AST5-CT-2006-030971

ADVICE
Autonomous Damage Detection and Vibration Control Systems

Specific Targeted Research Project

Priority 4 – Aeronautics and Space

Start date: 01/10/2006 – Duration: 45 months

ADVICE Publishable Final Activity Report

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Abstract:
This report describes the activities which have been performed, and the results which have been obtained during the full duration of the ADVICE project. It also contains the publishable results of the Final plan for using and disseminating the knowledge.

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Glossary

ADC	Analog/Digital Converters
AWR	Autonomous Wireless Receiver
AWT	Autonomous Wireless Transmitter
BEM	Boundary Element Method
CLD	Constrained Layer Damping
DI	Damage Index(ices)
FEM	Finite Element Modelling
FFT	Fast Fourier Transform
LW	Lamb Wave(s)
MEMS	Micro-Electromechanical Systems
RF	Radio Frequency
SACLD	Segmented Active CLD
SEM	Spectral Elements Method
SHM	Structural Health Monitoring
SPCLD	Segmented Passive CLD
SSHI	Synchronized Switch Harvesting on Inductor
VDC	Vibration and Damage Control
VDCu	Vibration and Damage Control unit

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1. Project execution

1.1 Summary description of project objectives

Title:	**Autonomous Damage Detection and Vibration Control Systems**		
Acronym:	ADVICE		
Contract Nr.:	AST5-CT-2006-030971		
Total Cost:	3.072.456 €	**EU Contribution:**	1.758.028 €
Starting Date:	01/10/2006	**Duration:**	45 months
Web-site:	www.advice-project.eu		

Background

The ADVICE project is a multidisciplinary research project that aims at the development of state of the art technologies for structural health monitoring and vibration damping in aeronautical structures. Bringing together different research activities in one common project will drive new synergies that can lead to new possibilities for aircraft design, maintenance and cabin environment concepts.

Structural health monitoring

Maintenance and service life evaluation has always been a concern in the aeronautical industry. Over the past century, the approach taken by manufacturers has evolved from safe-life static designs to fail-safe, then damage tolerant, allowing an overall reduction of the weight of the structure, increasing its performances and better predicting the possible failure mechanisms. Maintenance takes an important part when certifying the airworthiness of an aircraft. Regular overhaul and various inspection techniques range from visual inspection to Eddy Current and Fluorescent Penetrant Inspection. They are required to follow the evolution of the integrity of the structure.

The industry is now turning its attention to a new approach to increase the reliability of an aircraft and reduce the time it must spend in maintenance: Structural Health Monitoring. SHM aims at continuously tracking the state of the structure to record any changes in behavior and give out a warning when a situation is identified as potentially threatening (using threshold values, neural networks, user interfaces...). This domain of research has been described as a promising upcoming technology, but still requires the development of new integrated approaches to be available for use on aircrafts.

Vibration damping

Focus is also set on vibration damping in aircrafts. Reducing vibration levels in the structure can have an impact on the service life and maintenance requirements in structures. Fatigue is often the source of unexpected failure or crack propagation in parts and vibration damping can have an impact on the amplitude of vibration at a local level, which can increase, in an optimistic case, the average time allowed, and at least increase the safety factor between maintenance checks in some parts.

Energy harvesting

In direct link with both previously cited research areas is energy scavenging, that is a growing area of research due to the increase in demand for micro-sensors. The devices that can be developed for health monitoring and vibration damping sometimes need to be placed in remote or hidden areas and renewable energy sources must be sought out to provide the necessary power for their proper use. Mechanical vibrations are one of the possible sources of energy. Thanks to the creation of ultra low power devices and new energy storage and energy management techniques, new solutions can be proposed to create autonomous sensors forming a distributed network, harvesting vibration energy available in the structure.

These three research areas are at the basis of the developments foreseen in the ADVICE project

Project objectives

The objective of ADVICE is to design, model, develop and validate a smart wireless network of self-powered devices that can be used for simultaneous damping of structural vibrations and detection of damage in airplane and helicopter structures (named further as VDCu – Vibration and Damage Control unit).

Indeed, most of the systems developed so far require separate wiring arrangements for power supply and data transmission, thus, contributing to further cabling proliferation. That is why one of the major objectives of the proposed project is to design systems that harvest energy from adjacent zones of the structure and use radio waves for data transmission.

We can identify three categories in the scientific objectives of the project:

1) Development of a Vibration and Damage Control unit:

- Development and optimisation of the self-powered standalone Synchronized Switch Damping and Harvesting (SSD or SSH) system. The objective is a 30% increase of the damping and harvesting performance.
- Development of the couple SSD - Segmented Constrained Layer system using either
    - the piezoelectric patch of the SSD device as constraining layer or
    - The SSH system as energy harvesting system supplying power to the SACLD system.
- The objective is a significant increase of the damping performance compared with the standalone self-powered SSD device, ideally approaching the performance of the externally powered Segmented Active Constrained Layer Damping device.
- Development of a smart Power Management module with on-chip energy converter operating under harsh environment, based on the Silicon On Insulator (SOI) technology.
- Development of a low power Lamb Wave transducer powered by the vibrations of the structure.
- Development of a non-intrusive, low power RF transmission module for VDCu identification with a communication distance of up to 3 meters.
- Optimisation of the interfaces between the piezoelectric devices and the composite substrate and fatigue analysis.
- Development of a numerical tool for the design, selection and characterization of the piezoelectric / composite interface.
- Development of a numerical tool for the optimum positioning of the VDCu's w.r.t. vibration damping, damage detection and signal quality.
- Prediction of the effect of the presence of the Vibration and Damage Control unit on the vibration of the structure (amplitude, frequency, mode shape).

2) Development of a smart network

- Development of the network algorithm based on the popular AODV (On Demand Distance Vector Routing) algorithm.
- Development of network management tools and APIs for the sake of reliability and ensure the collection of data.
- Development of the network nodes, routers and gateways with the sake of minimum energy consumption.

3) Damage identification and damping performance

- Development of novelty detection and pattern recognition algorithms for the determination of the damage signature / index.
- Development of a user friendly interface for data analysis with dedicated hardware.
- Numerical prediction of the damage evolution in the composite plate and prediction of the expected damage signature and mechanical response in terms of vibrations for the safe and damaged part.
- Extension and improvement of an existing numerical tool.

Description of the work

The work plan is divided into six related work packages overlapping in time:

- WP0 is dedicated to project management and risk registration.
- WP1 is mainly concerned with specifications: specification of the target applications, definition of the basic and performance requirement, specification of the test applications. It also includes an exhaustive technological and economical review.
- WP2 contains the design of the VDCu, of the network and of other hardware & software. WP2 is also concerned with the definition of measurement / SHM strategies.
- WP3 consists in the development & manufacture of the system. Note that the network is implemented with dummy VDCu's. Finally, WP3 leads to the delivery of recommendations for SYSTEM integration.
- WP4 is concerned with the integration, reliability & safety assessment, testing and validation of the system. The damping and detection efficiency of a set of 2 to 4 VDCu’s on a simple structure is validated.
- WP5 deals with the dissemination and exploitation of the results.

Expected Results

The main goal of the ADVICE project is to demonstrate the feasibility and the efficiency of a distributed autonomous wireless network of VDCus. Aside from the final demonstrator that will be a direct result of all the developments, there is a series of important expected results during and after the completion of the project.

The first expected achievement is a review of the current technologies, research and regulations in the different areas covered by the ADVICE project. A compilation of different possible target applications for medium to long term implementation is equally expected. It is also foreseen to contribute in the establishment of new regulations for vibration damping and structural health monitoring in aircraft structures. This project plans to participate in the development of a general approach to bring new technologies to the aeronautic industry.

New tools are expected to be developed by different partners in the project. May it be for damage detection (INSA, CENAERO), ultra-low power management (CISSOID), energy harvesting (INSA), vibration damping (PROTOS, AERNNOVA) wireless sensor networks (UCL), testing of SHM technologies (GOODRICH).

It is in the consortium objectives to increase the maturity of such a system keeping as long term objective an exploitable industrial application to be further developed after completion of ADVICE through a first, fully functional, Vibration and Damage Control unit for aircraft and helicopters. The ADVICE consortium members, consisting mainly of small and medium sized companies, share a strong interest in marketing ADVICE results. In fact, none of these companies would embark in such a costly technology development project, if there would not be clear exploitation and marketing plans behind this approach.

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1.3 Contractors involved

CENAERO	BE
CISSOID	BE
EADS	DE
AERNNOVA	ES
GOODRICH	FR
IAI	IL
INSA Lyon	FR
PROTOS	ES
PZL	PL
UCL	BE

1.4 Work performed and main achievements

In what follows, the work performed over the full duration of the project as well as the main achievements of ADVICE are summarized at the workpackage level.

1.4.1 WP1 – Specifications and requirements

1.4.1.1 Objectives

The content of Work Package 1 dedicated to the elaboration of specifications and requirements was completed over the first two years of the project. It regrouped all the disciplines as well as all the partners of the project. Work was divided into 5 main axes:

- **Target applications and performance requirements**: In order to understand possibilities in terms of energy harvesting, damage detection, vibration damping,... It was necessary to define several cases in which this system would show potential application and identify the conditions in which the system would operate.
- **Technological, theoretical and regulations reviews:** to explore the current state of the art in different fields, know about existing patents, ongoing research and key aspects the project could focus on.

- **Test structure design and simulation:** in accordance with the different target applications defined, a representative structure that would be used for the proof of concept of the ADVICE system needed to be designed and studied using numerical tools.
- **Vibration control and damage strategy**: Based on current knowledge, define how the system could operate in order to maximize chances of success of different objectives.
- **Requirements of the system:** Pre-design leading to the components characteristics and the estimated performance of the selected technologies.

Being the main starting point of the project and of the developments the ADVICE project would lead to, it was essential for all partners to have or reach a good understanding of:

- The needs of each partner in terms of inputs and outputs to produce.
- The challenges bound to the development of an autonomous wireless system for aircraft applications.
- The state of the art in the different fields in relation with the ADVICE project.
- Ways to prioritize and make technologies work together to reach a feasible solution that could be used as a proof of concept.

Most of the objectives of this work package were reached through collaborative participation to the elaboration of the deliverables.

1.4.1.2 Methodologies and approaches employed

The first task dedicated to the description of different target applications and performance requirements involved two different aspects. In the first, the different end-users of the project (Aernnova, EADS-IWG, IAI and PZL) defined possible applications on aircraft and helicopter structures for the ADVICE system and collected information useful for the identification of operating conditions, performance and possible benefits of the system for the structure. These target applications included structures such as:

- A Vertical stabilizer at the extremity of the tail boom of the PZL SW-4 multipurpose helicopter: This part undergoes important levels of vibration and high stress levels near the fixation points.

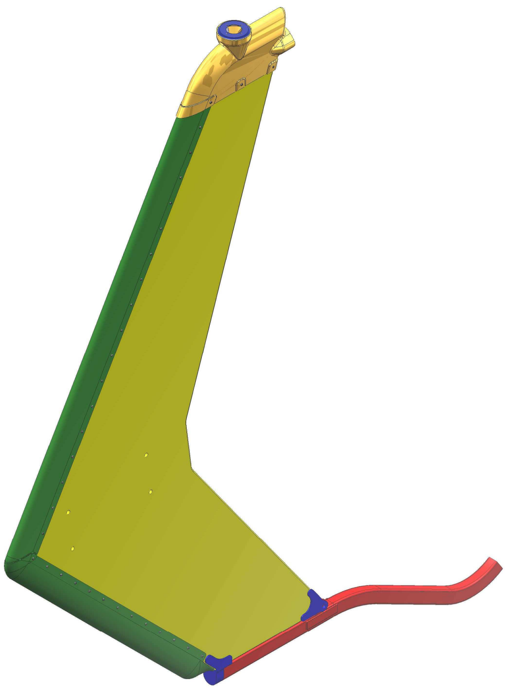


Figure 1: Target application 1 – Helicopter vertical stabilizer

- A leading edge of a G150 regional business jet: fixed complex shape made up of composite and metallic components undergoing pressure loads.

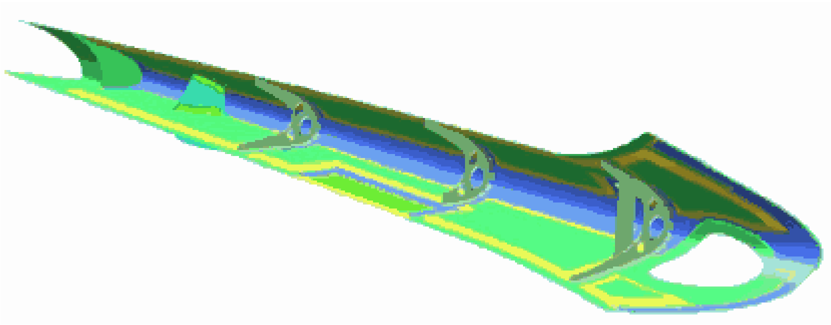


Figure 2: Target application 2 - Leading edge of a regional jet

- The inboard flap of a regional jet: moving carbon fiber composite/metallic part made up of three cells, one of which is filled with a rohacell foam.

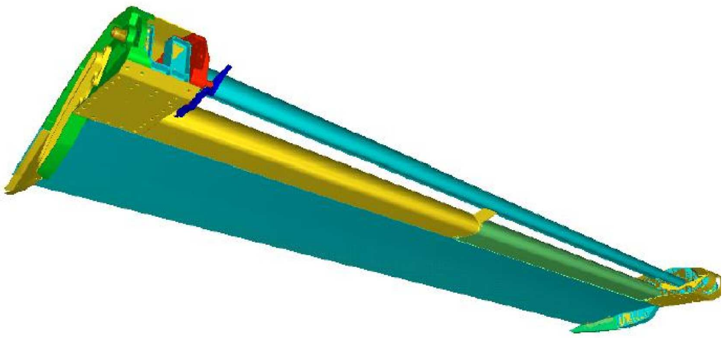


Figure 3: Target application 3 – Inboard flap

- Fuselage panel/door: stiffened composite or metallic structure presenting a large pressurized surface with interest for vibration damping in terms of acoustic comfort.

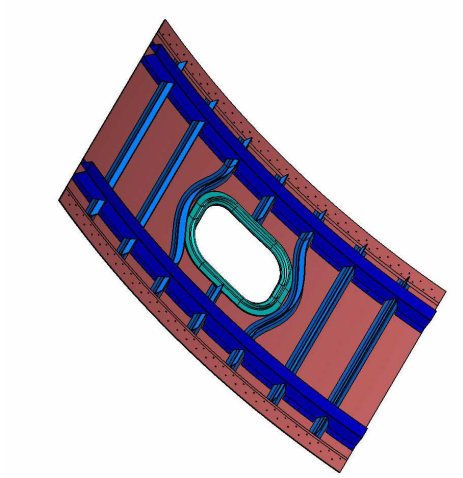


Figure 4: Target application 4 – Composite/Metallic fuselage panel

Information related to these structures included static pressure load distribution for the leading and trailing edges, vibration amplitudes for the fuselage and the vertical stabilizer, material definition and properties and sometimes the requirements in terms of detectability of damage. Performance requirements were taken from different regulation document or handbooks such as RTCA/DO-160D, MIL-HDBK-17-3F or MIL-STD-810-E.

The second aspect of this task focused on the prediction of the structural response of these parts through finite element modelling, first to have the modal characteristics of the parts (frequencies and shapes) and secondly to check the feasibility of Lamb wave inspection in these complex parts. Despite the high complexity of these parts, some results on Lamb wave propagation were obtained, showing several important elements.

First, care has to be taken to study the attenuation of the wave through the material in order to ensure that a signal with large enough amplitude will reach the sensors placed on the structure. Cases showed that over a distance of roughly less than a meter, the signal perceived at the sensor was less than 1% of the amplitude of the signal emitted.

Also, changes in structure properties, such as thickness or materials can have an impact on the propagation of such waves. In the figure below, the separation between two zones of different thickness is clearly visible, changing not only the amplitude of the signal, but also the wavelength. Lamb waves are dispersive, leading to changes in propagation speed too.

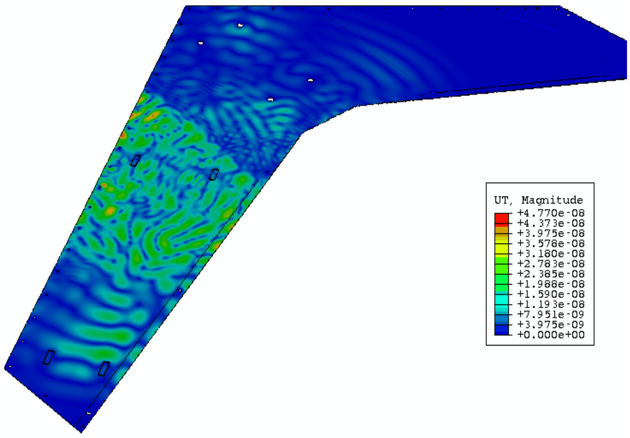


Figure 5: Lamb wave propagation in a vertical stabilizer panel

Only a limited amount of effort was put in this simulation task as Lamb wave propagation and signal processing was not mature enough to directly exploit results on a complex structure. Instead, work was focused on understanding the physics and interaction with damage on a more simple structure.

Finally, this task also was also dedicated to predicting the energy levels that would be available on the test structure. This also turned out to be a challenging task not only to find relevant information to characterize vibration levels that were going to be useful for piezoelectric energy harvesting, but also to quantify the strain in the structure as this depends on the location at which the harvesting unit will be placed.

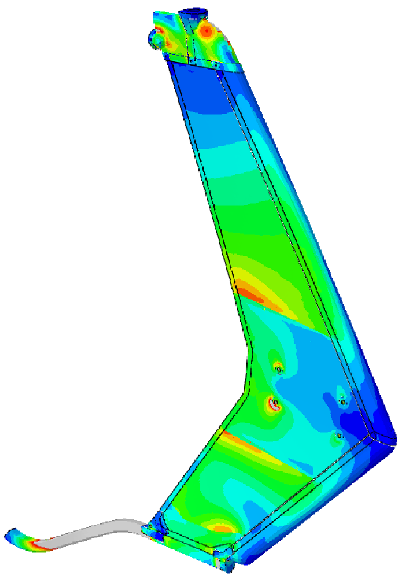


Figure 6: Strain distribution of a vertical stabilizer under vibrating loads

The second task consisted in collecting current documents, searching for new available sources and summarizing the overall knowledge in relation to the subjects covered by the project. The contribution of each partner took the form of a review structuring results of research, a list of bibliographical references and, if available, a copy of these documents to make them available to other partners in the context of the work done on the project.

The subjects covered by each partner are found in the table below.

