Automated Diagnosis for Helicopter Engines and Rotating parts

PUBLISHABLE FINAL ACTIVITY REPORT

Document Reference	ADHER/EC/WP1.1.MR10/1.1	
Version/Date present previous	1.1 1.0	12 January 2009 2 January 2009
Issued by	Eurocopter	
Authors	-	
Project Deliverable	n/a	
Release status	Public	
Distribution	ADHER Partners European Commission	

Project number:	AST5-CT-2006-030907
Project acronym:	ADHER
Project Title:	Automated diagnosis for helicopter Engines and rotating parts
Instrument:	STREP
Thematic Priority:	Aeronautics

Publishable Final Activity Report

Period covered: from 1 December 2006 to 30 November 2008

Date of preparation: 12 January 2009

Start of project: 1 December 2006 Duration: 24 months

Project coordinator name: Jean Pierre DERAIN

Project coordinator organisation name: Eurocopter

Revision: 1.1

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Acronyms

ADHER	Automated Diagnosis for Helicopter Engines and Rotating Parts
AE	Acoustic Emission
CBM	Condition Based Maintenance
CDF	Contextual Dependence Function
CU	Partner Cardiff University
CV	Contextual Variable
DBMS	Data Based Management System
EC	Partner Eurocopter
EHL	Elastohydrodynamic Lubrication
ENSC	Partner Ecole Nationale Supérieure de Cachan
HUMS	Health Usage Monitoring System
OCS	Oil Condition Sensor
ODM	Oil Debris Monitoring
PSD	Power Spectral Density
RPM	Rotations Per Minute
RSL	Partner RSL Systems
SPi	Sub Project i
STFT	Short-Time Fourier Transform
UP	Partner University of Patras
WPi	Work Package i
WT	Wavelet Transform

1. Project execution

1.1 Problem and scope

Aircraft availability, in-flight reliability and low cost maintenance are major concerns for helicopter operators. HUMS (Health Usage Monitoring System) implementing sensor based monitoring is an enabling technology seeking to provide a Condition Based Maintenance (CBM) relying on automated diagnosis/prognosis of the health of aircraft components. One challenge for HUMS is to implement automated low cost CBM systems as an alternative to periodic physical inspections. Existing HUMS technologies tend to generate high rates of false alarms due to the use of fixed alarm thresholds. Automated analysis of fleet operating data on engine and rotating parts recorded by on-board sensors is a major scientific direction to reach adaptive, reliable, and low cost HUMS systems. This direction is explored in project ADHER by,

- Addressing simultaneous Oil Debris Monitoring (ODM), vibration and Acoustic Emission (AE) monitoring using available sensors;
- Analysing new physical models for ODM and vibration characteristics of helicopter rotating parts (gearboxes, bearings, etc.) in order to calibrate "ageing effects" and "progressive emergence of failures";
- Designing and validating innovative software tools dedicated to self-adaptive diagnosis/prognosis of potential failures of helicopter rotating parts. Based on self-learning algorithms, these tools will analyse helicopter fleet data and their time evolution.

New physical models, and automatically learned functional relationships should improve links between sensor recorded features, helicopter usage, and operational regime characteristics.

1.2 Project objectives

The project main goal is to enable "fleet scale" health monitoring for helicopters, with robust failure diagnosis and possibly prognosis, relying on multi-sensor monitoring and automated analysis of sensor recorded data. The aim is to reduce false alarm rates and maintenance costs and to increase operational aircraft availability, enabling efficient scheduling of preventive maintenance.

The main scientific and technological objectives of project ADHER are:

1. To obtain a better understanding of the physical behaviour of ODM, vibration and acoustics sensing through new theoretical models and through a series of test bench experiments on helicopter gearboxes, especially in terms of "ageing effects" and of "progressive emergence of failures" for rotating parts.
2. To define innovative auto-adaptive algorithms enabling data-driven automatic learning to analyse empirical time evolutions of sensor data and to generate anticipative health diagnosis, taking account of vehicle context variables. To test these algorithms on helicopter fleet vibration data.
3. To evaluate the feasibility of automated health monitoring of helicopter fleets.

1.3 Work breakdown structure

The project work breakdown structure includes three sub-projects (SP) divided into work packages (WP):

- SP1 is concerned with project management and dissemination towards potential en users (WP1.1), project scope specification (WP1.2) and results assessment (WP1.3).
- SP2 addresses experimental data acquisition and physical modelling of three key categories of measurements known to have discriminating capabilities to monitor the health of helicopter rotating parts: Oil Debris (WP2.1), Vibrations (WP2.2) and Acoustic Emissions (WP2.3). The main goal of SP2 is to reduce fault non detection rate.

