ont été enregistrés les progrès les plus intéressants.

Le moteur, y compris les entrées d'air et l'échappement, ainsi que les sous-systèmes de propulsion ont leurs propres systèmes de commande en plus du système de commande global de l'aéronef. Le symposium était axé spécifiquement sur le compresseur et la chambre de combustion de la turbine à gaz. L'adéquation des commandes actives pour ces organes a été démontrée en laboratoire ainsi que sur des moteurs réels, et ce type de commande pourrait trouver des applications dans un avenir proche sur des moteurs de véhicules terrestres, où il permettrait de réduire les niveaux de bruit à l'émission ainsi que les substances toxiques. La stabilisation des flux par les commandes actives permet, par exemple, d'obtenir des taux de compression plus élevés, ce qui pourrait se traduire à terme par des moteurs plus petits. Une autre conséquence pour les performances, qui est souvent négligée, est la diminution des coûts globaux de possession, et les économies réalisables au niveau de la maintenance et des réparations grâce à un meilleur diagnostic, qui a pour effet de compenser l'investissement initial plus élevé.

En dynamique des fluides, il est désormais possible de contrôler la couche limite et les écoulements tourbillonnaires autour des véhicules ou à l'intérieur des moteurs. La possibilité du contrôle de l'assiette par la modification des couches limites et des tourbillons, évitant ainsi l'emploi, coûteux en énergie et en poids, de gouvernes, a été démontrée et cette technique pourrait être mise en oeuvre pour la première fois dans des petits véhicules, des micro-avions et des véhicules sans pilote. Cette démarche permettrait d'éviter le flottement et le tremblement, ainsi que l'application de fortes charges pendant les manoeuvres. La mise en oeuvre de telles techniques dans des appareils hypersustentateurs, en particulier dans des véhicules aériens tels que les avions VSTOL, et l'utilisation de commandes

actives pour les tuyères orientables sont d'autres exemples de leur importance. L'application de la dynamique des fluides aux véhicules maritimes n'a pas été traitée. Ce sujet est d'ailleurs normalement strictement confidentiel. Une seule communication a été présentée sur les applications missiles.

Enfin, le symposium a souligné les nombreuses possibilités existantes dans le domaine des applications structurales. Les deux principales voies sont, d'un côté, les structures souples - concept connu depuis le début de l'aéronautique, mais actuellement en cours de réexamen grâce aux possibilités offertes par les nouvelles servocommandes rapides, les progrès réalisés en informatique et enfin et surtout par les lois de commande. Ces structures peuvent être utilisées pour le contrôle de l'assiette du véhicule, ainsi que pour compenser d'éventuelles vibrations non désirées des structures, à la différence de la solution qui consiste à les rendre rigides et par conséquent, plus lourdes. En plus des servocommandes individuelles, pour lesquelles les systèmes micro-électro-mécaniques (MEM) offrent une solution très intéressante, les matériaux dits intelligents peuvent être employés. Les deux techniques sont au tout début de leur développement, tant du point de vue des mécanismes que de celui des théories.

Différents enseignements ont été tirés de ce symposium. Il est urgent de développer des servocommandes rapides et fiables, ainsi que des capteurs de fonctionnement fiable même dans des environnements défavorables, et en particulier à des températures ambiantes élevées et sous de fortes charges vibratoires. Il est évident que le développement des théories et des lois de commande doit suivre cette cadence. En conclusion, suite à ce symposium, la leçon la plus importante à retenir pour la RTO en général et pour AVT en particulier est que le développement est en cours pour des véhicules aériens, spatiaux, maritimes et terrestres, qu'il existe des similitudes et des analogies entre toutes ces catégories de véhicules, et que la possibilité d'en tirer des avantages mutuels doit être examinée en lançant les activités techniques appropriées.

Click inside the blue boxes or on the titles to view the corresponding section

Contents

Session II: Active Flow Control of Nozzle/Jet

Session III: Drag and Buffet Control

Session IV: Noise Control

Session V: Vortex Control

Session VI: Flight Vehicle Active Control

Programme Mechanical Systems, Structures and Materials (MSSM)

Session I: Smart Structures Applications

Session II: Active Control Technology for Load Alleviation

Session III: Active Elements for Structural Design

Session IV: Active Materials and Applications

Programme Power Systems and Propulsion (PSP)

Session I: Applications Overview

Session II: Compressor Stall/Surge - Measurements

Session III: Compressor Stall/Surge - Control

Session IV: Combustion Instabilities - Measurements and Predictions

Session V: Combustion Instabilities - Control Fundamentals - Part I

Session VI: Combustion Instabilities - Control Applications

Theme

The performance demands of future vehicles and engines are becoming increasingly challenging with the trends to high manoeuvrability, lower specific fuel consumption, higher thrust-to-weight ratios and lower life-cycle cost. This applies to both military and commercial vehicles and engines.