	CENAERO	***CISSOID***	***DDL***	***EADS-CRC***	***AERNNOVA***	***GOODRICH***	***IAI***	***INSA-LYON***	***PROTOS***	***PZL***	***UCL***
Energy Harvesting								X			
Energy storage devices		X									
Low power RF transmission											X
RF networks											X
Vibration damping technologies					X			X	X		
SHM with Lamb Waves and damage index	X							X			
Numerical methods for simulation of Lamb Waves	X										
Measurement strategies			X			X					
Adhesive bonding of piezoelectric patches on structures	X										
Impact on maintenance cost and program					X	X	X				
Regulations on embedded vibration damping devices				X							
Regulations on embedded monitoring in composite structures			X								
Regulations on RF pollution							X				
Regulations on real monitoring of structures					X						
Anterior development of similar systems	X			X	X		X			X	

All contributions were assembled and organized to form one structured document. The lists of bibliographical references were collected in a database in order to simplify their use for the report and also for other documents. A few numbers describing the review work done during this task are given:

- 126 pages
- 424 references
- 165 documents available on the portal or accessible through external web links

In order to define a structure on which the system could be tested, partners involved in the third task used data coming from the different target applications to choose suitable materials, damage types and test configurations. An important element in the definition of this structure was to have similar behavior in terms of vibration characteristics (frequencies, response to solicitations, boundary conditions,...) to be able to characterize the vibration harvesting and damping with a wide band frequency response. This led to the design of a square composite reinforced panel with a set of different possible boundary conditions.

Simulations were again done with two different objectives:

1. Evaluate the optimum position for vibration harvesting and damping and estimate the energy levels that could be achieved depending on the vibration loading on the panel
2. Predict the propagation of Lamb waves in an orthotropic composite structure and the ability to detect changes in the signal propagation due to local damage.

These two objectives were achieved allowing to find the best position for piezoelectric patches for harvesting functions as well as evaluating the impact on the Lamb wave of different parameters.

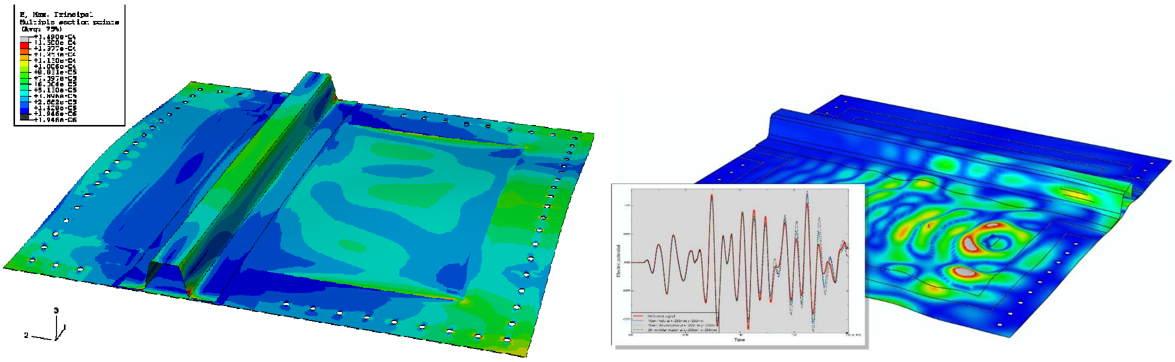


Figure 7: Numerical simulations of strain distribution under random vibrations and Lamb wave propagation in the ADVICE test structure

a) Strain distribution in the panel undergoing random vibration b) Lamb wave propagation and effect of different damage types.

The two other tasks in this work package were dedicated to the design of the system through the development of a VDC (Vibration and Damage Control) strategy and the requirement of the system. These tasks involve much interaction between the different partners in order to take all the specificities of different technologies into account. This would later help the feasibility check during the testing phase of the project.

The strategy was quickly dictated by the energy requirements of the system and the fact that the energy levels available were not of large magnitude. The approach taken was to keep define the VDCu as the Lamb wave emitting unit (that would be autonomous) and the end-node (Lamb wave receiver) would be externally powered. Depending on the energy balance, the option of making the end-node autonomous would only require to add the harvesting capabilities to this unit. Below is a representation of how the VDCu and end-node/Router were designed to work.

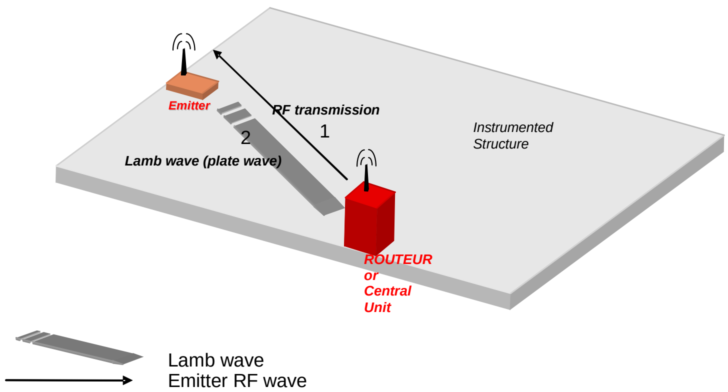


Figure 8: Communication and health monitoring strategy for autonomous wireless systems

Finally, the last task of this workpackage focused on the requirements of the different components of the system. Each functionality was analyzed separately to lay out the blueprints of design for energy management, lamb wave emission, RF communication, test structure design requirements, constrained layer damping... and work on the integration of the designs in the system.

The different contributions were compiles into a deliverable that fully documented the characteristics and requirements of the one-dimensional system that has been built on the demand of the consortium. This demonstrator system consists in a simplified prototype of self-powered Lamb Waves (LW) and radio Frequency (RF) transmission on 1D sample, and is operational at T0+12 as targeted in our success measurement table of the project proposal. This helped to propose a first definition of the basic characteristics and requirements of the system for energy consumption and performance of VDCu (energy harvesting and LW components) and also of the receiver. Based on the specifications of the target applications (task 1.1), INSA provided an estimate of the resulting energy balance under realistic vibration levels.

1.4.2 WP2 – System design and virtual integration

1.4.2.1 Objectives

The objectives of the second workpackage of the ADVICE project are to design and to virtually integrate the whole VDC system with regards to the requirements and characteristics of the VDCu, of the network, of the electrical systems and of the receiver and of the central station which were all defined in the previous workpackage.

The work performed comprises:

- the validation of the strategy feasibility using the one-dimensional demonstrator,
- the SOI integration of the energy harvesting SSHI (power management module) and SSDI (damping module) circuitry,
- the design of the RF communication module (in particular, the development of a unique low power RF module featuring both emission (TX) and reception(RX) modes),
- the measurement of the consumption the Digital Signal Processing (DSP) module of a platform based on System-on-chip (SoC from Texas Instrument) for the estimation of the damage index,
- the investigation of bonding issues for the integration of piezo-patches to the host structure,

and finally the main achievement resulting from it are is the completion of the system design.

1.4.2.2 Methodologies and approaches employed

The VDC strategy that was chosen in WP1 is here implemented according to the methodologies described in this section, with regards to the specifications of the target application and the energetic requirements of the system.

Energy harvesting

The retained material for energy harvesting are surface mounted piezoelectric PZT ceramics, whose surface, shape, bonding conditions and locations were optimized using numerical tools. The energy extraction is performed by Synchronous Switch Harvesting on Inductor (SSHI technique). Apart from the very brief sequence of Lamb wave emission, the energy harvesting circuit is connected to the piezoactive material and running continuously.

Towards the development of the energy harvesting subcomponent using the SOI technology, CISSOID validated the model based on the results obtained by INSA for the standard AC configuration (Figure 9, where spice simulation using the modified electronic switch proposed by CISSOID shows a good agreement with theoretical SSHI previsions, for both power magnitude and dependency with the electric load) (Figure 9) as well as for the electrical waveforms of the SSHI technique (Figure 10)

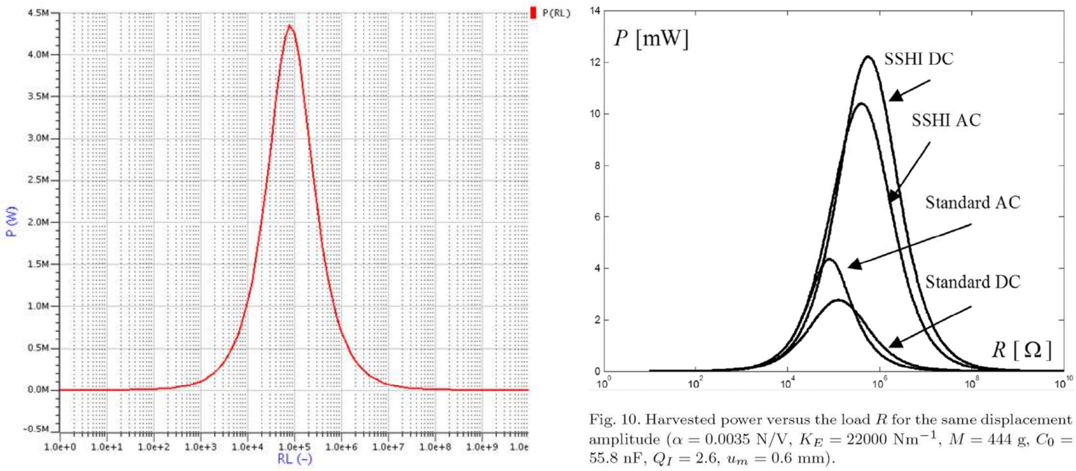


Figure 9. Standard AC simulation in SPICE: output power versus load

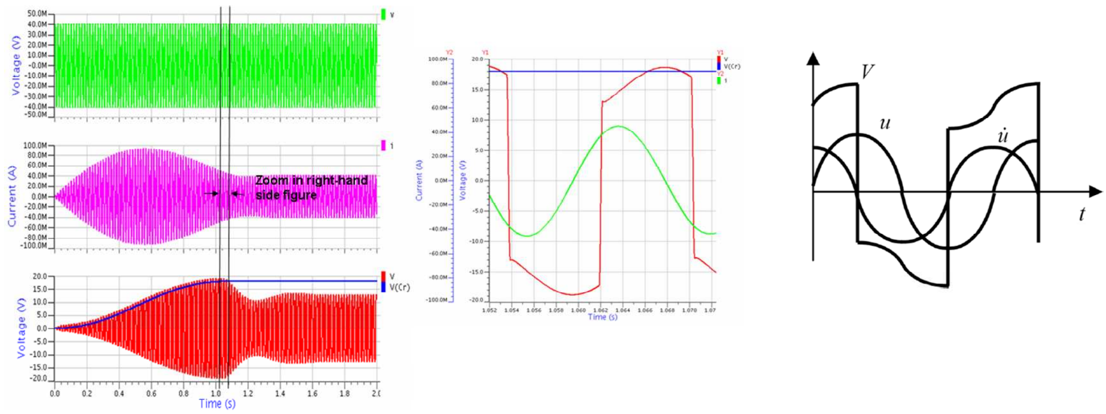


Figure 10. Simulation of the SSHI parallel voltages (left) and theoretical voltages (right).

Damping

Vibration damping is performed by SACLD device aside from the VDCu. Preliminary study of the comparison between SACLD, PCLD and SPCLD damping using the same piezoelectric patches as those used for energy harvesting and other materials concludes that: e detection strategy comprises the following signal processing:

- when using piezoceramics only, usually harder than an aluminum or composite base plate, their rigidity will have the strongest influence on frequency changes
- the harder the constraining layer, the higher the variation, so even using a steel constraining layer with a piezofilm sensor would imply a higher damping increase than using a ceramic sensor and a piezofilm actuator (so, a trade-off between the increase of damping and the wanted power from energy harvesting module has to be found)
- There is an almost negligible influence of segmentation when it is applied in a way that preserves the basic energy harvesting configuration.

Additional damping is available thanks to a SSDI module of the VDCu. Towards this end, a dedicated smart switch has been developed using SOI technology, featuring an enable/disable pin. One can also note that even when SSDI is not used, some reduction of structural vibrations also results from the electromechanical conversion performed by SSHI (but knowing that the technology developed in ADVICE is optimised for energy harvesting, in particular the electrical impedance of the DC-DC converter which links the rectifying and the energy storage stages is closer to the optimum load for SSHI than the one required for SSDI).

RF communication strategy

The examination of the whole structure starts right after landing. The global wireless network topology is presented in Figure 11. It features:

- **a gateway**, which role is to communicate with the base-station, and send commands for interrogating the VDCus. The Gateway contains two modules: one for RF communication (with End-nodes) and one for serial communication (with the base station),
- **end-nodes**, deployed in a mesh network, which role is to interrogate VDC'us, receive Lamb waves and send calculated data to the gateway. The end node is permanently powered by external supply,
- **VDCus**, deployed in a star network around each end-node, which role is to act as autonomous Lamb wave actuators.

It was decided to adopt an energy efficient polling strategy, where data transmission (RF communication and/or the LW transmission) is dictated by the master node (called router or End-node). Communication between Gateway and End-Node is based on the following polling scenario.

1 - The Gateway sends command to the end node to interrogate the VDCus
2 - End node interrogates VDCus, receives lamb waves from them and calculates FFT of the Lamb wave signature.
3 - When the end-node receives the command to transfer FFT data, it sends it to the gateway with the ID of each VDCu, for the calculation of a damage index.
4 - The End-Node successively interrogates each VDCu present in his sub-network for sending lamb wave.
5 - As a slave node, the VDCU wakes-up periodically (with a low duty cycle e.g for 10ms every 10 seconds for instance), checks its available power and wait for the polling from the master node. During its period of listening, if the VDCu receives command from End-node, it sends the Lamb wave as well as its ID, and returns to sleep mode.

The main drawback of this sequential VDCu interrogation is that it leads to longer wake-up processes, then longer interrogation sequence (period of the duty cycle times the number of VDCus), but its great advantage is that data retransmission is no longer necessary (because there is no risk of packet collision), which leads to substantial energy savings.

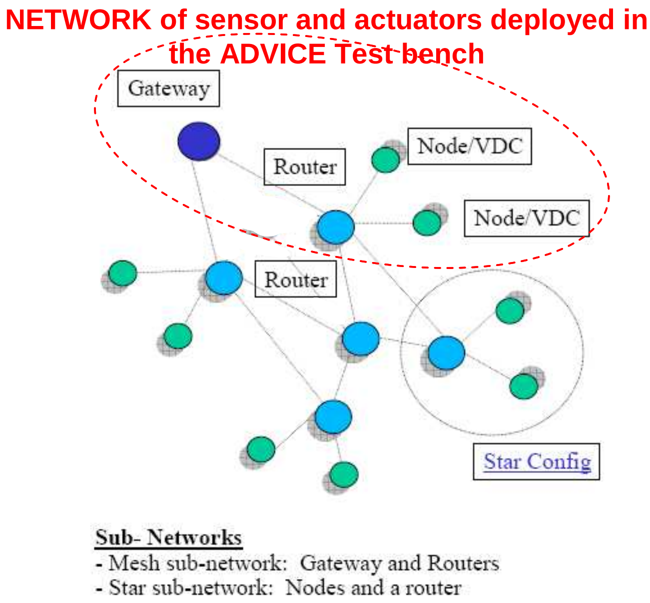


Figure 11. Global network topology for wireless SHM and overview of the simplified network deployed in ADVICE's test rig

Damage detection

The damage detection follows the structural Health Monitoring scheme of interrogating the structure through transmission of ultrasonic guided waves. One of the piezo patches of the VDCu is used to launch a wavepacket into the structure, the sensing of the propagating Lamb wave being ensured by another piezoelement situated on the receiving node (Figure 29 in paragraph 1.4.4.3 shows the numerical simulation of the Lamb wave propagation in the ADVICE's test structure employed between VDCu 1 and End-node).

For energy savings concerns, the electrical signal introduced into the transmitter is a simple 100µs short square burst. Signal tailoring relies on the shape of the emitter and on the use of external additional components (such as a solenoid to form an oscillating circuit with the clamped capacitance of the piezoactuator)

The damage detection strategy comprises the following signal processing:

- the calculation of the Fourier Transform of the ultrasonic signatures received through embedded FFT algorithm within the processing core of the End-node,
- the computation by the base station of a Damage Index (DI) based on the Fourier coefficient,
- the evaluation of the severity and (if applicable) the position of the damage by Neural Networks, also implemented in the base station.

1.4.2.3 Conclusions

The achievements of WP2 are the design of the system, based on the VDC strategy selected in WP1 and in accordance with the identified constraints and requirements and the design of its components: VDC unit, network, “data treatment & analysis” station (base station).

1.4.3 WP3 – System development and manufacture: Preliminary tests

1.4.3.1 Objectives

Workpackage 3 objectives are the development and manufacture of VCDus, of the central station and of the network according to the system design and following the visa for development both delivered in workpackage 2. Development and test of these main features are done in parallel, each of them being managed by a leading partner responsible for checking dependencies, identifying blocking points, and monitoring the global progress of the manufacture and tests. Individual tests of the different modules will precede joint tests that require the assembly of the test rig and the test structures.

1.4.3.2 Methodologies and approaches employed

VDCu development, manufacture & test
Development and test of the power management module of the VCDu were achieved through joint experiments between CISSOID and INSA. It has been chosen to integrate surface mounted SMT components for the power management module. The main criteria considered for selecting these components are compactness and performances.
A first test chip containing the SSHI and SSDI circuits has been implemented and fabricated on XFAB 1 µm SOI Process. The fabricated wafer has been diced and dies have been packaged for PCB test. The design of the test setup PCB and test prototype with building blocks (switch, rectifier, comparator, DC-DC converter, …) have been finished (Figure 12). The complete system SSHI module + Rectifier + DC-DC Converter + Storage device has been tested using a specific test structure provided by INSA (Figure 13).