- SP3 focuses on innovative multi-sensor diagnosis software tools and explores the diagnosis potential of self-learning algorithms. SP3 addresses helicopter fleet sensor data base (WP3.1), self-learning tools for vibration based diagnosis/prognosis (WP3.2), multi-sensor data fusion for diagnosis (WP3.3), automatic elimination of defective sensor data (WP3.4) and evaluation of the developed prototype tools (WP3.5). The main goal of SP3 is to reduce false alarm rate.

1.4 Contractors

The project consortium includes five partners with complementary profiles:

Organisation	Country	Profile	Role in project
Eurocopter	France	Industry Helicopter manufacturer	Project coordinator. Coordinator of SP1 End user Industrial requirements. Impact analysis and exploitation
RSL Electronics	Israel	Industry Maintenance specialist	Technology provider Technological requirements. Helicopter fleet data base. Validation of diagnosis/prognosis tools. Impact analysis.
Cardiff University	United Kingdom	Research Mechanics	Theoretical research Wear related models. Correlations with experimental data.
University of Patras	Greece	Research Mechanics	Coordinator of SP2 Experimental research Oil debris monitoring. Vibration analysis. Acoustics emissions
Ecole Normale Supérieure de Cachan	France	Research Self learning methods	Coordinator of SP3 Theoretical research on self-learning algorithms for diagnosis and prognosis. Data fusion for multi-sensor based diagnosis. Automatic data correction and processing. Software tools development and testing.

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1.5 Work performed

1.5.1 Functional specifications of the project scope (WP1.2)

The objectives of this work package were to define the types of helicopter rotating part failures to diagnose or anticipate and the gravity levels to take into account, and to specify test scenarios and pragmatic norms for performance evaluation.

The partners have gathered information related to,

- Failure types and failure levels to be diagnosed and or anticipated;
- Vibration sensors to be used and vibration features to focus on;
- Additional sensors (Oil Debris + Acoustic Emission) to be used and guidelines for their use in the test platform;

- Failure test scenarios to address;
- Types, structure, quantity and qualification in term of representing “healthy” and “degraded” situations of fleet exploitable HUMS data available in the project;
- Main new functionalities to be addressed in dedicated software to support experts and technical teams in charge of fleet data exploitation;
- Norms and guidelines to be used to assess the quality of the final project results.

The collected information was organised and described in two reports:

- “Potential End-User Requirement”. This report contains in particular a table describing each requirement which was used at the end of the project to assess if end user expectations were satisfied by the ADHER results.
- “Project scope and functional specification”

1.5.2 Impact analysis (WP1.3)

The objective of this work package was to perform a synthesis of all the project results with the aim to target possible industrial and technological continuations of the project.

The main activity was dedicated to the assessment of the project technical achievements with an industrial point of view, which means that the results were not considered for their scientific value but rather for their potential application in the aeronautical field. Project result performances were assessed against the objectives defined at the beginning of the project.

Work was carried out with the ENSC software and the RSL Database. Because some data contents were unknown for security reason, it was necessary to identify all defaults in the database by using specific methods developed by EC in order to evaluate the pertinence of the self-learning software. Contextual data were unknown and thus physical links were unknown; this is why all variables had to be selected for the self-learning analysis.

Selection of variables for the learning phase and the diagnosis phase of the self-learning method is based on harmonics analysis of mechanical parts. It was found that some specific harmonics were relevant to detect unbalance and misalignment defects and that other harmonics were needed to identify other defaults like gear damage, tooth crack or bearing failures.

It was found that the multi-sensor fusion method increases signal/noise ratio and sturdiness. If sensors are of the same type, the gain is equivalent to 0.5 times the number of sensors. Thus, diagnosis based on a multi-sensor fusion method should mix signals from different kinds of sensors, such as accelerometers, microphones, acoustic emission sensors, etc.

In order to optimise the diagnosis software and to detect all failures described in the RSL database, it was proposed to select variables according to mechanical parts characteristics, such as gear and bearing parameters.

Other WP1.3 activities concern the analysis of test bench results and of sensors potential benefits.

a) <u>Oil Debris Monitoring (ODM)</u>

ODM is not an advantageous method compared to existing diagnosis methods in terms of precision and early detection ability. However, ODM is very interesting for industrial applications because it allows diagnosis based on a signal totally different from conventional signals that are mainly based on vibration monitoring. In this way, ODM can bring robustness and redundancy to HUMS, which are both needed to obtain agreement from airworthiness authorities for carrying out on-condition maintenance.