Active control technology is aimed at enhancing system behaviour by controlling dynamics processes such as flow instabilities, vibrations, structural deformation, combustion, noise, etc. Conventional design including passive control has brought vehicle technology to its present high level and in many cases has reached the limits. While active Flight/Ride Control is a technique already in use, a new quality of tools offer improvements in the behaviour of overall systems as well as in sub-domains. These tools are the development of smart materials, innovative manufacturing technologies, computer technology, sensors and actuators, micro-mechanic technology (MEMS) and the improved insight into process laws. Smaller, more efficient, more powerful and more integrated solutions are becoming possible. The potential exceeds by far that which can be achieved nowadays by careful system design and the use of passive components.

The Symposium will predominantly look at aircraft related technologies because in aircraft the need for active control technologies is very high. Other vehicles can greatly benefit from the transfer developed for air vehicles.

The Symposium will review the current status of active control and execute the short term and long term application potential. Three main streams are offered, namely flow flight control, structure control and engine control. In the field of flow control the symposium will focus on drag reduction techniques, vortex stabilisation, thrust vectoring, and noise control. The flight control session offers recent results of flight test experiences. In the structures and materials field adaptive structures, buffet-control, gust alleviation as well as new actuators are presented. The engine domain will focus on stall/surge and combustion instability control with presentations on laboratory and full-scale experiments for applications to gas turbines, ramjets and solid propellant motors. Different aspects of active control will be addressed, ranging from physical understanding to the control process, controller, sensors and activators and its integration into the whole system.

Thème

Les spécifications de performances des futurs moteurs et véhicules sont de plus en plus redoutables, l'accent étant mis sur une grande maniabilité, une consommation spécifique de carburant réduite, un plus grand rapport poussée-poids et des coûts globaux de possession plus modestes. Ces exigences concernent les moteurs et les véhicules tant civils que militaires.

La technologie des commandes actives a pour objectif d'améliorer la réponse du système en contrôlant les phénomènes dynamiques, tels que les écoulements instationnaires, les vibrations, les déformations structurales, la combustion, le bruit, etc. Les techniques de conception classiques, intégrant des commandes passives, qui ont porté la technologie des véhicules à son haut niveau actuel, commencent à atteindre leurs limites. En effet, la technique des commandes actives de vol/de confort est déjà employée, mais des solutions techniques d'une qualité novatrice promettent d'améliorer le comportement global des systèmes et des sous-systèmes. Il s'agit de matériaux intelligents, de technologies de fabrication novatrices, de technologies informatiques, de capteurs et de servocommandes, de la micromécanique (MEMS) et d'une meilleure compréhension des lois régissant les processus. Désormais, des composants et des systèmes plus petits, plus efficaces, plus puissants et plus intégrés sont envisageables. Les perspectives dépassent de loin ce qui est réalisé avec des composants passifs, et ce même avec une conception très soignée des systèmes.

Ce symposium examinera principalement les technologies aéronautiques puisque la demande de technologies de commandes actives pour aéronefs est très importante. Cela étant, d'autres véhicules pourraient profiter du transfert des technologies développées pour véhicules aériens.

Ce symposium fera le point des connaissances actuelles dans le domaine des commandes actives et évaluera les possibilités à court et à long terme. A la suite de la cérémonie d'ouverture plénière du lundi matin, trois grands axes seront proposés, à savoir les performances, la stabilité et le contrôle, la physique des fluides; les systèmes mécaniques, les structures et matériaux; les génératrices et les propulseurs. En ce qui concerne le contrôle des écoulements le symposium privilégiera les techniques de réduction de la traînée, la stabilisation des tourbillons, l'orientation de la poussée et le contrôle du bruit. La session sur les commandes de vol présente les résultats d'essais en vol récents. Dans le domaine des structures et matériaux, des structures adaptatives, le contrôle du tremblement, l'atténuation des rafales et les nouveaux actionneurs sont présentés. Les sessions sur les moteurs seront consacrées au calage/pompage et au contrôle des instabilités de combustion, avec des présentations sur des expériences conduites en laboratoire et sur le terrain pour applications aux turbomoteurs, aux statoréacteurs et aux moteurs à propergol solide. Différents aspects des commandes actives seront examinés, allant de la description du processus physique au processus de contrôle, au contrôleur, aux capteurs et aux actionneurs et à l'intégration des commandes actives dans le système global.