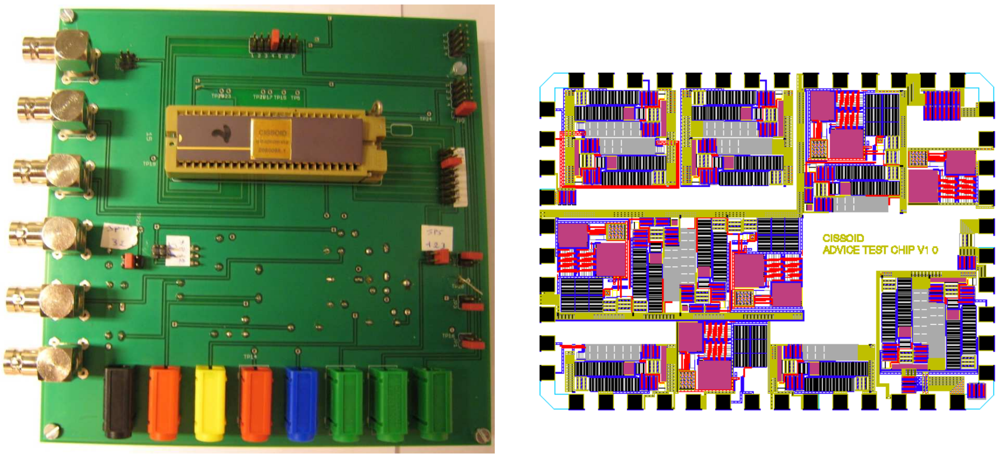


Figure 12. Printed Circuit Board (PCB) development, test PCB with SOI chip version 1.0

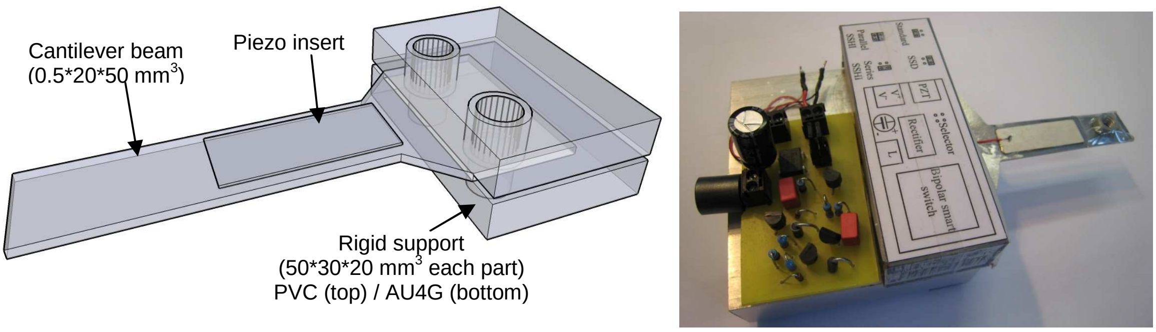


Figure 13. Miniaturized Test structure

Later on, a redesign of circuits based on the test results, leads to the definitive version of the chip, the power management ASIC (Application Specific Integrated Circuit) being packaged in a plastic 16 leads SOIC (Small Outline Integrated Circuit, shown in Figure 14).

Figure 14. PCB of the VDCu power management module, with SOI chip version 1.1

Validation of RF communication between devices

To validate, the operational RF module developed on the same platform for VDCu , End-nodes and gateway, the test setup shown in Figure 15 has been realized, with in particular one self-powered VDCu and one externally powered VDCu for accuracy verification.

Figure 16, shows the duty cycle of the VDCu, which wakes-up every 10s and stays in RX mode during 10 ms for listening if there is interrogation from End-Node. Every each listening sequence of the VDCu consumes approximately 1.0362 mJ (when the microcontroller is running at 32 MHz). Figure 17 shows the associated variation of the voltage due to this sleep, wake-up and listen sequence, and the following table details the measured consumptions:

Interval	Description	Duration	Current	Datasheet	Energy
1	VDCu on Sleep mode	10 s	0.001 mA	0.5 µA	0.0033 mJ
2	Wake-up of the VDCu (MCU run on 32MHz clock)	1 ms	12 mA	10.5 mA	0.0396 mJ
3	Radio RX mode ON	10 ms	29 mA	26.7 mA	0.957 mJ
4	Turn OFF RADIO RX mode	0.1 ms	20 mA	--	0.0066 mJ

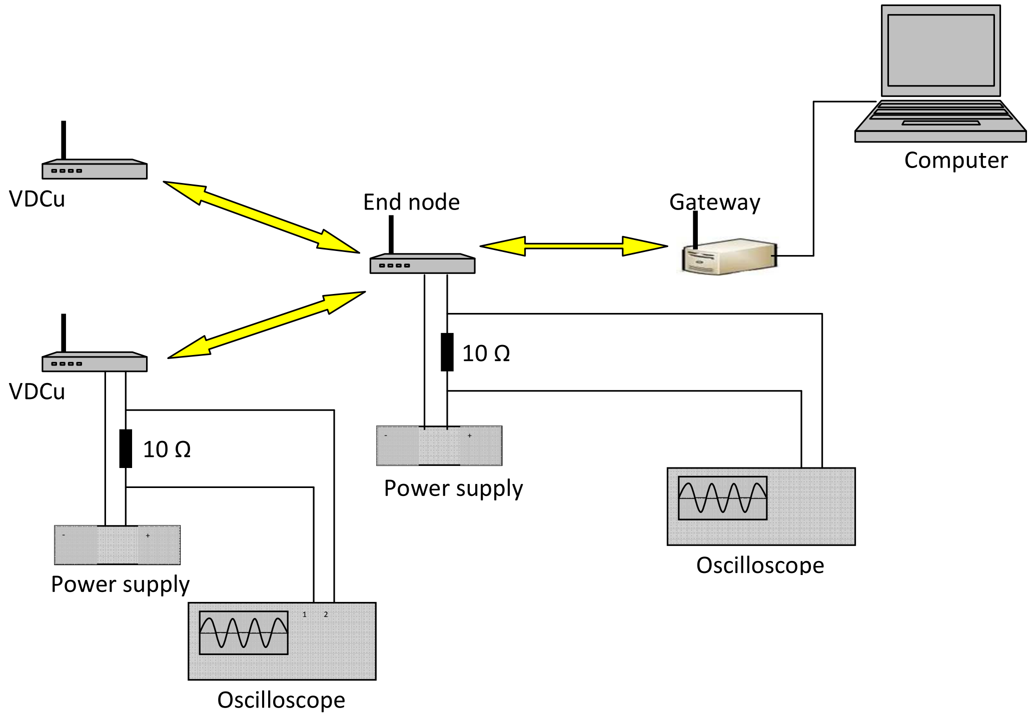


Figure 15. RF communication test setup

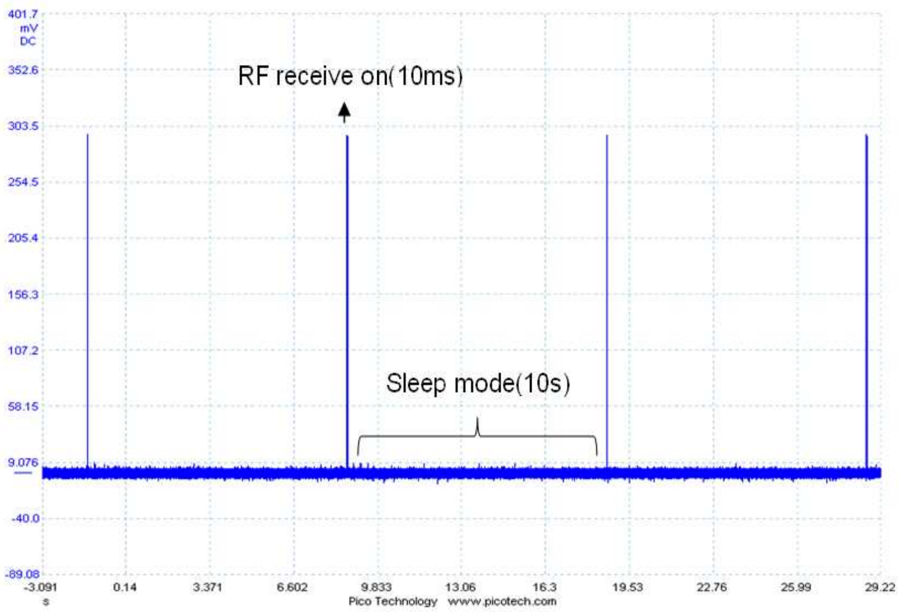


Figure 16. VDCu wake up sequences

Where an interrogation from End-Node occurs, every listen/transmit/ sequence of the VDCu consumes less energy than the previous case because the consumption is mainly due to the receiving mode, which last for a shorter period because of the polling. Figure 18 shows the associated variation of the voltage due to this sleep, wake-up and listen sequence, and the following table details the measured consumptions:

Interval	Description	Duration	Current	Datasheet	Energy
1	VDCu on Sleep mode	10 s	0.001 mA	0.5 µA	0.033 mJ
2	Wake-up of the VDCu (MCU run on 32MHz clock)	1 ms	12 mA	10.5 mA	0.0396 mJ
3	Radio RX mode ON	10 ms	29 mA	26.7 mA	0.957 mJ
4	Turn OFF RADIO RX mode	0.1 ms	20 mA	--	0.0066 mJ

VDCu consumption in this case = 0.033 + 0.0396 + 0.957 + 0.0066 = 1.0362 mJ

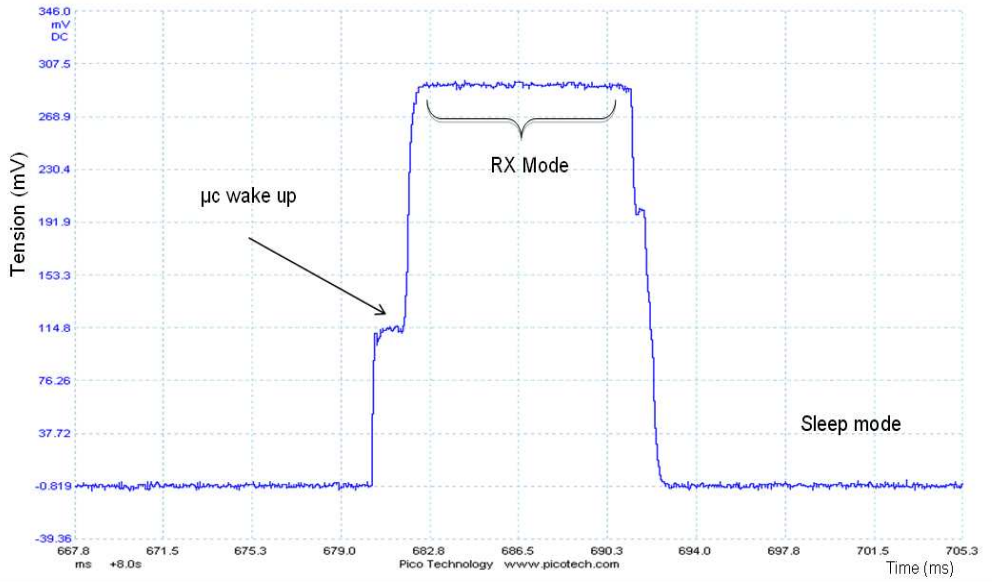


Figure 17. VDCu power consumption when not interrogated by End-node

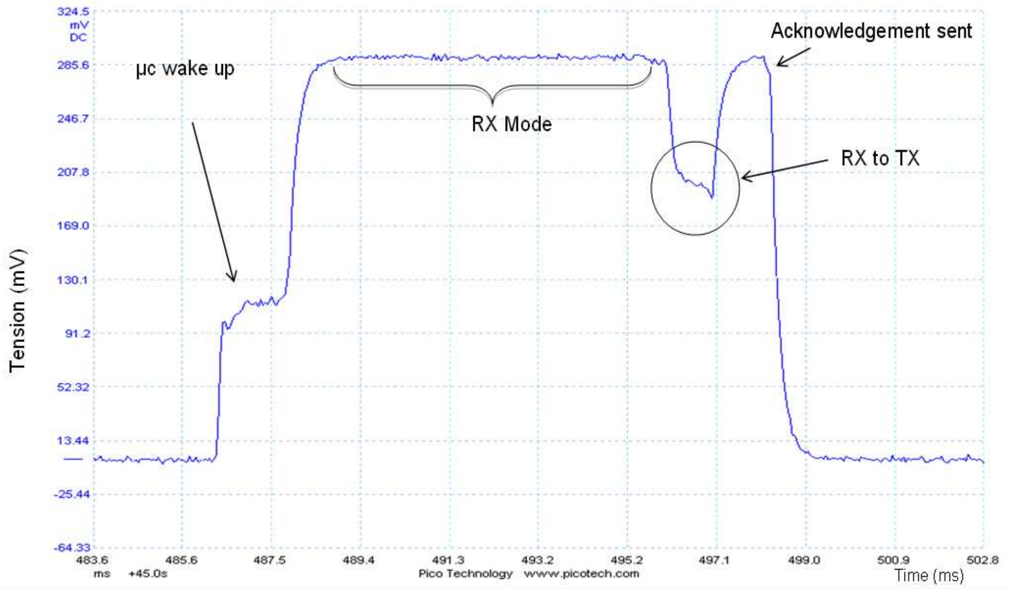


Figure 18. VDCu power consumption when interrogated by End-node

Final assembly of the VDCu

Finally, all VDCu electronics have been merged, and successfully tested after two bugs being fixed:

- DC-DC startup
- Addition of Zener diode for over-voltage protection

The manufactured VDCu is presented in Figure 19, showing the previously described power management module along aside the CC2430 circuit (this component is highly suited for systems where ultra low power consumption is required. It includes high performance and low power 8051 microcontroller core. Low power consumption of CC2430 is insured by various operating modes) as well as the SMD antenna placed on the circuit board.

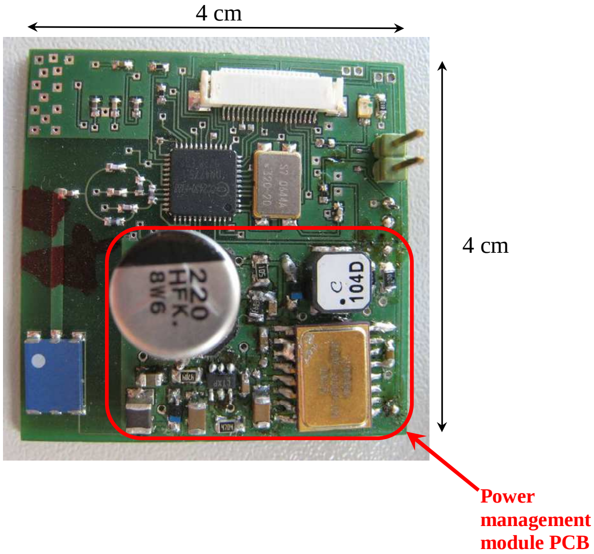


Figure 19. Final common VDCu PCB merging CISSOID's power management module (see Figure 14) and UCL CPU and RF modules

Central station development, manufacture & test

GOODRICH developed, manufactured & tested the central station, which is in charge of controlling the execution of VDC sequences and retrieving and computing all VDCus and End-nodes data. The central station main functionalities are:

- to perform internal Built-in Test (BIT)
- to monitor VDCu activity and integrity (VDC network status)
- to detect the the aircraft ground/taxiway conditions
- to initiate the VDC sequence
- to receive DI and VDcu IDs (and LW signature as a provision)
- to manage, consolidate and store historical data
- to analyse structural change and survey evolution
- to synthesise results and display on a MMI (Pilot/Maint. crew)
- to generate structural change report for maintenance Crew

GOODRICH also developed a man-machine interface (MMI) which allows maintenance crew to identify possible damage location on the aircraft. It comprises three different profiles:

- ☐ The global profile, which displays the aircraft's global status. The pilot can have a comprehensive view of the synthetic state of the plane, globalized for different sections. A three-color indicator can for example be used to render the situations when :
  - no structural change is detected in the section and all VDCus operational, or
  - a structural change is diagnosed or at least one VDCu measure was not acknowledged, or
  - a structural change appeared in the section.

- ☐ The Structure Maintenance profile, which enables the VDC structure diagnosis. This profile will display global data, but will also allow the user to zoom on particular regions if a structural change is to be located. Once the zoom performed, the last five damage Index values (for instance) can be displayed by clicking on the targeted VDCu.

- ☐ The VDCu System Maintenance Profile, which performs internal VDC system diagnosis. In that profile, the user can access all system data like full VDCu information or the end-node status. Clicking buttons give access to more detailed information such as
  - graph of the DI history
  - maintenance history
  - VDCu answers history …

In the frame of the ADVICE project, since the Central Station is not an airworthiness device, this MMI is applicable on a demonstrator supposed to represent part of the aircraft structure. Indeed, this activity does not focus on electronic hardware development but mainly on the development of the software application. The software has been developed using Microsoft Visual Studio 2008 and Microsoft SQL Server Express 2005. The development language selected is Visual C++.
The demonstrator MMI also integrates commands to initiate the VDC sequence on demand.

Final compatibility check

To ensure the continuous compatibility between the multiple sub-components in the developed devices, GOODRICH took in charge the compatibility of them, and towards this aim, it asked each partner to describe his interface with other partners. A template interface specification document was provided to help the partners in this survey and to ensure that each partner on both side agree on the data. After the design phase and during the development phase, the compilation of the interface forms allowed checking the compatibility between the modules inside the components and between the components of the global system. This was aimed to decrease the chance of incompatibilities while integration will take place, in order to reduce the risk of subsequent delays in solving them.

1.4.3.3 Conclusions

To fulfil its ambitious requirements, the VDCu should comprise a microgenerator, a Lamb wave transmitter, a Radio Frequency unit, a core processor and a power management module. Assembling all these features in one single energetically autonomous device was a great challenge. It has proven to be feasible thanks to the joint efforts and the good coordination of the different developers involved in WP3 combining a wide range of expertises such as:

- wireless Network communication,
- piezoelectric materials,
- low power technology,
- energy harvesting,
- vibrations analysis,
- neural networks and embedded electronics development and programming.

The VDCu was initially planed to be assembled in one single package with limited surface and weight, to minimize the effect of the presence of the device on the vibration of the structure. Due to some delays in the integration of the different features of the VDCu, it has not been possible to built the appropriate packaging, but the final assembly has been done with compactness and light-weight in mind, the electronics being limited to a surface equal to the total surface occupied by the different piezoelectric patches to be bonded on the host structure.

The whole system integration, including VDCus, End-node, gateway and base station was only made possible by following important integration steps such as the permanent compatibility check through design phase by integrator, the virtual integration to evaluate interaction between components and the final compatibility check and recommendations for actual integration. This was accomplished thanks to the involvement of partners working on various innovative fields requiring much interaction in multidisciplinary activities from:

- theoretical studies, to phenomena modelling
- physical behaviours simulations
- electromechanical designs
- software developments
- hardware programming
- system integration

without forgetting the need for constant evaluation of compatibility and feasibility through evaluation of the energy balance.

1.4.4 WP4: Integration & Validation – safety & reliability assessment

1.4.4.1 Objectives

The system to validate consists in a set of test structures fitted with autonomous VDCu and an end node. A gateway and a central station complete the system for data collection and processing.
The system ensures the functions of health diagnostic of the test structures. It is in part autonomous as some energy is harvested from the mechanical strains generated under structural vibrations. This energy is scavenged by the VDCu electronics and used for sending an ultrasonic wave along the test structure skin. This wave (Lamb wave) propagation is affected by any damage on the structure. An analysis of the received wave by the end node electronics allows damage detection capability.
During the integration, the following functions had to be checked:

- Energy harvesting
- Power management
- Lamb wave generation and reception
- Damage computation
- Wireless network
- Data storage, consolidation and display

The tests objectives were to submit the system to vibration spectra representative of aircraft structures during flight and then evaluate the damage detection capability under these conditions.