Another potential advantage of the technology is its ability to monitor damage progression on rotating parts, from their entry into service until their end. Indeed, quantifying the mass of the particles released in the oil allows the system to assess the extent of parts wear. Even if a lot of work and experiments will be necessary to demonstrate this on a real industrial application, ODM could be a good candidate to perform diagnosis and, above all, prognosis.

b) Acoustic Emission (AE)

AE methods offer several advantages over classical vibration monitoring. Experiments on a single-stage gearbox have shown that AE proved superior to vibration data for early detection of small defects in gears, and that AE provided improved early damage detection compared to vibration monitoring. Moreover, AE is able to detect natural pitting on gears whereas vibration monitoring cannot. Other intrinsic advantages of AE are:

- It is a non-directional technique: one sensor is sufficient in contrast to vibration monitoring which may require information from the three axes.
- It is not affected by structural resonances linked to the flying spectrum since AE detects mainly high-frequency elastic waves.

Coupled with vibration monitoring, it is very likely that AE based monitoring techniques can cover the main types of gear defects.

c) Oil Condition Sensors (OCS)

The parameters that OCS is able to measure (viscosity, density, temperature and dielectric constant) can determine if the oil needs to be changed or not. Potential cost benefits could be very significant because the oil is changed very often in practice, despite its good lubrication properties.

The work performed and results obtained in WP1.3 are reported in the document "Benefit assessment of ADHER results".

1.5.3 ODM: Physical models and bench testing (WP2.1)

The objective of this work package was to develop numerical models of the lubricated contacts taking place between the gear teeth in the bench tests carried out at UP. The bench tests consist of a reference test with standard gears followed by tests where defects are introduced to the gears. These are monitored from a point of view of Oil Debris (WP2.1), Vibrations (WP2.2) and Acoustic Emission (WP2.3). The Physical Models developed in WP2.1 were intended to be compared with the monitoring signals produced to seek correlations between monitoring signals and physical changes in the lubricated contacts brought about by the defects introduced.

The oil debris monitoring instrumentation was fitted to the rig. A commercially available ODM sensor was installed in the oil circuit. The ODM output is the online monitoring of the cumulative Fe mass and Fe mass rate, as well as statistics regarding the particles' average size and non-metallic particle detection. These data have been successfully acquired during the experiments carried out using the test rig setup.

Profile information for the gears was planned to be provided by in-situ measurement at UP with an existing profile meter. The alternative of replica casting was used.

A software for transient Elastohydrodynamic Lubrication (EHL) of rough surfaces was developed and adapted to deal with extreme pressure events at surface asperity contacts. This was necessary to deal with the relatively lightly loaded test conditions occurring in the rig as asperity interaction was found to occur well in advance of the Hertzian contact zone. These developments to the software were successful and allowed systematic evaluation of the transient EHL conditions between the gear teeth.

The primary development of software was completed by month 12. The activity in months 13 to 24 was concerned with applying the software to the tests carried out at UP using the surface profiles from the measured gear teeth, or from replicas of the gear teeth. For each gear set supplied by UP the following activities were carried out:

- Detailed measurement of tooth profiles from teeth of the gear set;
- Selection of representative profiles for analysis at each of the three load cases considered;
- Full EHL Analysis of all profile interaction pairs;
- Post-processing to obtain extreme film and pressure behaviour statistics;

- Post-processing to obtain transient surface strain energy for comparison with AE measurements.

In addition:

- Detailed tests of fidelity of surface profiles taken from gear tooth replicas by comparison with measurements from the actual gear teeth were carried out;
- A tooth contact wear model was developed to provide predictions of material removal for the unhardened gears used in the UP tests.

The work performed and results obtained are reported in two documents together with the activities and results of the other two work packages of SP2 (see next sections). The first document was a comprehensive interim report after 12 months of work and the second document is a final report on all the SP2 activities conducted during the project.