Publications of the RTO Applied Vehicle Technology Panel

MEETING PROCEEDINGS (MP)

Design for Low Cost Operation and Support
MP-37, September 2000

Gas Turbine Operation and Technology for Land, Sea and Air Propulsion and Power Systems (Unclassified)
MP-34, September 2000

Aerodynamic Design and Optimization of Flight Vehicles in a Concurrent Multi-Disciplinary Environment
MP-35, June 2000

Structural Aspects of Flexible Aircraft Control
MP-36, May 2000

New Metallic Materials for the Structure of Aging Aircraft
MP-25, April 2000

Small Rocket Motors and Gas Generators for Land, Sea and Air Launched Weapons Systems
MP-23, April 2000

Application of Damage Tolerance Principles for Improved Airworthiness of Rotorcraft
MP-24, January 2000

Gas Turbine Engine Combustion, Emissions and Alternative Fuels
MP-14, June 1999

Fatigue in the Presence of Corrosion
MP-18, March 1999

Qualification of Life Extension Schemes for Engine Components
MP-17, March 1999

Fluid Dynamics Problems of Vehicles Operation Near or in the Air-Sea Interface
MP-15, February 1999

Design Principles and Methods for Aircraft Gas Turbine Engines
MP-8, February 1999

Airframe Inspection Reliability under Field/Depot Conditions
MP-10, November 1998

Intelligent Processing of High Performance Materials
MP-9, November 1998

Exploitation of Structural Loads/Health Data for Reduced Cycle Costs
MP-7, November 1998

Missile Aerodynamics
MP-5, November 1998

EDUCATIONAL NOTES (EN)

Measurement Techniques for High Enthalpy and Plasma Flows
EN-8, April 2000

Development and Operation of UAVs for Military and Civil Applications
EN-9, April 2000

Planar Optical Measurements Methods for Gas Turbine Engine Life
EN-6, September 1999

High Order Methods for Computational Physics, Published jointly with Springer-Verlag, Germany
EN-5, March 1999

Fluid Dynamics Research on Supersonic Aircraft
EN-4, November 1998

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems
EN-1, September 1998

TECHNICAL REPORTS (TR)

Verification and Validation Data for Computational Unsteady Aerodynamics
TR-26, October 2000

Recommended Practices for Monitoring Gas Turbine Engine Life Consumption
TR-28, April 2000

A Feasibility Study of Collaborative Multi-facility Windtunnel Testing for CFD Validation
TR-27, December 1999

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13. Keywords/Descriptors

Flight control	Fluid dynamics	Structural design
Control equipment	Hydraulic jets	Combustion control
Boundary layer control	Nozzles	Combustion stability
Flow control	Thrust vector control	Aerodynamic stability
Aerodynamic characteristics	Drag	Compressors
Military aircraft	Buffeting	Stalling
Gas turbines	Noise reduction	Surges
Helicopters	Vortices	Smart structures
Aircraft engines	Loads (forces)	Smart materials
Performance		

14. Abstract

The Symposium analysed the potential of active control technology for the performance demands of future vehicles and engines, in particular high manoeuvrability, lower specific fuel consumption, higher power-to-weight ratios and lower life-cycle cost. Performance, stability, control, fluid dynamics, structural and engine layout questions were dealt with in 5 keynotes and 77 papers. The following sessions were held:

– Boundary Layer Control
– Active Flow Control of Nozzle/Jet
– Drag and Buffet Control
– Noise Control
– Vortex Control
– Flight Vehicle Active Control
– Smart Structures Applications
– Active Control Technology For Load Alleviation
– Active Elements for Structural Design
– Active Materials and Applications
– Applications Overview
– Compressor Stall/Surge - Measurements
– Compressor Stall/Surge - Control
– Combustion Instabilities - Measurements and Predictions
– Combustion Instabilities - Control Fundamentals
– Combustion Instabilities - Control Applications

The Symposium was organised by the Applied Vehicle Technology Panel (AVT).

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