1.4.4.2 Methodologies and approaches employed

Ten test structures in carbon fibre composite material have been manufactured, using aircraft structures manufacturing processes. To increase representativity, a stiffener was implemented.
The system capability to diagnose the health was evaluated by comparing the results from healthy structures and damaged structures. The damages type were either a through hole or blind hole or delamination.

The following shows the positions of End Node and VDCu defined according to simulations providing the best configuration.

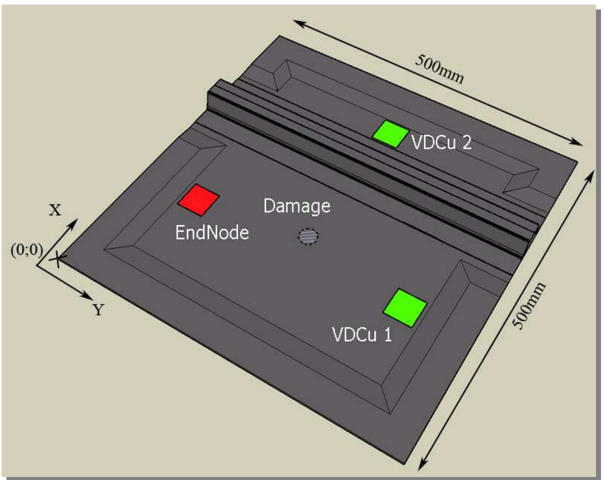


Figure 20: VDCu and End node locations on test structure

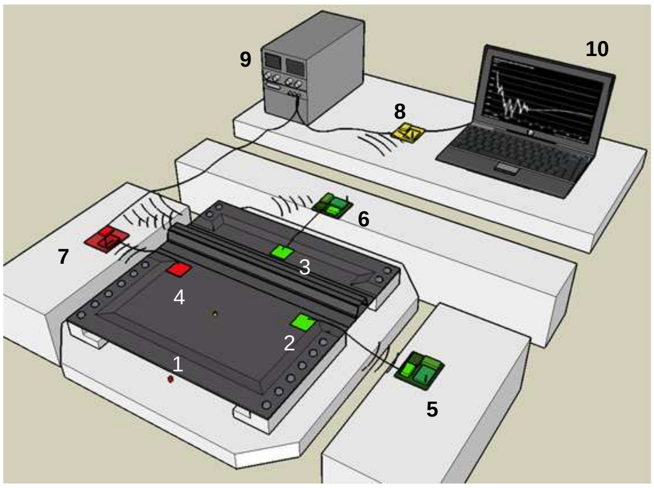
The end node function is to process the two lamb wave signals coming from the VDCu 1 and VDCu2 and to calculate so called “Damage indexes” for each transmission, which results from a comparison between the signals acquired and a pristine “healthy” reference signal.
By radio frequencies the end node transmits the damage indexes to the central station, via a gateway. The gateway is a communication relay between several end nodes and the central station. The central station correlates all the received damages indexes to compute a health diagnostic of the structures. This is obtained by a neural network, comparing the set of received damage indexes to a database of training data. The training data allow the neural network to distinguish damage cases from healthy cases. The outcome is a score called “maintenance score” used for maintenance decision making. The central station thus displays the

results to the maintenance crew by visually pointing on an aircraft global view at the structures requiring maintenance action.
Each sub-system was validated before integration. The integration allows confirming the compatibility between all sub-systems and evaluates the capability of the system to operate as expected.

To validate the system functionalities, the following test set up have been designed.
For the energy harvesting validation, a shaker has been used to generate aircrafts vibration spectra and thereby identifying the energy storage capacity.
For power management, the electronics have been equipped with test points to monitor the levels of energy consumed during the functional sequences versus the scavenged energy.
For Lamb wave generation and reception, the ultrasonic wave signals (analogic and digital) have been monitored.
The damage index computation from the end node was compared to the theoretical Matlab post treatment of the lamb wave signals.
For the wireless network validation, all signals were duplicated in RF and RS232 communication. Communications through both paths were compared.
For the central station validation, the database content was checked by validating that the damage index computed by the end node was identical to the one stored in the central station. The damage index was then visualized on the screen showing a plane on which the test structure was a wing partial area.

1.4.4.3 Work performed and end results

The Figure 21 presents the set up configuration with remote electronics and powered End Node.



LEGEND

1- Test structure screwed on shaker
2- Piezoceramic – VDCu1
3- Piezoceramic – VDCu2
4- Piezoceramic – End node
5- Remote electronics – VDCu - autonomous
6- Remote electronics – VDCu - autonomous
7- Remote electronics – End node - powered
8- Electronics – Gateway - powered
9- Power supply
10- Central station

Figure 21: Test actual set up configuration

The test structure has been equipped with piezoceramics patches glued on the positions providing maximum strain under vibratory excitation. Five ceramic slices are used per VDCu, four dedicated to the energy harvesting function while the fifth slice is used to generate the Lamb waves.

The following figure symbolises the principle of connections between the piezoceramic patches and the electronics circuits, either the VDCu or the End node.

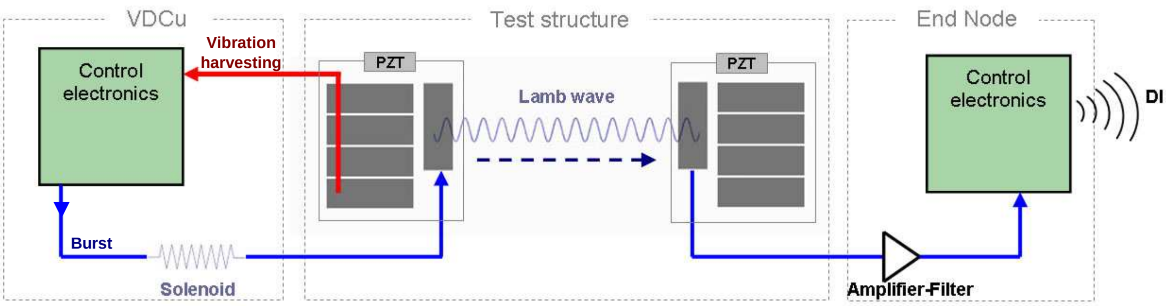


Figure 22: Connections layout

The piezoceramics patches have been tested to check that the coupling factor, which represents the capacity of the piezoceramics to convert mechanical energy into electrical energy, had satisfactory values, confirming that the gluing process was homogeneous throughout all the slices.

The circuit boards, called “control electronics”, have been connected remotely to the components presented in the Figure 22. The same circuit boards have been used to for the manufacturing of the VDCu, end nodes and gateway as shown on the Figure 23.

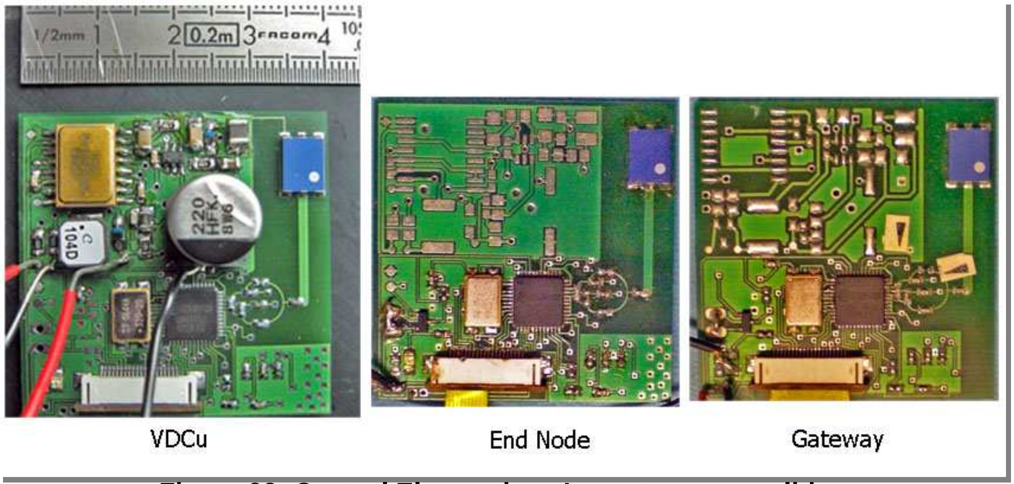


Figure 23: Control Electronics - Layout commonalities

The installation on the shaker is presented in the following figures:

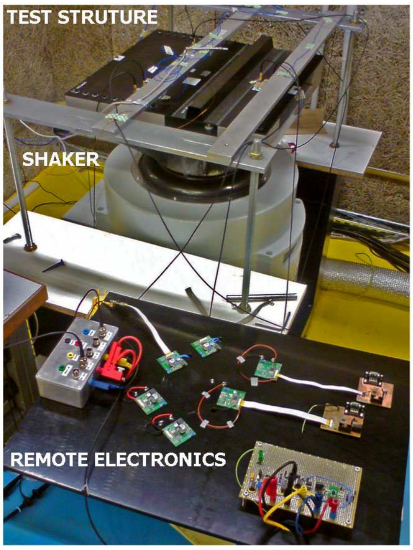


Figure 24: Shaker installation

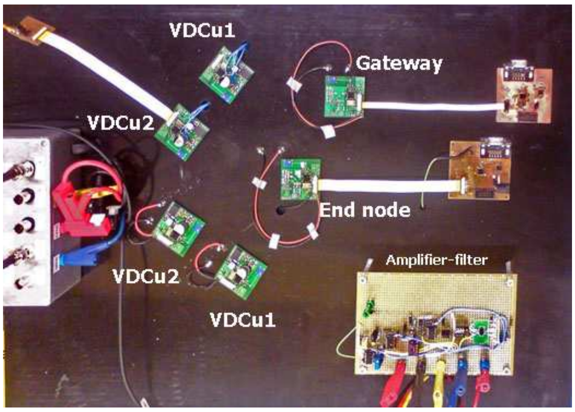


Figure 25: layout of hardware connections for testing

Energy harvesting

The monitoring of the energy scavenging within the electronics is presented in the Figure 26 where the block diagram represents the harvesting module, showing on the left the voltage available at the Piezoceramic and on the right, the voltage available at the input of the microcontroller downstream, regulated at 3,7V by a DC-DC converter.

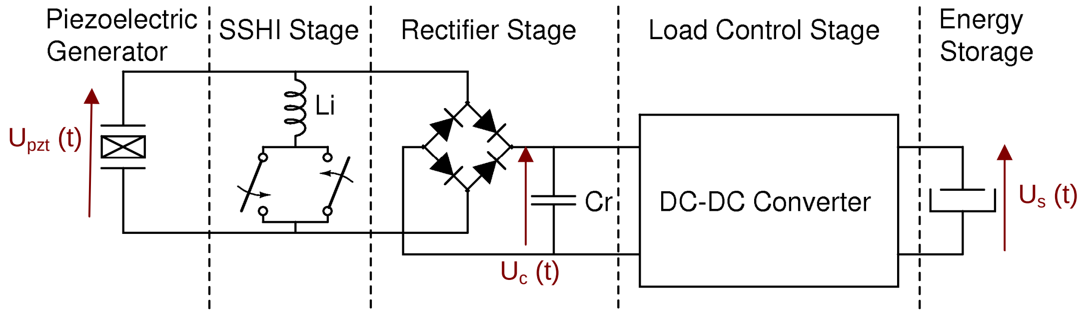


Figure 26: Harvesting circuit measurements

The piezoelectric generator block converts the mechanical vibration to electrical signal via the piezoelectric effect.
SSHI stands for "Synchronized Switch Harvesting on Inductor". This circuit uses a smart switch and an inductor to enhance the harvesting capabilities of the piezoelectric generator.
The rectifier circuit converts the AC signal received from the piezoelectric generator using full bridge rectification to DC energy that is stored in capacitor Cr.
The load control circuit has two main functions: First, it guarantees optimal load that should be seen from the rectifier for maximum output power. Second, it converts a varying DC voltage from 4 to 40 V to a fixed DC voltage of 3,7V used to power the microcontroller downstream the circuit.

The energy harvesting capability has been evaluated under three types of random vibrations: white noise, airplane random vibration spectrum per DO160 section 8 and helicopter random & sine spectrum per DO160 section 8.

The measurement of the duration necessary to trigger the DC-DC converter has allowed comparing the levels of energy harvested. The DC-DC converter wakes up when its input voltage Uc reaches 10,7 Volts. The following figure shows the charging of the Capacitor (Uc voltage) during the vibration phase and then shows the energy consumption once the DC-DC converter allows the circuit to be supplied.

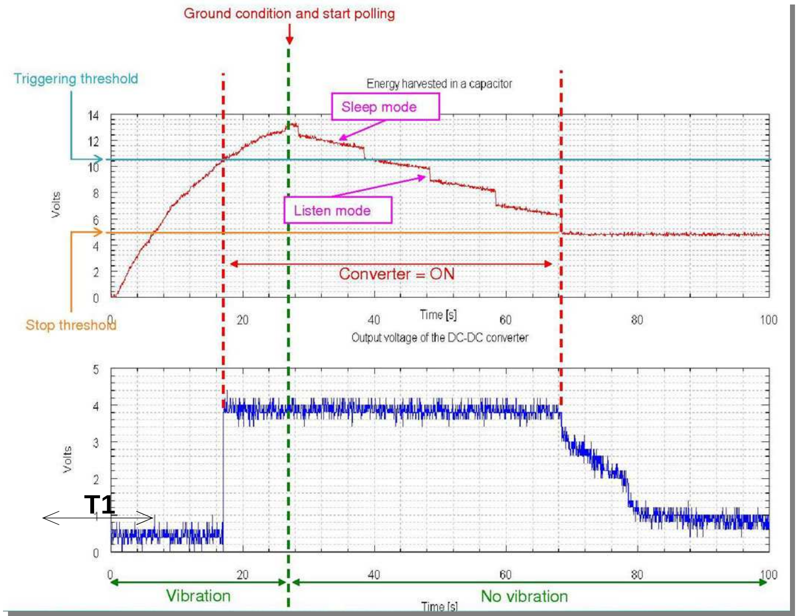


Figure 27: Energy harvesting and power consumption

On the top figure, the Uc voltage at the capacitor charges when random vibrations are applied. The voltages passes 10,7 V allowing the DC-DC-converter to start (bottom) regulating the output voltage Us at 3,7 Volts. The duration "T1" to reach 10,7 Volts varies with the level of vibrations.

From a white noise of 0,00225g²/Hz, the charging reaches 10,7 volts after 700 seconds (11 minutes, 40 sec). The threshold for waking up the system is therefore defined at 0,002125 g²/Hz in white noise.

The scavenged energy allows an operating duration of 50 seconds which is considered at the current stage of the project and for concept demonstration purpose sufficient to answer to the End Node request for diagnosis.

The system revealed very sensitive to external environmental parameters like electromagnetic susceptibility, test setup layout and all aspects affecting the test structure modal response like temperature and boundaries conditions… Indeed, the preliminaries tests performed in sequences showed inconsistent results proving that some uncontrolled parameters interfered with the systems. To investigate the results inconsistencies, additional tests have been conducted to try to obtain repeatable results.

By analysing the voltage obtained, the strain was deduced on the bases of the piezoceramics coupling coefficient.

$$V_{pzt} = 2.08V/\mu def$$

This allows evaluating the applicability of the system on an Aircraft. The minimum random strain levels necessary to wake up the system are thus 2.17µdef RMS and 8.65µdef Peak.

Power consumption

Once the VDCu capacitor is charged above 10,7 Volts, the DC-DC converter turns ON. The 3,7 V power supply of the electronics is established. The next steps are made of three different modes: first the sleep mode, a wake up and RF reception mode (Rx), and then a lamb wave emission mode.

The sleep mode corresponds to the stand by state of the microcontroller. During this mode, the energy consumption is minimized. The wakeup mode is periodically set to 10 seconds. The wake up corresponds to a RF listening sequence which last 10µsec. Once a communication is established with the end node, a lamb wave is launched.

On the Figure 28, the steps N°1, 2 and 3, the cons umption levels of each mode is seen by the slope values.

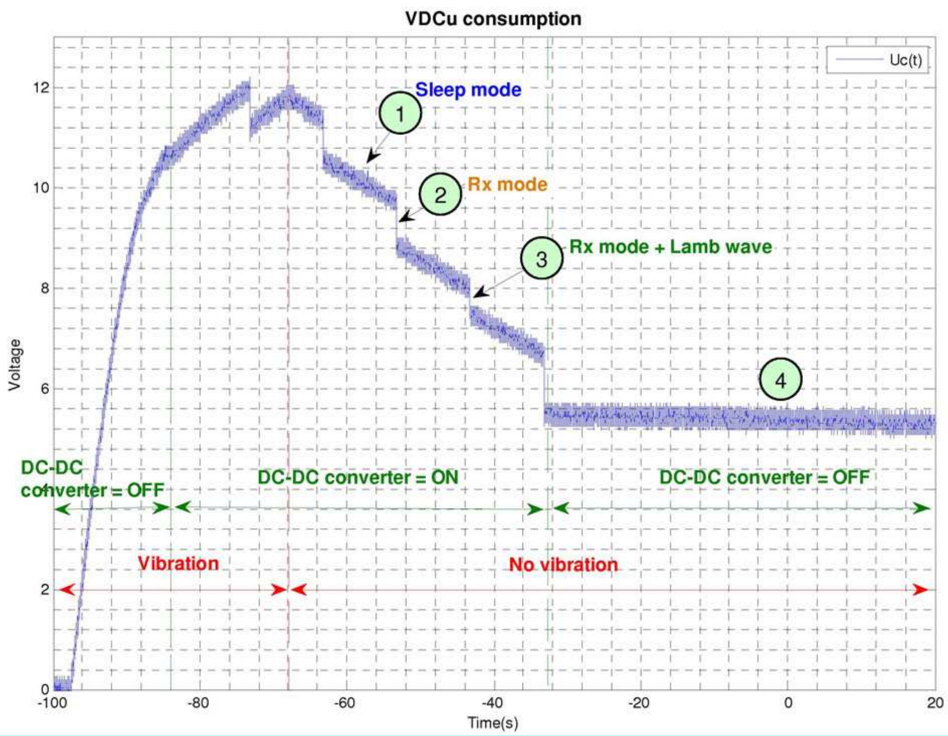


Figure 28: Energy consumption modes

Table 1: Power consumptions

#	Consumptions	Current	Energy	Power
1	Sleep mode	17,6 µA	0,3 mJ	0,15 mW
2	Rx mode	13,2 mA	0,6 mJ	64 mW
3	Rx mode + lamb wave	11,2 mA	0,4 mJ	85 mW
4	Converter OFF	1,1 µA	30 µJ	10 µW

Once the voltage has decrease below 5Volts, the DC-DC converter turns OFF.

The balance between the harvested energy and the consumption allows performing five attempts during 50 seconds. In the frame of this demonstration, this was sufficient to obtain a communication between the VDCu and the end node, and hence, a lamb wave emission for the health diagnosis.