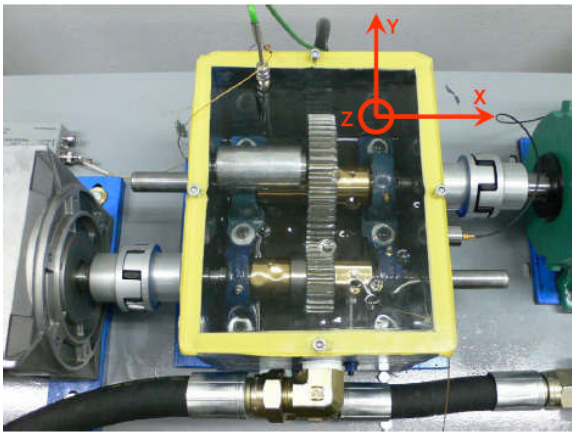
1.5.4 Vibrations: Bench tests and sensor data analysis (WP2.2)

The objectives of WP2.2 were as follows:

- Acquire experimental multi-sensor data (vibration, acoustic emission and acoustic microphone) on bench tests with a lab scale gearbox;
- Set-up and confirm the operation of a commercial ODM sensor in the oil-circuit;
- Assess the impact of certain contextual variables such as oil temperature, load, and revolution speed on vibration and acoustic microphone recordings;
- Monitor the degradation progression in four gear defect states in a series of multi-day tests;
- Assess the diagnosis capability of a plethora of candidate parameters extracted from post-processing the acquired vibration and acoustic microphone recordings in time and/or frequency domains;
- Acquire gear profile measurements periodically during the tests (input to WP2.1).

A test rig was built made of the following parts:

- 1 stage gearbox with two gears (25 and 53 teeth);
- 3- phase 5 hp motor controlled by inverter (220V, 9A, 50Hz, 1400rpm);
- Single phase generator with continuous power consumption control (load fluctuation), 4.2KVA, 3000rpm, 50Hz ;
- An oil pump of the wet type without oil recirculation;
- Ball bearing supported shafts.



Experimental gear box set up

Significant effort was dedicated towards the acquisition of the recordings. A special software was developed for the multiple recordings acquisition. An experimental procedure was initially proposed consisting of no more than 12-hour tests. The initially proposed test procedure proved too short in terms of gear damage and wear. Longer, multi-hour tests were needed in order to see damage on the gears.

Significant effort was also dedicated to advanced signal processing of the acquired waveforms. State-of-the-art signal processing techniques such as wavelet transform were used to extract additional features from the recordings. Wavelet transform decomposition was performed and wavelet-based parameters were extracted from all types of recordings. The goal was to assess which parameters have the most interesting behaviour and thus diagnosis capability during a test.

In parallel with vibration recordings an acoustic microphone was put on the test bench and acoustic measurements were conducted. The results were comparable with vibration recordings monitoring and the diagnosis value of both methods turned out to be more or less the same.

Successful tests were conducted at gears with artificially induced (via wire erosion) crack and at gears with chipped tooth to simulate spallation. An improved setup was designed and built, and additional tests were executed to verify the findings. Very interesting and realistic ODM behaviours were observed combined with interesting evolutions of specific parameters/condition indicators. Among the plethora of candidate parameter/diagnosis indicators that were proposed using several signal processing schemes a limited set was concluded that seems to work effectively in all tests. These parameters have shown an excellence in differentiating, and thus diagnosing, gear wear throughout the tests.

Tests to identify contextual parameters (oil temperature, speed and load) effect upon vibration and AE recordings were also performed. It was found that they do have an impact on both vibration and AE recordings, though the effect varies according to which parameter is investigated.

As mentioned in section 1.5.3, the work performed and results obtained within this WP are reported in two documents, a comprehensive interim report after 12 months of work and a final report on all the SP2 activities conducted during the project.

1.5.5 Acoustic emission monitoring: Feasibility study (WP2.3)

The objectives of WP2.3 are the same as for WP2.2. Acoustic Emission (AE) monitoring in rotating machinery is quite new and this feasibility study aimed to assess the possible advantages of the method compared to vibration and acoustic microphone monitoring.

According to ASTM E 750, acoustic emission is defined as transient elastic waves that are produced due to sudden energy release in a material or structure. Sources of AE in rotating machinery include impacting, asperity contacts, cyclic fatigue, friction, material loss, cavitations, etc. For instance, the interaction of surface asperities and impingement of the bearing rollers over a defect on an outer race will result in the generation of AE. These emissions propagate on the surface of the material as Rayleigh (i.e. surface) waves and the displacement of these waves is measured with an AE sensor.

Frequencies associated with AE activity cover a broad range between 20 kHz and 1 MHz, well above vibrations or acoustic microphone. Some advantages -in theory at least- of the method is that AE is non-directional and one AE sensor is sufficient to perform the task compared to other techniques such as vibration monitoring which can require information from three axes. Since AE is produced at microscopic level it is highly sensitive and offers opportunities for identifying defects at an earlier stage when compared to other condition monitoring techniques. A typical example is the proven ability to detect the earliest stages of bearing degradation. As AE only detects high-frequency elastic waves, it is insensitive to structural resonances and typical mechanical background noise (<20 kHz).