Wireless communication
The control electronics were remotely positioned as shown on the figure 21. The communication between the VDCu, end node and gateway was checked by using spy bus. The consistence of the messages sent and received by the central station was checked on the way back, after the complete communication loop was performed.

The tests performed have shown that the communication between the components was satisfactory, although the repeatability was sensitive to the positioning of the electronics. A thorough study of robustness is still required to evaluate the parameters influencing the reliability of this communication path, such as the distance and the obstacles (like stiffeners on the structure).

Lamb wave transmission and reception
The lamb wave transits between the VDCu and the End Node through the skin of the structure. In the frame of the demonstration, two VDCu were used to generate lamb waves directed towards a unique end node as shown on the figure below. The positioning was chosen to identify the influence of the obstacles (stiffener) on the signal treatment.

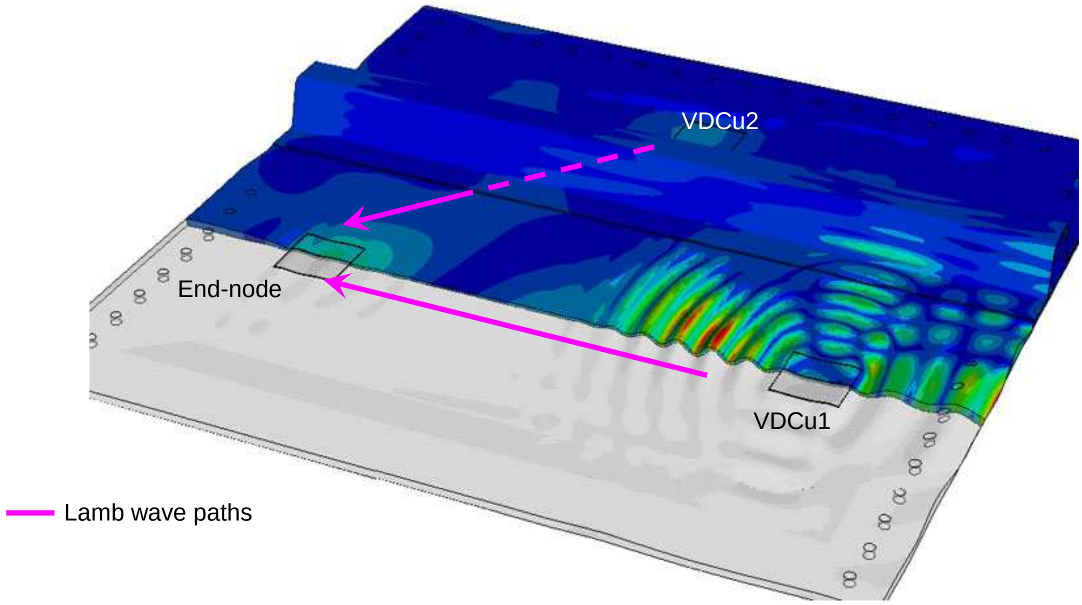


Figure 29: Lamb wave propagation from VDCu 1 to End Node

The signal measured at the EndNode piezoceramic is show on the Figure 30 (top).

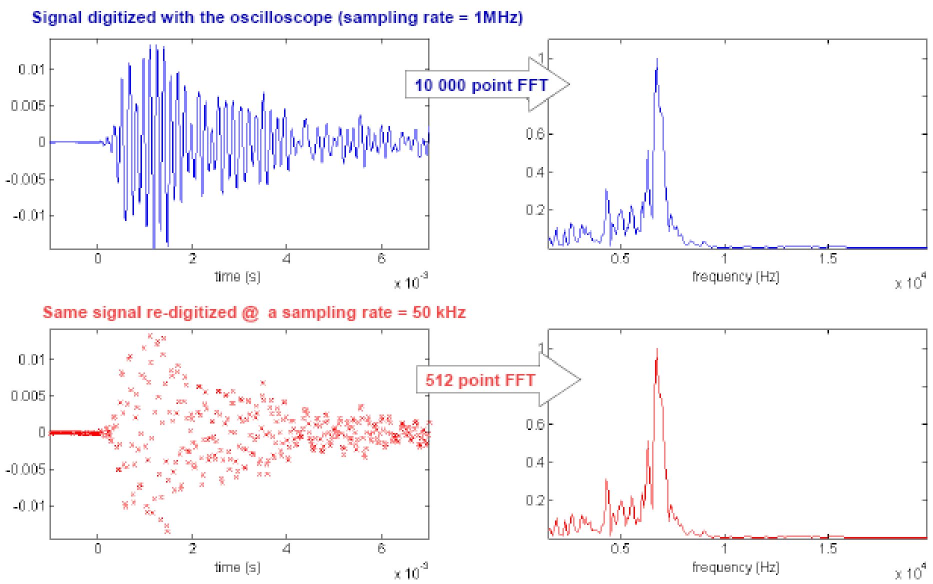


Figure 30:Lamb wave reception – FFT

This signal is digitalized by the End node at a sampling frequency of 46,7 kHz, which provides sufficient precision for the fast Fourier transform calculation.

Damage diagnostic

Damage detection functionalities are centralized at the level of the central station of the ADVICE system. The data collected at the level of the End-nodes (see Figure 31) during the Lamb wave propagation is collected at the end of each polling in order to process the different damage indices and evaluate the severity and (if applicable), the position of the damage.

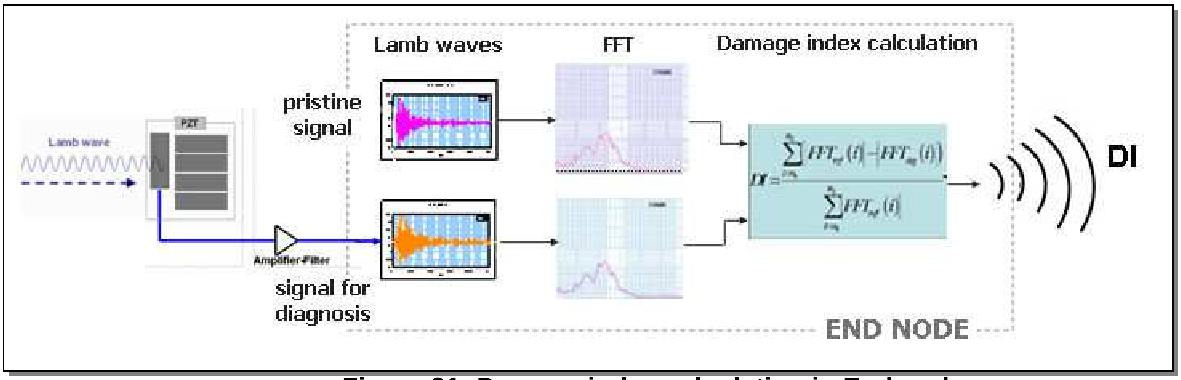


Figure 31: Damage index calculation in End node

Although the outputs on the different test structures used for the project are limited (only 2 VDCus and one end-node are used), the data allowed a first assessment and a proof of concept of the system functioning as a theoretically autonomous damage control unit.

Out of the 11 panels manufactured, eight were used to make measurement on the pristine and damaged state structure. Tests were carried out first on the pristine panels in order to characterize the reference signature and look at the influence of external parameters on the test structure behaviour (calculation of the damage index) as well as other reversible modifications to the test structures. Then the panels were later tested with progressive damage.

The test planning consisted in the following situations:

- Panel in pristine state
- Panel under various reversible conditions
    - Added mass (with/without shear coupling, i.e. adhesive paste)
    - Humid surface (water droplets on composite structure surface
    - Controlled temperature
    - Controlled humidity
- Panel with modified boundary conditions
- Progressively damaged panel.

- **ADDED MASS**

Adding a mass on the panel can alter the Lamb wave propagation through the panel. This effect was studied with a 100g aluminium cylinder that was placed at different locations. The attenuation on the signal increases when adhesive is used as the interaction of the added mass with the shear waves is then present. Then thickness of glue does not have an important effect on the damage index.

- **TEMPERATURE**

Temperature effects have an important influence on the Lamb wave propagation of the test structure. While Lamb wave propagation dynamics are first of all modified due to some changes in material properties, the boundary conditions are also modified due to the difference in thermal expansion coefficient between materials. The piezoceramic behavior can also be modified due to these temperature changes.

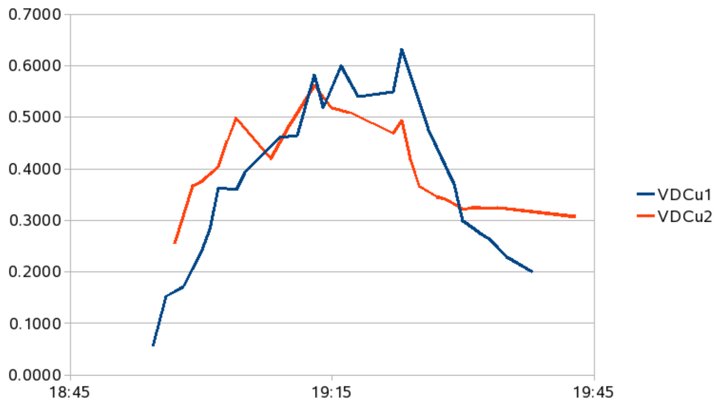


Figure 32: Evolution of the damage index coming from VDCu1 and 2 at different moments during the temperature cycle (20℃ down to -40℃ and back)

The damage index was recorded at different times during the temperature cycle for both VDCus. As show in Figure 32, the damage index increases to 0.6 before dropping back to 0.2 (for VDCu1) and 0.3 (for VDCu2). Further investigations could be done in order to study the influence of several temperature cycles as well as the influence of the speed at which the temperature varies.

- **HUMIDITY**

The panel was sprayed with water and measurements of the Lamb wave propagation were made between the VDCus and End nodes. The Lamb wave interacts with the film of water on the surface. The effect on frequency shifts is negligible, while the amplitude of the signal and FFT decrease.

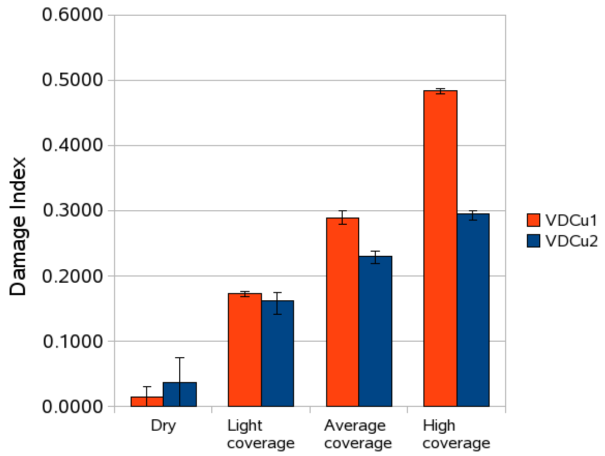


Figure 33: Damage index from VDCu1 and VDCu2 for different levels of water on the test panel

- **DAMAGES**

Two damage types were implemented in order to have a fast and effective way to progressively damage the panel without jeopardizing the operation of the VDCus and most of all, the bonded piezoelectric patches.

- A blind hole
- A through hole

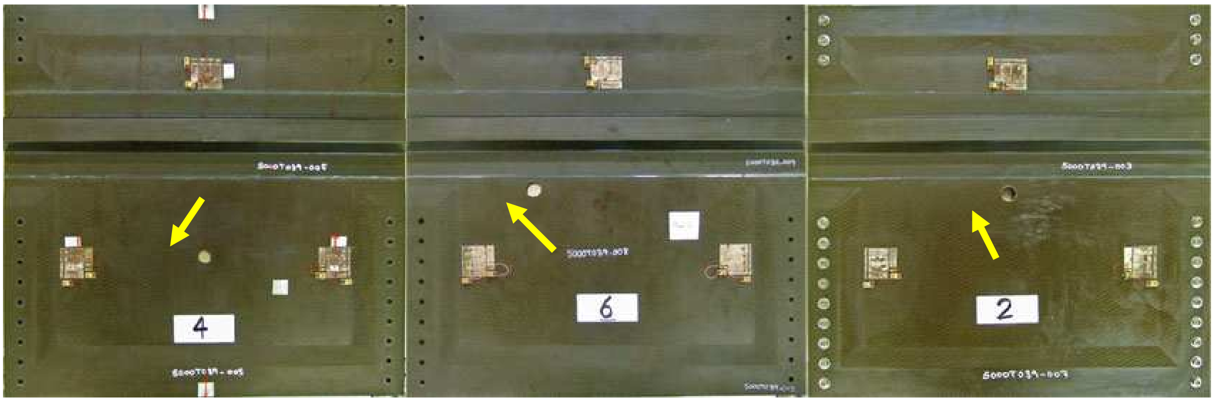


Figure 34: through hole positioned on the different paths between VDCus & End Node

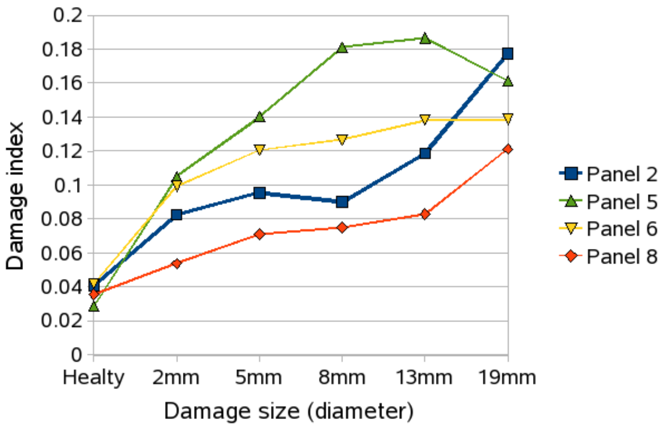


Figure 35: Damage index evolution from VDCu1 on panels

Even if a trend in the damage index can be observed for all the different panels, we clearly see in this Figure 35 that the interaction of the Lamb wave with damage is highly complex and that it is difficult to predict what will be the effect of a parameter on the damage index.

Neural network

Damage detection algorithms have been designed and implemented using a neural network to process the inputs sent by the different end-nodes. This neural network is feed-forward and based on a multilayer perceptron model.

The neural network showed its ability to use a training set in order to adapt neural parameters and obtain a response function that can eventually recognize damage index patterns. The sensitivity of the system in laboratory conditions was satisfactory as it was able to detect damage size of smaller diameter than that found in the requirements for the system.

Training by simulation is foreseen to be able to consider different damage cases that the neural network can use to help identify possible damage without necessarily having to damage several manufactured structures. The results also show that the neural network identifies the severity of the damages if a damage type has already been “learned” by the neural network. In other cases, a confidence level on results indicates if the structure is drifting from the original configuration.

Central station

The Central Station is part of the complete VDC system as the terminal device in charge of collecting and computing the data transmitted by the end Node. The Central Station is in charge of collecting all the Damage indexes and RF identifiers of the VDCus bonded to the structure under test. Software layers are linked together through the transmission and reception of dedicated data.

- **Data acquisitions**: Composed of hardware and software mechanisms to collect from external devices all input data required for the correct operation of the Central Station application.
- **Communication protocol**: To convert received data from external devices into Central Station usable information.

- **Built in Tests**: Contains Central Station functions that monitor the correct operation of the Central Station in terms of software and hardware monitoring.
- **Database:** Contains all historical data stored from previous structural change analysis and all system and configuration parameters.
- **Data Storage and Consolidation:** Contains all functions that manage the Data Base in terms of retrieving and updating corresponding data.
- **Structural change analysis:** Software part responsible for analyzing data stored in Database and to detect if a structural change has occurred. **Data synthetic display generation:** Software module responsible for performing a synthesis of the data to be displayed for the Man Machine Interface and Maintenance Communication interface.
- **Man Machine Interface:** Graphical interface for users displaying the results of structural change analysis and providing interfaces for setting up the system.

The displays seen on Figure 36 shows the different possibilities to access the aircraft health diagnosis once polling has been sent.

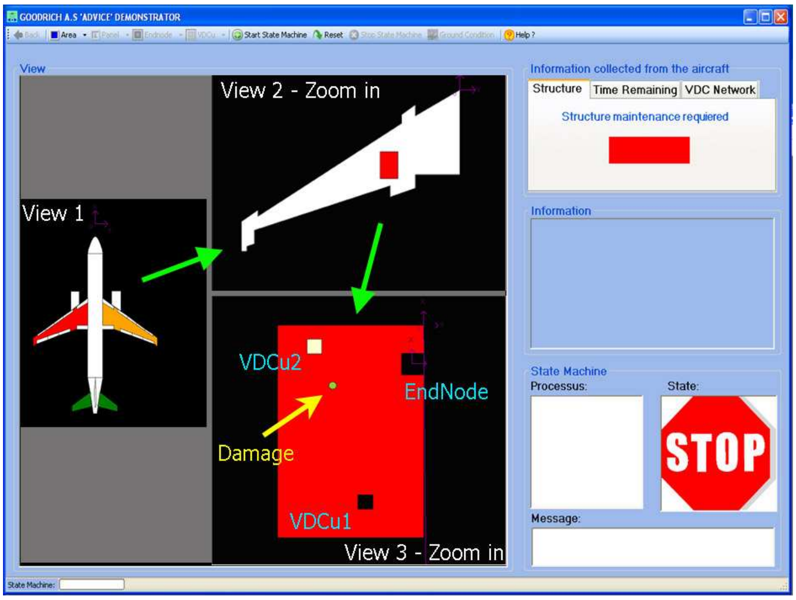


Figure 36: central station display after diagnosis request

Damping

Between the viscoelastic layer and the structure there is a PZT patch that operates as a sensor to know the vibration conditions of the structure. The constraining of the viscoelastic is done with another PZT on the top surface of the viscoelastic layer.

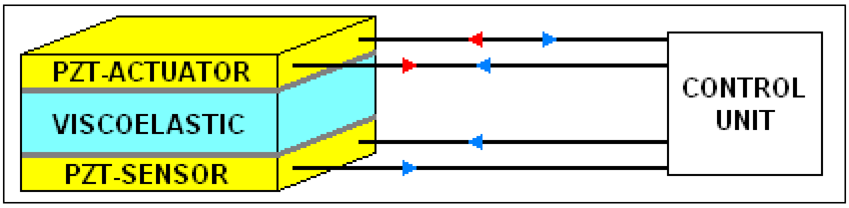


Figure 37: SACLD principle

The SACLD was composed of the following components:

- 4 piezoelectric patches acting as sensors
- 4 viscoelastic patches and another
- 4 piezoelectric patches acting as actuators
- These elements are square shaped, 50x50mm and placed in the centre of the panel

The purpose for the tests performed was to find the proper tuning resistance to optimize the damping capabilities of the SACLD.

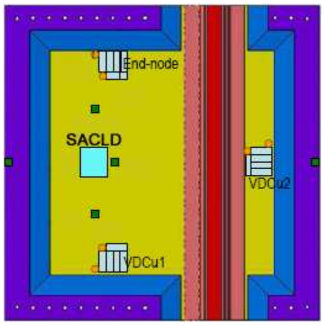


Figure 38: SACLD location

Loss Factors were calculated for all modes as seen by all three accelerometers. The analysis and assessment of the vibration test measurements has shown an appreciable increment on the damping capabilities of the structure due to the application of the passive damping SACLD device*.*

1.4.4.4 Degree to *which* the objectives were reached

The following paragraphs give the limitations of the demonstrator developed in the frame of this project. Many limitations are coming from a limited integration of the system but don't affect the purpose of the demonstration which as shown a proof of concept.

VDCu

The VDCu is not fully integrated since the control electronics does not integrate the solenoid used to enhance the lamb wave signal generation.
The control electronics is not fitted on the piezoceramics and integrated into a packaged system as it has not been fully designed for vibrations robustness.
The components size on the control electronics (esp. the main capacitor) highly reduces the capability to be packaged in a compact installation.

Low power RF communication

The energy consumption of the sleep mode of the control electronics is too high compared to the scavenged energy, resulting in a full dissipation of the available power in 50 seconds once the minimum energy threshold has been reached. This small duration limits the robustness of the communication in case of repeated attempts when external conditions prevent clear and quick contact.

RF Network

The test campaign has been performed with only one sub-network composed of one end Node and two VDCus. Multiple sub-networks need to be performed for a full network capability assessment.
The communication strategy chosen relies on the RF listening at VDCu level to start the data exchange. This strategy is energy consuming because of the RF reception power requirements at VDCu level.
The polling strategy chosen between end node and VDCu has revealed an impossibility to prevent the VDCu from dissipating its scavenged energy immediately after reaching the wake up energy threshold. The energy is lost after 50 seconds preventing a diagnostic to be launched once the aircraft has landed and is in ground conditions. Loss of energy is not only due to the consumption of RF strategy, it is also due to the consumption of energy harvesting module.

The limits of the network communication have not been tested. In order to be completely exhaustive on the communication aspects, communication limits need to be further investigated like for example: communication length evaluation, robustness to obstacle (stiffener), communication robustness evaluation (repeatability and reliability).

Damage index

The damage index depends on the structure topology. A stiffener highly reduces the lamb wave amplitude and alters the quality of the transferred signal. The damage index in this case presents high variability without any structural change.
The damage index repeatability within the tested system was poor because the calculation is dependent on the lamb wave variations, which revealed highly sensitive to environmental and boundary conditions during the test campaign.
As a consequence, damage index can not be based on a polling performed on a vibrating structure, which excludes in-flight diagnostics, and imposes a fully stable aircraft state (let alone other environmental conditions variations).

Neural network
The neural network sometimes shows difficulties to make neural parameters converge in order to sufficiently reduce the error function, especially when the network size is too large. This indicates that an optimal network size has to be identified depending on the number of inputs that are available and the complexity of the patterns that need to be recognized.

On a given structure, the neural network is unable to perfectly distinguish different locations of damages with the two input signals that it is given. A larger number of VDCus must be used.

The detection of the type of damage has not been proven and needs further studies.

The system has been tested only on artificial damage (drilled blind or through holes), not with more realistic types of damage (impacts or delaminations).

Small changes in environmental conditions can create conditions (damage indices) similar to those found when damage actually occurs. More information must be collected either in terms of number of signals (VDCus), post-processing of signal (FFT or wavelet coefficients instead of damage index) or recording of external parameters (temperature, humidity, pressure,...).

Training through simulations is currently limited due to the important calculation time still necessary to complete the propagation of the wave in the structure.

1.4.4.5 Conclusions

This testing campaign has allowed characterising the quality of the system developed and tested within the Advice project, presenting the various achievements made in a wide range of technical domains which have required numerous expertises and great coordination within the consortium to commonly converge towards an ambitious goal.

Combining energy harvesting, structural damping, RF network, health diagnostic algorithm has proved to be feasible. The system showed encouraging results and paves the way for further activities to increase the maturity of the technology.

1.4.5 General conclusions

The ADVICE project led to the successful development of an autonomous wireless system that can be used for the detection of damage in structures, but also for the damping of structural vibrations. Several important milestones and technical improvement were achieved first at component level (each individual function of the system) and also on a global level (the system operating as a whole). The major technological developments and research included:

- Low power vibration harvesting through direct coupling on the structure and non linear processing of the electric signal
- Low power energy management solutions developed with SOI technology and optimized for a given environment
- Communication and polling strategies based on predictions of available energy
- Automated structural analysis of composite structures through Lamb waves
- Development of a centralized network and data management tool with associated APIs and man-machine interface.
- Representative numerical and experimental analysis of a composite structure installed on a electromagnetic shaker

Most of the initial objectives of the project were achieved, although some difficulties were encountered and some changes in strategy or objectives were made during the project. A nine month extension of the project was requested due to problems in the developments and testing of electronic boards as well as delays in the different testing phases due to compatibility issues during integration. Actions were taken on problems that were identified, but a few issues still remained at the time of the demonstration mostly in terms of robustness and communication errors between the gateway and the end-nodes.

Changes were made in the approach adopted for the development of the vibration damping elements (SSDI & SACLD) due to the fact that the priority was set quite early on vibration harvesting. These changes led to deviations from the initial objectives in terms of damping.

The project led to interesting results in the characterization of a direct coupling harvesting solution installed on a composite panel. An important amount of additional effort was put in the identification and the proper exploitation of vibration harvesting tests on the shaker. Damage detection algorithms such as neural networks were investigated throughout the project and led also to interesting outputs related to the parameters that can influence the healthy/damaged signal as well as the possible solutions and the requirements to be able to identify damage and eventually locate it. These elements show a high potential of damage detection through Lamb waves, but require further research work that can based on the outcome and conclusions of this project.

The system as a whole still has to be considered at a low TRL level. Exploiting the ADVICE system (VDCus, End-Nodes and Central Station) will thus require additional research and development efforts in order to better control the influence of external parameters on the system (damage detection, harvesting, communication), and also improve the robustness and reliability of components and prediction of damage to further progress towards industrial exploitation. This should clearly be pursued through new research projects or interaction with other results from other projects.

On a component level, some elements can be exploited more rapidly such as the coupling between the harvesting methods and the power management, or the numerical prediction of Lamb wave propagation through layered composite materials. These are further detailed in the exploitation plan.

The partners of the ADVICE consortium have managed to develop a proof-of-concept for an autonomous wireless damage and vibration control system through identifications of goals, indicators of success, common requirements, prediction and analysis, development of components and finally integration and testing. Though the project was extended, overall, most objectives have been met with recommendations and lessons learnt having been identified and some paths to improvement and exploitation drawn out.

2. Dissemination and Use – Publishable results

2.1 Project and results overview

2.1.1 Project summary

EC PROGRAMME (see annex 1)	FP6-AEROSPACE
PROJECT TITLE	Autonomous Damage Detection and Vibration Control Systems
PROJECT ACRONYM:	ADVICE
CONTRACT NUMBER :	AST5-CT-2006-030971
PROJECT WEB SITE (if any) :	www.advice-project.eu
COORDINATOR:	
Coordinator's name	Dr. Anne Nawrocki
Coordinator e-mail	anne.nawrocki@cenaero.be
Coordinator telephone	+32 71 91 93 30
Coordinator organisation name	CENAERO
Coordinator organisation full address	Bâtiment Eole, 1er étage Rue des Frères Wright 29 B-6041 Gosselies Belgium
PARTNERS NAMES :	• CISSOID (BE) • EADS (DE) • AERNNOVA (ES) • GOODRICH (FR) • IAI (IL) • INSA Lyon (FR) • PROTOS (ES) • PZL (PL) • UCL (BE)
EC PROJECT OFFICER:	
EC PO name	Remy Denos
EC PO e-mail	remy.denos@ec.europa.eu
EC Directorate General	Directorate General Research

2.1.2 Overview of main project results

No.	Self-descriptive title of the result	Category (A, B, C)*	Partner(s) owning the result(s) (**) (referring in particular to specific patents, copyrights, etc.) & involved in their further use	Type of Result (***)
1	Optimal localization of piezoelectric material for energy harvesting from mechanical vibration	A	Cenaero	Scientific
2	Analysis of physics of Lamb wave propagation through finite element modeling	B	Cenaero	Scientific
3	Damage detection test campaign results and processing	B	Cenaero, Goodrich, INSA	Scientific, Database
4	Neural network software training and validation for damage detection in representative composite structure	B	Cenaero	Scientific, Software
5	Zigbee platform compatible with autonomous or low powered sensors network	A	UCL	Scientific Software Lab Prototype Demonstrator

* Category A: results usable outside the consortium
B: results usable within the consortium
C: non usable results

2.2 *Description of each publishable result*

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
1	Optimal localization of piezoelectric material for energy harvesting from mechanical vibration

CONTACT PERSON(S) FOR THIS RESULT

Title, First name and Family name*	Ir. David Dumas
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Organisation*	CENAERO
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E-mail*	david.dumas@cenaero.be
URL	www.cenaero.be
Specific Result URL	-

SUMMARY*

The identification of the optimal position of piezoelectric elements for the harvesting of mechanical vibration energy is done through numerical FEM analysis. Results are obtained based on the material properties of the structure and the piezoelectric patches as well as the vibration spectrums obtained for the structure. This can be done at a particular frequency or over any range of frequencies.

Through modal steady state and random vibration analysis, the strain/acceleration energy content of the structure is identified and zones that could host the piezoelectric material are pin-pointed based on different possible criteria. Impact of the integration of the new harvesting material on the local strains is also known. The output is available in terms of acceleration, strain and voltage levels at the level of the piezoelectric material.

This technique can also be used to identify the best locations for vibration damping through extraction of strain energy (direct coupling) or acceleration (indirect coupling).

SUJECT DESCRIPTORS*

Subject descriptors codes	7	99	373	378	565

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	X
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	29	35.2	35.3		

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development		**FIN**	Financial support	
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	X
JV	Joint venture		**CONS**	Available for consultancy	X
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Use of finite element tools and adequate pre- and post-processing methods to evaluate the output in terms of energy levels obtained with piezoelectric material coupled onto a structure. Effort and time reduction in pre-design phase on autonomous systems and so-called “smart” structures.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Companies requiring evaluation of structural vibrations for identification of high energy content zones in order to damp or harvest energy using piezoelectric materials

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
5	Wireless network platform based on Zigbee standard compatible with autonomous or low powered sensors network

CONTACT PERSON(S) FOR THIS RESULT

Title, First name and Family name*	Pr. Denis FLANDRE
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Organisation*	UCL
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Fax	+32.10.47.2598
E-mail*	Denis.flandre@uclouvain.be
URL	http://www.dice.ucl.ac.be/~flandre/
Specific Result URL	-

SUMMARY*

In the context of ADVICE project, UCL has developed a star-mesh wireless network system based on Zigbee protocol standard and communicates on peer-to-peer and polling scenarios.
The developed hardware for communication is a small electronic board (40x40 mm) and based on system-on-chip from Texas Instrument, a software managing the wireless communication network and power was been developed at all level of the network, this software is flexible with a larges sectors and applications need low power or self power systems.
The obtained results from testing the system under ADVICE project prove good performances for low powered system and compatible with others developed systems by ADVICE partners.
As low powered communication systems is one of major recent scientific researches, the reached objective of the system encourages to exploiting results for others applications and collaboration on future researches to improve the performance of the system.

SUJECT DESCRIPTORS*

Subject descriptors codes	7	192	199	679	

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	x
Guidelines, methodologies, technical drawings	x
Software code	x
Experimental development stage (laboratory prototype)	x
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	x
Partnership / other contractual agreement(s)	x
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	x
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	62	64	73.l	

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	X
JV	Joint venture		**CONS**	Available for consultancy	
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

The obtained results as show performances of low power wireless communication system can be exploited for different application fields and sectors. The system can be tested or developed with others power sources than structural vibrations, its also compatible with wireless communication systems need long battery life.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Developed low power communication platform look for partners to research for developing harvesting energy and enlarging field application of the system.

ANNEX 1 : FP6 EC programmes

FP6-AEROSPACE

FP6-CITIZENS

FP6-COORDINATION

FP6-EURATOM-FISSION

FP6-EURATOM-FUSION

FP6-EURATOM-JRC

FP6-EURATOM-NUCHORIZ

FP6-EURATOM-NUCTECH

FP6-EURATOM-NUWASTE

FP6-EURATOM-RADPROT

FP6-FOOD

FP6-INCO

FP6-INFRASTRUCTURES

FP6-INNOVATION

FP6-IST

FP6-JRC

FP6-LIFESCIHEALTH

FP6-MOBILITY

FP6-NEST

FP6-NMP

FP6-POLICIES

FP6-SME

FP6-SOCIETY

FP6-SUPPORT

FP6-SUSTDEV

ANNEX 2: SUBJECT DESCRIPTOR CODES

1 ACARIANS

2 ACCIDENTOLOGY

3 ACCOUNTING

4 ACOUSTICS

5 ADMINISTRATIVE SCIENCES, ADMINISTRATION

6 ADULT EDUCATION, PERMANENT EDUCATION

7 AERONAUTICS

8 AGEING

9 AGRICULTURAL CHEMISTRY

10 AGRICULTURAL ECONOMICS

11 AGRICULTURAL ENGINEERING/TECHNOLOGY

12 AGRICULTURAL MARKETING/TRADE

13 AGRICULTURAL PRODUCTION SYSTEMS

14 AGRICULTURAL SCIENCES, AGRICULTURE

15 AGRI-FOOD, AGRI-ENVIRONMENT

16 AGRONOMY

17 AIR TRAFFIC CONTROL OPERATIONS/PROCEDURES/SLOT ALLOCATION

18 AIR TRAFFIC MANAGEMENT/FLOW MANAGEMENT

19 AIR TRANSPORT TECHNOLOGY

20 AIRCRAFT

21 AIRPORT OPERATIONS/PROCEDURES

22 ALGAE

23 ALGEBRA

24 ALGEBRAIC TOPOLOGY

25 ALGORITHMS AND COMPLEXITY

26 ALLERGOLOGY

27 ALTERNATIVE PROPULSION SYSTEMS

28 ANALYTICAL CHEMISTRY

29 ANIMAL BANKS AND REPOSITORIES

30 ANIMAL BIOTECHNOLOGY

31 ANIMAL BREEDING/REPRODUCTION/NUTRITION

32 ANIMAL FEED, ANIMAL PRODUCTION

33 ANIMAL HEALTH, ANIMAL WELFARE

34 ANIMAL PARASITIC DISEASES

35 ANIMAL PHYSIOLOGY

36 ANIMAL PRODUCTS

37 ANTHROPOGENIC IMPACT ON ECOSYSTEMS

38 ANTHROPOLOGY

39 ANTIBIOTICS

40 ANTICANCER THERAPIES

41 ANTI-FRAUD

42 APPLIED MATHEMATICS

43 APPLIED PHYSICS

44 AQUACULTURE, AQUACULTURE TECHNOLOGY

45 ARCHIVISTICS/DOCUMENTATION/TECHNICAL DOCUMENTATION

46 ARCTIC ENVIRONMENT

47 ARTIFICIAL INTELLIGENCE

48 ARTS

49 ASSESSMENT AND MANAGEMENT OF LIVING RESOURCES

50 ASTRONOMY

51 ASTROPHYSICS/PLANETARY GEOLOGY

52 ATOMIC AND MOLECULAR PHYSICS

53 AUDIOVISUAL COMMUNICATION

54 AUTOMATION, ROBOTIC CONTROL SYSTEMS

55 BACTERIOLOGY

56 BANKING

57 BENCHMARKING TECHNIQUES

58 BIOASSAYS

59 BIOCATALYSTS

60 BIOCHEMICAL TECHNOLOGY

61 BIOCHEMISTRY, METABOLISM

62 BIOCOMPUTING, MEDICAL INFORMATICS, BIOMATHEMATICS, BIOMETRICS

63 BIODEGRADATION

64 BIODIVERSITY

65 BIOFERTILIZERS

66 BIOGAS PRODUCTION

67 BIOLOGICAL COLLECTIONS: MUSEA AND RELATED INFORMATION RESOURCES

68 BIOLOGICAL ENGINEERING

69 BIOLOGICAL MONITORING/RISK FACTORS AND ASSESSMENT

70 BIOLOGICAL SCIENCES, BIOLOGY

71 BIOMASS PROCESS INTEGRATION AND ENVIRONMENTAL IMPACTS

72 BIOMECHANICS, BIOMEDICAL ENGINEERING

73 BIOMEDICAL ETHICS

74 BIOMEDICAL SCIENCES

75 BIOMOLECULES, BIOPLASTICS, BIOPOLYMERS

76 BIOPHYSICS, MEDICAL PHYSICS

77 BIOREACTORS

78 BIOREMEDIATION

79 BIOSAFETY

80 BIOSENSORS

81 BIOTECHNOLOGY, BIOENGINEERING

82 BIOTRANSFORMATION

83 BOREAL FOREST

84 BRAIN DEVELOPMENT

85 BRAIN THEORY, BRAIN MAPPING

86 BROADBAND TECHNOLOGIES

87 BROADCASTING

88 BROKERAGE SERVICES

89 BUILDING CONSTRUCTION, SHELL SUSTAINABILITY

90 BUSINESS COMMUNICATION

91 BUSINESS ECONOMICS/STUDIES, ORGANISATION AND PROCESSES

92 CARBOCHEMISTRY, PETROCHEMISTRY, FUELS AND EXPLOSIVES TECHNOLOGY

93 CARBOHYDRATES AND OTHER MACROMOLECULES METABOLISM

94 CARBON DIOXIDE CAPTURE/STORAGE/DISPOSAL

95 CARDIOVASCULAR SYSTEM

96 CARE AND HEALTH SERVICES, HELP TO THE HANDICAPPED

97 CELL COMMUNICATION

98 CENTRAL AND EASTERN EUROPEAN COUNTRIES

99 CERAMIC MATERIALS AND POWDERS

100 CERTIFICATION

101 CHEMICAL METROLOGY

102 CHEMICAL TECHNOLOGY AND ENGINEERING

103 CHEMISTRY/HOMOGENEOUS AND HETEROGENEOUS CATALYSIS/THEORETICAL/NANOCHEMISTRY

104 CHRONOLOGY, DATATION TECHNOLOGY

105 CIVIL ENGINEERING (INCL PAVEMENTS AND STRUCTURES)

106 CLINICAL GENETICS, BIOLOGY

107 CLINICAL PHYSICS, RADIOLOGY, TOMOGRAPHY, MEDICAL INSTRUMENTATION, MEDICAL IMAGING

108 CLINICAL RESEARCH, CLINICAL TRIALS, COMPUTERISED CLINICAL SYSTEMS

109 COAL MINING TECHNOLOGIES

110 COASTAL MORPHOLOGICAL CHANGES AND COASTAL DEFENSE MECHANISMS

111 COASTAL ZONE ECOSYSTEMS AND MANAGEMENT

112 COATS AND SURFACE TREATMENT

113 COGNITIVE SCIENCE

114 COLLOIDS

115 COMBINATORIAL CHEMISTRY

116 COMBINED HEAT AND POWER SYSTEMS

117 COMBUSTION BASICS AND EFFICIENCY

118 COMMERCIAL AND INDUSTRIAL ECONOMICS

119 COMMON AGRICULTURAL POLICY

120 COMMUNICATION ENGINEERING/TECHNOLOGY

121 COMMUNICATION SCIENCES/HUMAN COMPUTER INTERACTIONS

122 COMMUNITY DEVELOPMENT, COMMUNITY STUDIES

123 COMPANY RE-ENGINEERING/ORGANISATIONAL DEVELOPMENT

124 COMPOSITE MATERIALS

125 COMPUTATIONAL BIOLOGY

126 COMPUTATIONAL CHEMISTRY AND MODELING

127 COMPUTATIONAL MATHEMATICS/DISCRETE MATHEMATICS

128 COMPUTATIONAL PHYSICS

129 COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL

130 COMPUTER TECHNOLOGY/GRAPHICS, META COMPUTING

131 COMPUTER-BASED TRAINING

132 CONDENSED MATTER: ELECTRONIC, MAGNETIC AND SUPERCONDUCTIVE PROPERTIES

133 CONDENSED MATTER: MECHANICAL AND THERMAL PROPERTIES

134 CONDENSED MATTER: OPTICAL AND DIELECTRIC PROPERTIES

135 CONDENSED MATTER: SOFT MATTER AND POLYMER PHYSICS

136 CONSUMER SCIENCES, CONSUMERS' RIGHTS

137 CONTROL ENGINEERING

138 COOPERATIVE WORKING

139 CORROSION

140 COSMOLOGY

141 CRIMINOLOGY

142 CROP, CROP INPUTS/MANAGEMENT/YIELD ESTIMATION

143 CULTURAL HERITAGE: PRESERVATION AND RESTORATION/CULTURAL STUDIES

144 CULTURE COLLECTIONS: MICROBIAL, CELL, TISSUE, GERMPLASM

145 CURRICULUM STUDIES

146 CYBERNETICS

147 CYTOGENETICS

148 CYTOLOGY, CANCEROLOGY, ONCOLOGY

149 DATA PROTECTION, STORAGE TECHNOLOGY, CRYPTOGRAPHY

150 DATABASES, DATABASE MANAGEMENT, DATA MINING

151 DECENTRALISED GENERATION OF ELECTRICITY/HEAT

152 DECISION SUPPORT TOOLS

153 DEEP WATER EXPLOITATION

154 DEMOGRAPHY

155 DESIGN, DESIGN ENGINEERING

156 DEVELOPMENT OF CLEAN FUELS FOR TRANSPORT

157 DEVELOPMENT POLICIES AND STUDIES

158 DEVELOPMENT TECHNOLOGY, ANIMAL GROWTH, ONTOLOGY, EMBRYOLOGY

159 DIAGNOSTICS, DIAGNOSIS

160 DIGITAL SYSTEMS, DIGITAL REPRESENTATION

161 DISABILITIES, HANDICAPS AND HANDICAPPED

162 DISEASES: RARE/CHRONIC/DEGENERATIVE, ETIOLOGIC FACTORS

163 DIVERSIFICATION IN AGRICULTURE/FORESTRY

164 DNA CHIP

165 DNA THERAPIES

166 DOWNSTREAM PROCESSING

167 "DRILLING TECHNOLOGY; DEEP DRILLING"

168 DRUG ABUSE, ADDICTION

169 DRUG DISCOVERY, PROFILING, TARGETING

170 DRYLAND AND ARID ZONE ECOSYSTEMS

171 EARTH OBSERVATION APPLICATIONS AND POLICY

172 EARTH OBSERVATION TECHNOLOGY AND INFORMATION EXTRACTION

173 EARTH SCIENCE, EARTH OBSERVATION/STRATIGRAPHY/SEDIMENTARY PROCESSES

174 EARTH SCIENCES FOR CLIMATE RESEARCH

175 ECOLOGY, ECOSYSTEMS, ECOLOGICAL EVOLUTION/DYNAMICS

176 ECONOMIC AND ENVIRONMENT IMPACTS

177 ECONOMIC AND SOCIAL SCIENCES

178 ECONOMICS IN AGRICULTURE/FORESTRY/RURAL DEVELOPMENT

179 ECONOMICS OF DEVELOPMENT/GROWTH/INNOVATION

180 ECONOMICS, ECONOMIC PLANNING

181 ECOSYSTEM RESEARCH AND CONSERVATION

182 ECOTOXICOLOGY

183 EDUCATION AND TRAINING, LIFELONG LEARNING, REMOTE LEARNING

184 EDUCATIONAL MULTIMEDIA

185 EDUCATIONAL SCIENCES

186 ELECTRICAL ENGINEERING/TECHNOLOGY

187 ELECTROMAGNETISM

188 ELECTRONIC COMMERCE, ELECTRONIC PAYMENT, ELECTRONIC SIGNATURE

189 ELECTRONIC DATA INTERCHANGE

190 ELECTRONIC HEALTH RECORDS

191 ELECTRONIC PUBLISHING, AUTHORING TOOLS

192 ELECTRONICS, ELECTRONIC ENGINEERING

193 EMERGENCY MANAGEMENT

194 EMISSION

195 EMPLOYMENT STUDIES

196 ENDOCRINOLOGY, SECRETING SYSTEMS, DIABETOLOGY

197 ENERGY AND CLIMATE CHANGE

198 ENERGY CONVERSION PROCESSES OR CYCLES/CONVERSION FROM COAL

199 ENERGY MANAGEMENT SYSTEM

200 ENERGY MARKET ANALYSIS

201 ENERGY PRODUCTION FROM BIOMASS / WASTE

202 ENERGY RESEARCH/RTD POLICY

203 ENERGY, RENEWABLE ENERGIES, ELECTRICITY STORAGE

204 ENGINEERING, CONCURRENT ENGINEERING

205 ENTOMOLOGY, PLANT PARASITOLOGY

206 ENTREPRENEURSHIP, SPIN OFFS, NEW TECHNOLOGY BASED BUSINESS

207 ENVIRONMENT, ENVIRONMENTAL SCIENCE

208 ENVIRONMENTAL ECONOMICS/NATURAL RESOURCES ECONOMICS

209 ENVIRONMENTAL HEALTH

210 ENVIRONMENTAL IMPACTS/INTERACTIONS

211 ENVIRONMENTAL INDICATORS/MONITORING/RISK ASSESSMENT

212 ENVIRONMENTAL LAW/TREATIES/POLICY

213 ENVIRONMENTAL TECHNOLOGY/ENGINEERING, POLLUTION CONTROL

214 EPIDEMIOLOGY

215 ERGONOMICS

216 EROSION

217 EUROPEAN INTEGRATION

218 EUROPEAN LAW

219 EUROPEAN STUDIES

220 EVALUATION

221 EXPLOITATION OF RESEARCH RESULTS

222 EXTENSIFICATION

223 EXTERNALITIES

224 FARMHOUSE CONSTRUCTION

225 FARMING SYSTEMS

226 FERMENTATION

227 FINANCIAL SCIENCE, FINANCE

228 FINE CHEMICALS, DYES AND INKS

229 FISH/FISHERIES

230 FISHING METHODOLOGIES/SELECTIVITY

231 FOOD AND DRINK TECHNOLOGY

232 FOOD CHEMISTRY, FOOD INGREDIENTS

233 FOOD MICROBIOLOGY

234 FOOD PROCESSING/PACKAGING

235 FOOD QUALITY MANAGEMENT/POLICY/LABELLING

236 FOOD TOXICOLOGY

237 FOREST ECOSYSTEMS

238 FOREST GENETICS

239 FOREST PHYSIOLOGY AND PATHOLOGY

240 FOREST POLICY, FOREST MANAGEMENT

241 FOREST PROTECTION

242 FOREST SCIENCES

243 FORMAL SAFETY AND ENVIRONMENTAL ASSESSMENT

244 FREIGHT TRANSPORT

245 FUEL CELLS

246 FUELS: ALTERNATIVE FUELS IN TRANSPORTS

247 FUNCTIONAL FOODS

248 FUNGI

249 FUTURE AND EMERGING TECHNOLOGIES

250 GAS CONVERSION

251 GAS TURBINES FOR ENERGY CONVERSION

252 GASES, FLUID DYNAMICS, PLASMAS/ELECTRIC DISCHARGES

253 GASTRO-ENTEROLOGY

254 GENDER ISSUES, GENDER STUDIES

255 GENE THERAPY

256 GENERAL PATHOLOGY, PATHALOGICAL ANATOMY

257 GENETIC COMPARATIVE ANALYSIS

258 GENETIC ENGINEERING

259 GENETIC MAPPING, GENE SEQUENCE

260 GENETIC RESISTANCE

261 GENETIC SELECTION

262 GENETICALLY MODIFIED ORGANISMS

263 GENETICS

264 GENOMES, GENOMICS

265 GEOGRAPHIC INFORMATION SYSTEMS

266 GEOGRAPHY

267 GEOLOGICAL ENGINEERING/GEOTECHNICS

268 GEOMETRY/TOPOLOGY

269 GEOPHYSICS, PHYSICAL OCEANOGRAPHY, METEOROLOGY, GEOCHEMISTRY, TECTONICS

270 GERONTOLOGY AND GERIATRICS

271 GLOBAL CHANGE: BIOGEOCHEMICAL AND HYDROLOGICAL CYCLES

272 GLOBAL CHANGE: CLIMATE CHANGE

273 GLOBAL CHANGE: HUMAN HEALTH

274 GLOBAL CHANGE: LAND COVER AND DEGRADATION

275 GLOBAL CHANGE: OZONE AND ATMOSPHERIC COMPOSITION

276 GLOBAL CYCLES OF ENERGY AND MATTER

277 GREEN TECHNOLOGIES/CHEMICALS

278 GRID CONNECTION

279 HAZARDS: INDUSTRIAL

280 HAZARDS: NATURAL

281 HEALTH AND POPULATION, HEALTH EDUCATION

282 HEALTH FINANCING / ECONOMICS

283 HEALTH RISK EVALUATION

284 HEALTH SCIENCES/POLICIES/LAW

285 HEALTH SERVICE MANAGEMENT

286 HEALTH SYSTEMS RESEARCH

287 HEALTH, HEALTH PHYSICS

288 HETEROGENEOUS CATALYSIS

289 HIGH CONTAINMENT, HIGHT CONTAINMENT FACILITIES

290 HIGH FREQUENCY TECHNOLOGY, MICROWAVES

291 HIGH-THROUGHPUT SCREENING

292 HISTOLOGY, CYTOCHEMISTRY, HISTOCHEMISTRY, TISSUE CULTURE

293 HISTORY

294 HISTORY AND PHILOSOPHY OF SCIENCE AND MEDICINE

295 HOME SYSTEMS

296 HORMONES

297 HORTICULTURE, ORNAMENTAL PLANTS

298 HUMAN FACTORS IN TRANSPORT

299 HUMAN GENETICS

300 HUMAN RIGHTS

301 HUMAN SCIENCES, HUMANITIES

302 HVAC SYSTEMS AND MANAGEMENT

303 HYBRID AND ELECTRIC VEHICLES

304 HYDROBIOLOGY, MARINE BIOLOGY, AQUATIC ECOLOGY, LIMMOLOGY

305 HYDROCARBONS EXPLORATION AND PRODUCTION

306 HYDROELECTRICITY/SMALL HYDRO/HYDROPOWER

307 HYDROGEN

308 HYDROGEOLOGY, GEOGRAPHICAL AND GEOLOGICAL ENGINEERING

309 IDENTIFICATION SYSTEMS

310 IMAGING, IMAGE PROCESSING

311 IMMUNOLOGY, IMMUNOTHERAPY, IMMUNOASSAYS

312 IN VITRO TESTING/TRIAL METHODS

313 INDUSTRIAL ENGINEERING

314 INDUSTRIAL POLICY/RELATIONS

315 INDUSTRIAL PSYCHOLOGY/SOCIOLOGY

316 INDUSTRIAL TECHNOLOGY/ECONOMICS

317 INFECTIONS

318 INFORMATICS

319 INFORMATICS LAW

320 INFORMATION MANAGEMENT

321 INFORMATION TECHNOLOGY/SCIENCE

322 INFRASTRUCTURE MANAGEMENT

323 INLAND NAVIGATION

324 INNOVATION ASSISTANCE

325 INNOVATION FINANCE

326 INNOVATION MONITORING

327 INNOVATION POLICY/STUDIES

328 INNOVATION TRAINING

329 INORGANIC CHEMISTRY

330 INSECTS

331 INSTRUMENTATION TECHNOLOGY

332 INTANGIBLE INVESTMENTS

333 INTEGRATED ENVIRONMENTAL ASSESSMENT

334 INTEGRATED GLOBAL SAFETY

335 INTEGRATION OF RENEWABLE ENERGY SYSTEMS

336 INTELLECTUAL PROPERTY

337 INTELLIGENT AGENTS

338 INTELLIGENT VEHICLES AND WATERBORNE TRANSPORT SYSTEMS

339 INTERMODAL TRANSPORT

340 INTERNATIONAL COMMERCE/ECONOMICS

341 INTERNATIONAL TREATIES / MULTILATERAL AGREEMENTS

342 INTERNET TECHNOLOGIES

343 INVERTEBRATES

344 JOURNALISM

345 KNOWLEDGE ENGINEERING

346 LABOUR MARKET STUDIES/ECONOMICS

347 LAND USE PLANNING/LANDSCAPE/LANDSCAPE ARCHITECTURE

348 LANGUAGE SCIENCES/ENGINEERING/TECHNOLOGY, LINGUISTICS

349 LARGE SCALE GENERATION OF ELECTRICITY/HEAT

350 LASER TECHNOLOGY

351 LAW: INTERNATIONAL / PRIVATE / PUBLIC

352 LEARNING MECHANISMS

353 LIBRARY SCIENCE/SYSTEMS

354 LIFE CYCLE MANAGEMENT

355 LIPIDS, STEROIDS, MEMBRANES

356 LIQUID BIOFUELS

357 LOGISTICS

358 LOW INPUT PRODUCTION

359 MACROECONOMICS (INCL. MONETARY ECONOMICS)

360 MACROMOLECULAR CHEMISTRY/NEW MATERIAL/SUPRAMOLECULAR STRUCTURES

361 MACROSOCIOLOGY

362 MAINTENANCE MANAGEMENT

363 MANAGEMENT OF ENTERPRISES

364 MANAGEMENT OF URBAN AREAS

365 MANAGEMENT STUDIES

366 MARINE ECOSYSTEMS

367 MARINE SCIENCES/MARITIME STUDIES

368 MARINE: INSTRUMENTATION AND UNDERWATER TECHNOLOGY

369 MARINE: OCEANOGRAPHY (PHYSICAL AND OPERATIONAL)

370 MARITIME SAFETY

371 MARKET ANALYSIS/ECONOMICS/QUANTITATIVE METHODS

372 MARKET STUDY, MARKETING

373 MATERIALS TECHNOLOGY/ENGINEERING

374 MATHEMATICAL ANALYSIS/PARTIAL DIFFERENTIAL EQUATIONS

375 MATHEMATICAL LOGIC: SET THEORY, COMBINATORICS/SEMANTICS

376 MATHEMATICAL PHYSICS

377 MATHEMATICS

378 MECHANICAL ENGINEERING, HYDRAULICS, VIBRATION AND ACOUSTIC ENGINEERING

379 MEDIA STUDIES/LAW/MASS COMMUNICATIONS

380 MEDICAL ANTHROPOLOGY

381 MEDICAL SCIENCES/RESEARCH

382 MEDICAL TECHNOLOGY

383 MEDICINAL CHEMISTRY

384 MEDICINE (HUMAN AND VERTEBRATES)

385 MEMBRANE TECHNOLOGY

386 MENTAL STRESS

387 METABOLIC REGULATION AND SIGNAL TRANSDUCTION

388 METAL TECHNOLOGY AND METAL PRODUCTS

389 METALLURGY

390 METROLOGY, PHYSICAL INSTRUMENTATION

391 MICROBIAL BIOTECHNOLOGY, MICROBIAL MODELLING

392 MICROBIAL SYSTEMATICS/DIVERSITY

393 MICROBIOLOGY

394 MICROECONOMICS (THEORETICAL AND APPLIED)

395 MICROELECTRONICS

396 MICROENGINEERING, MICROMACHINING

397 MICROSYSTEMS

398 MINING

399 MOBILE COMMUNICATIONS

400 MODELLING/MODELLING TOOLS, 3-D MODELLING

401 MOLECULAR BIOLOGY

402 MOLECULAR BIOPHYSICS

403 MOLECULAR DESIGN, DE NOVO DESIGN

404 MOLECULAR EVOLUTION

405 MOLECULAR GENETICS

406 MOLECULAR MARKERS AND RECOGNITION

407 MONOCLONAL ANTIBODIES

408 MOTHER AND CHILD HEALTH

409 MOTORS AND PROPULSION SYSTEMS

410 MOUNTAIN AND HIGHLAND ECOSYSTEMS

411 MULTIMEDIA

412 MULTISENSORY TECHNOLOGY, MULTI-SENSING

413 MUSEUM SCIENCE

414 MYCOLOGY

415 NANOBIOTECHNOLOGY

416 NANOFABRICATION, NANOTECHNOLOGY

417 NARROW BAND TECHNOLOGIES

418 NATURAL GAS

419 NATURAL HISTORY OF DISEASES

420 NATURAL OILS, FATS AND WAXES

421 NATURAL RESOURCES EXPLORATION

422 NATURAL SCIENCES

423 NEMATODS

424 NETWORK TECHNOLOGY, NETWORK SECURITY

425 NETWORKED ORGANISATIONS

426 NEUROBIOLOGY, NEUROCHEMISTRY, NEUROLOGY, NEUROPSYCHOLOGY, NEUROPHYSIOLOGY

427 NEUROINFORMATICS

428 NEUTRON PHYSICS

429 NEW MEANS OF TRANSPORT

430 NITROGEN FIXATION

431 NOISE AND VIBRATIONS

432 NON-COMMUNICABLE DISEASES

433 NON-LINEAR DYNAMICS AND CHAOS THEORY

434 NON-METALLIC MINERAL TECHNOLOGY

435 NUCLEAR CHEMISTRY

436 NUCLEAR ENGINEERING AND TECHNOLOGY

437 NUCLEAR MEDICINE, RADIOBIOLOGY

438 NUCLEAR PHYSICS

439 NUCLEIC ACID METABOLISM

440 NUCLEIC ACIDS, POLYNUCLEAOTIDES, PROTEIN SYNTHESIS

441 NUMBER THEORY, FIELD THEORY, ALGEBRAIC GEOMETRY, GROUP THEORY

442 NUTRITION

443 OBSERVATION SYSTEMS / CAPACITY / DATASETS / INDICATORS

444 OCCUPATIONAL HEALTH, INDUSTRIAL MEDICINE

445 OCEAN / ENERGY

446 ODONTOLOGY, STOMATOLOGY

447 OFFSHORE TECHNOLOGY, SOIL MECHANICS, HYDRAULIC ENGINEERING

448 ON-LINE INFORMATION SERVICES, ON-LINE DEMOCRATY, ON-LINE BUSINESS

449 OPERATIONS RESEARCH, ACTUARIAL MATHEMATICS

450 OPTICAL MATERIALS

451 OPTICS

452 OPTRONICS

453 ORGANIC CHEMISTRY

454 ORGANIC FARMING

455 ORGANIC WASTE

456 ORGANOMETALLIC CHEMISTRY

457 ORPHAN DRUGS

458 OTHER RENEWABLE ENERGY OPTIONS

459 OTORHINOLARYNGOLOGY, AUDIOLOGY, AUDITIVE SYSTEM AND SPEECH

460 PALEOCLIMATOLOGY

461 PALEONTOLOGY/PALEOECOLOGY

462 PAPER TECHNOLOGY, RECYCLING

463 PARASITOLOGY (HUMAN AND ANIMAL)

464 PARTICLE PHYSICS/FIELDS THEORY

465 PASSENGER TRANSPORT

466 PATENTS, COPYRIGHTS, TRADEMARKS

467 PATHOLOGY

468 PATHOPHYSIOLOGY

469 PERIPHERALS TECHNOLOGIES (MASS DATA STORAGE, DISPLAY TECHNOLOGIES)

470 PERI-URBAN AGRICULTURE

471 PESTICIDES, BIOPESTICIDES

472 PETROCHEMISTRY, PETROLEUM ENGINEERING

473 PETROLOGY, MINERALOGY, GEOCHEMISTRY

474 PHARMACEUTICALS AND RELATED TECHNOLOGIES

475 PHARMACOLOGICAL SCIENCES, PHARMACOGNOSY, TOXICOLOGY

476 PHOTONIC NETWORKS

477 PHOTOVOLTAIC SYSTEMS, CELLS AND MODULES MANUFACTURING, TECHNOLOGY DEVELOPMENT

478 PHYSICAL CHEMISTRY/SOFT MATTER

479 PHYSICAL GEOGRAPHY, CARTOGRAPHY, CLIMATOLOGY

480 PHYSICAL MEDICINE, KINESITHERAPY, REVALIDATION, REHABILITATION

481 PHYSICAL SCIENCES

482 PHYSICAL STRESS

483 PHYSICS OF FLUIDS

484 PHYSIOLOGICAL DISORDERS

485 PHYSIOLOGY

486 PHYTOREMEDIATION

487 PHYTOTECHNOLOGY, PHYTOPATHOLOGY, CROP PROTECTION

488 PIPELINE TECHNOLOGY

489 PLANT AND ASSOCIATED MICROORGANISM BIOTECHNOLOGY

490 PLANT BIOCHEMISTRY

491 PLANT BIOLOGY

492 PLANT GENETICS/SELECTION/BREEDING

493 PLANT HEALTH/PROTECTION

494 PLANT INPUTS/NUTRITION/PRODUCTION

495 PLANT PHYSIOLOGY

496 PLANT PRODUCTS

497 POLITICAL SCIENCES/THEORY/ECONOMY/COMPARATIVE POLITICS

498 POLYMER TECHNOLOGY, BIOPOLYMERS

499 POPULATION GENETICS

500 PORT MANAGEMENT

501 POSITIONING AND GUIDANCE SYSTEMS

502 POST HARVEST TREATMENT - FOOD

503 POST HARVEST TREATMENT - NON-FOOD

504 PRECISION ENGINEERING

505 PRION DISEASES

506 PROBABILITY THEORY

507 PROCESS EFFICIENCY

508 PROCESS ENGINEERING

509 PRODUCTION TECHNOLOGY

510 PROGRAMMING/INFORMATION SYSTEMS

511 PROJECT ENGINEERING

512 PROTEINS, ENZYMOLOGY, PROTEIN ENGINEERING

513 PROTEOMES, PROTEOMICS

514 PSYCHIATRY, MEDICAL PSYCHOLOGY, PSYCHOSOMATICS

515 PSYCHOLOGICAL SCIENCES, PSYCHOLOGY

516 PUBLIC ADMINISTRATION

517 PUBLIC HEALTH

518 PUBLIC PERCEPTION, PUBLIC RELATIONS

519 PUBLIC POLICY STUDIES

520 PUBLISHING

521 PULP TECHNOLOGY

522 QUALITY, QUALITY CONTROL, TRACEABILITY

523 QUANTUM INFORMATION PHYSICS

524 QUANTUM MECHANICS

525 QUANTUM TECHNOLOGY

526 R&D POLICY AND PROGRAMME EVALUATION AND IMPACT ASSESSMENT

527 RADIODIAGNOSTICS, RADATION BIOLOGY

528 RADIOECOLOGY

529 RAILWAY TRANSPORT TECHNOLOGY

530 REACTION MECHANISMS AND DYNAMICS

531 REACTOR SAFETY

532 REFERENCE MATERIALS/METHODS

533 REFRIGERATION AND COOLING

534 REGIONAL ECONOMICS/STUDIES/DEVELOPMENT

535 REHABILITATION SYSTEMS

536 REMOTE SENSING

537 REPRODUCTIVE HEALTH

538 REPRODUCTIVE MECHANISMS

539 RESEARCH METHODOLOGY IN SCIENCE

540 RESEARCH NETWORKING

541 RESEARCH POLICY

542 RESERVOIR CHARACTERISATION AND MONITORING

543 RESIDUES

544 RESPIRATORY SYSTEM

545 RE-STRUCTURING OF PUBLIC ADMINISTRATIONS

546 ROAD SAFETY

547 ROAD TRANSPORT TECHNOLOGY

548 RTD SYSTEMS AND POLICIES AND THEIR INTERACTION WITH OTHER RELATED POLICIES

549 RURAL DEVELOPMENT, RURAL SOCIOLOGY AND SOCIO-ECONOMICS

550 SAFETY TECHNOLOGY

551 SAMPLE BANKS

552 SATELLITE (TECHNOLOGY, SYSTEMS, POSITIONING, COMMUNICATION)

553 SCIENCE AND TECHNOLOGY INDICATORS

554 SCIENCE POLICY

555 SCIENCE, TECHNOLOGY AND THE MEDIA

556 SEA FOOD

557 SEARCH AND RESCUE

558 SECURITY SYSTEMS

559 SEMICONDUCTOR PHYSICS AND TECHNOLOGIES

560 SENSORY SCIENCE, SENSORS, INSTRUMENTATION

561 SEROLOGY AND TRANSPLANTATION

562 SET ASIDE

563 SIGNAL PROCESSING

564 SILVICULTURE, FORESTRY, FOREST TECHNOLOGY

565 SIMULATION, SIMULATION ENGINEERING

566 SIMULATOR TRAINING

567 SKELETON, MUSCLE SYSTEM, RHEUMATOLOGY, LOCOMOTION

568 SMART CARDS

569 SOCIAL ECONOMICS

570 SOCIAL LAW

571 SOCIAL MEDICINE

572 SOCIAL SHAPING OF TECHNOLOGY

573 SOCIETAL BEHAVIOUR

574 SOCIO-ECONOMIC ASPECTS OF ENVIRONMENTAL CHANGE

575 SOCIO-ECONOMIC RESEARCH

576 SOCIO-ECONOMICAL IMPACTS IN AGRICULTURE/FORESTRY/RURAL DEVELOPMENT

577 SOCIO-ECONOMICS

578 SOCIOLOGY

579 SOFTWARE ENGINEERING, MIDDLEWARE, GROUPWARE

580 SOIL SCIENCE, AGRICULTURAL HYDROLOGY, WATER PROCESSES

581 SOLAR CONCENTRATING TECHNOLOGIES AND APPLICATIONS

582 SOLID STATE PHYSICS

583 SOUND ENGINEERING/TECHNOLOGY

584 SPACE TECHNOLOGY

585 SPATIAL INTEGRATION IN BUILT ENVIRONMENT

586 SPEECH COMMUNICATION

587 SPEECH PROCESSING/TECHNOLOGY

588 STANDARDISATION, STANDARDISATION OF NEW TECHNOLOGIES

589 STATISTICAL PHYSICS

590 STATISTICS

591 STRUCTURAL BIOLOGY/DETERMINATION/FUNCTION

592 SUPERCONDUCTORS

593 SURFACE CHEMISTRY

594 SURFACE PHYSICS

595 SURVEILLANCE

596 SURVEYING

597 SYNTHESIS AND NEW MOLECULES

598 SYSTEMS ANALYSIS AND MODELS DEVELOPMENT

599 SYSTEMS DESIGN/THEORY

600 SYSTEMS ENGINEERING

601 SYSTEMS, CONTROL, MODELLING, AND NEURAL NETWORKS

602 TECHNOLOGICAL SCIENCES

603 TECHNOLOGY ACCEPTABILITY

604 TECHNOLOGY ASSESSMENT AND FORESIGHT

605 TECHNOLOGY EVALUATION/MANAGEMENT

606 TECHNOLOGY POLICY

607 TECHNOLOGY TRANSFER

608 TECHNOLOGY WATCH/VALIDATION

609 TELECOMMUNICATION ENGINEERING/TECHNOLOGY

610 TELESERVICES, TELE-WORKING, TELE-PAYMENT, TELE-MEDICINE

611 TESTING, CONFORMANCE TESTING

612 TEXTILES TECHNOLOGY

613 THERAPEUTIC SUBSTANCES

614 THERMAL ENGINEERING, APPLIED THERMODYNAMICS

615 THERMODYNAMICS

616 TIMBER ENGINEERING

617 TISSUE BANKS/ENGINEERING

618 TOTAL QUALITY MANAGEMENT

619 TOWN AND COUNTRY PLANNING

620 TOXICITY AND TOXINOLOGY

621 TRACTION/PROPULSION SYSTEMS

622 TRAFFIC CONTROL SYSTEMS

623 TRAFFIC ENGINEERING/INFRASTRUCTURE/MANAGEMENT SYSTEMS

624 TRANSACTION SYSTEMS

625 TRANSGENE EXPRESSION

626 TRANSGENIC CROP PLANT

627 TRANSHIPMENT SYSTEMS

628 TRANSPORT DEMAND MANAGEMENT

629 TRANSPORT ECONOMICS

630 TRANSPORT INFORMATION SYSTEMS, FLEET MANAGEMENT

631 TRANSPORT INFRASTRUCTURE/MANAGEMENT SERVICES

632 TRANSPORT MODELLING/SCENARIOS

633 TRANSPORT OF GAS AND LIQUID FUELS

634 TRANSPORT POLICY/LAW

635 TRANSPORT SAFETY/SECURITY

636 TRANSPORT TECHNOLOGY/ENGINEERING

637 TRANSPORT TELEMATICS

638 TRANSPORT, TRANSMISSION AND DISTRIBUTION OF ELECTRICITY

639 TROPICAL AGRICULTURE

640 TROPICAL ECOSYSTEMS

641 TROPICAL FORESTRY

642 TROPICAL MEDICINE

643 URBAN DEVELOPMENT/ECONOMICS

644 URBAN FORESTRY

645 URBAN GOVERNANCE AND DECISION MAKING

646 URBAN QUALITY OF LIFE

647 URBAN SOCIOLOGY

648 URBAN TRANSPORT

649 URBAN: SUSTAINABLE CITIES AND RATIONAL RESOURCE MANAGEMENT

650 URBAN: TECHNOLOGIES FOR THE BUILT ENVIRONMENT

651 UROLOGY, NEPHROLOGY

652 USER CENTRED DESIGN, USABILITY

653 USER MODELLING

654 VACCINES

655 VACUUM/HIGH VACUUM TECHNOLOGY

656 VEHICLE TECHNOLOGY

657 VENTURE CAPITAL

658 VESSEL TRAFFIC MANAGEMENT

659 VETERINARY MEDICINE

660 VIRTUAL ORGANISATIONS

661 VIRTUAL REALITY

662 VIRUS, VIROLOGY

663 VULCANOLOGY/SEISMOLOGY

664 WASTE BIOTREATMENT

665 WASTE MANAGEMENT/RECYCLING

666 WATER RESOURCE MANAGEMENT/ENGINEERING

667 WATER TRANSPORT TECHNOLOGY, SHIPBUILDING

668 WATER: FRESH WATER ECOSYSTEMS

669 WATER: HYDROLOGY

670 WATER: MONITORING / QUALITY / TREATMENT

671 WATER: RATIONAL AND EFFICIENT USE

672 WATERBORNE TRANSPORT

673 WAVE/TIDAL ENERGY

674 WEEDS

675 WELFARE STUDIES

676 WETLAND ECOSYSTEMS

677 WIND ENERGY MANUFACTURING/TECHNOLOGIES

678 WIND TURBINE ENVIRONMENTAL IMPACT

679 WIRELESS SYSTEMS, RADIO TECHNOLOGY

680 WOMEN'S STUDIES

681 WOOD ENGINEERED PRODUCTS, PARTICLE AND FIBRE BOARDS

682 WOOD PROCESSING BY MECHANICAL MEANS

683 WORLD TRADE ORGANISATION

ANNEX 3: NACE codes for business activities

Division	Description
Section A	*Agriculture, hunting and forestry*
01	*Agriculture, hunting and related service activities*
02	*Forestry, logging and related service activities*
Section B	*Fishing*
05	*Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing*
Section C	*Mining and quarrying*
10	*Mining of coal and lignite; extraction of peat*
11	*Extraction of crude petroleum and natural gas; service activities incidental to oil and gas*
	extraction, excluding surveying
12	*Mining of uranium and thorium ores*
13	*Mining of metal ores*
14	*Other mining and quarrying*
Section D	*Manufacturing*
15	*Manufacture of food products and beverages*
16	*Manufacture of tobacco products*
17	*Manufacture of textiles*
18	*Manufacture of wearing apparel; dressing and dyeing of fur*
19	*Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear*
20	*Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials*
21	*Manufacture of pulp, paper and paper products*
22	*Publishing, printing and reproduction of recorded media*
23	*Manufacture of coke, refined petroleum products and nuclear fuel*
24	*Manufacture of chemicals and chemical products*
25	*Manufacture of rubber and plastic products*
26	*Manufacture of other non-metallic mineral products*
27	*Manufacture of basic metals*
28	*Manufacture of fabricated metal products, except machinery and equipment*
29	*Manufacture of machinery and equipment n.e.c.*
30	*Manufacture of office machinery and computers*

31	*Manufacture of electrical machinery and apparatus n.e.c.*
32	*Manufacture of radio, television and communication equipment and apparatus*
33	*Manufacture of medical, precision and optical instruments, watches and clocks*
34	*Manufacture of motor vehicles, trailers and semi-trailers*
35	*Manufacture of other transport equipment*
35.1	*Building and repairing of ships and boats*
35.2	*Manufacture of railway and tramway locomotives and rolling stock*
35.3	*Manufacture of aircraft and spacecraft*
a	*Manufacture of helicopter*
b	*Manufacture of aeroplanes for the transport of goods or passengers, for use by the defence forces, for sports or other purposes*
c1	*Manufacture of parts and accessories of the aircraft of this class*
d2	*Others*
36	*Manufacture of furniture; manufacturing n.e.c.*
37	*Recycling*
Section E	*Electricity, gas and water supply*
40	*Electricity, gas, steam and hot water supply*
41	*Collection, purification and distribution of water*
Section F	*Construction*
45	*Construction*
Section G	*Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods*
50	*Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel*
51	*Wholesale trade and commission trade, except of motor vehicles and motorcycles*
52	*Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods*
Section H	*Hotels and restaurants*
55	*Hotels and restaurants*
Section I	*Transport, storage and communication*

[1] Includes: major assemblies such as fuselages, wings, doors, control surfaces, landing gear, fuel tanks, nacelles, airscrews, helicopter rotors and propelled rotor blades, motors and engines of a kind typically found on aircraft, parts of turbojets and turbopropellers

[2] This includes: manufacture of gliders, hang-gliders, manufacture of dirigibles and balloons, manufacture of spacecraft and spacecraft launch vehicles, satellites, planetary probes, orbital stations, shuttles, manufacture of aircraft launching gear, deck arresters, etc.
manufacture of ground flying trainers However 35.3 should **exclude**:manufacture of parachutes, military ballistic missiles, ignition parts and other electrical parts for internal combustion engines, instruments used on aircraft, and air navigation systems.

60	*Land transport; transport via pipelines*
61	*Water transport*
61.1	*Sea and coastal water transport*
e	*Transport of passenger or freight over water*
f	*Operation of excursion, cruse or sightseeing boats*
g	*Operation of ferries, water taxis, etc.*
62	*Air transport*
h	*Transport of passenger or freight by airlines*
63	*Supporting and auxiliary transport activities; activities of travel agencies*
63.1	*Cargo handling and storage*
63.2	*Other supporting transport activities*
i	*Operation of terminal facilities such as harbours and piers, waterway locks etc.*
j	*Airport and air-traffic control activities*
63.3	*Activities of travel agencies and tour operators; tourist assistance activities n.e.c.*
63.4	*Activities of other transport agencies*
k	*Forwarding of freight*
64	*Post and telecommunications*
Section J	*Financial intermediation*
65	*Financial intermediation, except insurance and pension funding*
66	*Insurance and pension funding, except compulsory social security*
67	*Activities auxiliary to financial intermediation*
Section K	*Real estate, renting and business activities*
70	*Real estate activities*
71	*Renting of machinery and equipment without operator and of personal and households goods*
72	*Computer and related activities*
73	*Research and development*
l	*Research and experimental development on natural sciences and engineering*
m	*Research and experimental development on social sciences and humanities*
74	*Other business activities*
Section L	*Public administration and defence; compulsory social security*
75	*Public administration and defence; compulsory social security*
Section M	*Education*
80	*Education*
Section N	*Health and social work*

85	*Health and social work*
Section O	*Other community, social and personal service activities*
90	*Sewage and refuse disposal, sanitation and similar activities*
91	*Activities of membership organisations n.e.c.*
92	*Recreational, cultural and sporting activities*
93	*Other service activities*
Section P	*Private households with employed persons*
95	*Private households with employed persons*
Section Q	*Extra-territorial organisations and bodies*
99	*Extra-territorial organisations and bodies*

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