Acoustic emission proved quite capable of diagnosing gear wear and proved advantageous in cases of diagnosing propagating faults. AE showed ability in diagnosing crack propagation and superiority compared to vibration and ODM monitoring.

As mentioned in section 1.5.3, the work performed and results obtained within this WP are reported in two documents, a comprehensive interim report after 12 months of work and a final report on all the SP2 activities conducted during the project.

1.5.6 Base of vibration data recorded on rotating parts of a helicopter fleet (WP3.1)

The objective of WP3.1 was to develop a database of recorded vibrations of a large helicopter fleet to serve as foundation to support the development of automatic diagnosis tools.

Development was done in two steps:

– Functional and technical specifications of the database;

– Realization of the database using a standard DBMS commercial system.

Specifications are descried in the report "Functional and technical specifications of the helicopter fleet vibrations database".

Vibration data were extracted and converted from airborne-specific to the standard format. The extracted database includes data from 4 Helicopters where each helicopter had vibration raw data from 18 vibration sensors. The time period of the vibration database is from 2004 to 2006 corresponding to about 2000 flight hours.

The whole database size is about 100 GB. A first part of about 60% was delivered in October 2007 and the final database was delivered in March 2008.

1.5.7 Specification of self-learning software tools for diagnosis/prognosis based on vibration data (WP3.2)

The objectives of WP3.2 were,

- To provide a technical description of current state-of-the-art commercial software tools for vibrations diagnosis and prognosis;
- To develop a suite of advanced self-learning software tools for vibrations diagnosis and prognosis.

Nowadays, accelerometers and shaft speed sensors are installed on helicopter critical components and most of the data recorded by on board sensors on engine and rotating parts are systematically analysed after each flight to provide monitoring of the equipment and to help the diagnosis of potential failures as soon as possible. Monitoring systems are, most of the time, exclusively based on the analysis of the vibrations linked to shaft speed signals. In aeronautics, several contextual variables such as load, thermodynamics parameters or flights conditions are known to influence vibration regimes, and the evolution of these contextual variables are far from constant between flights or even during flights. Methods to analyse vibration data taking into account contextual information are missing from most of the monitoring software based tools.

Specification of self-learning software tools for diagnosis/prognosis based on vibration data have been written in Matlab and codes were developed.

Several pre-processing steps were implemented to extract relevant features from vibration signals:

- Sampling change of vibration signals with respect to the RPM signal in order to eliminate shaft speed influence on vibrations;
- Power spectrum estimation of the re-sampled signals to compute the order decomposition of vibration signals;
- Estimation of energies at given spectrum pointers to extract specific gear and teeth features.

An innovative approach for analysing helicopter fleet data was then introduced. This method is based on theoretical concepts of conditional entropy. Information theoretic methods were introduced and used to automatically select groups of the most relevant contextual variables for explaining each vibrations outcome descriptor. Information theoretic methods can be used to quantify the amount of information brought by any contextual variable to a given descriptor of the order frequency decomposition. Results showed that statistical variations in contextual variables have an influence on some descriptors of the order frequency signal, like the frequency of the major peaks or the energy at a given pointer.

An approach to monitoring has then been proposed based on self-learning algorithms. This approach is based on a first modelling of the descriptor outcome given the contextual variables. A score of risky behaviour can also be computed for each sensor and for each record.

Software development started during year 1 and prototypes were obtained in April 2008. The proposed diagnosis approach implemented by the tools was assessed with sub-sets of data extracted from the database supplied by RSL within WP3.1. Very encouraging results have been obtained showing that diagnosis could be performed with somewhat moderate performance levels. Improvements were subsequently obtained with the developments performed within WP3.3 and WP3.4.

Two reports were released concerning WP3.2: “State-of-the-art for off-the-shelf vibrations diagnosis software tools” and “Empirical impact analysis for contextual variables”.

1.5.8 Advanced aggregation methods for multi-sensor diagnosis (WP3.3)

The objective of WP3.3 was to produce a system allowing intelligent fusion between several detectors.

The development of the system was conducted in two stages:

– Development of an hybrid diagnosis system dedicated to vibration based detections;

– Development of an empirical system able to make a fusion of any kind of data (vibration, ODM, trends, etc).

A software was developed by ENSC, dedicated to auto-adaptive diagnosis of potential failures of rotating parts. Diagnosis is based on the analysis of vibration signals recorded by sensors from different groups given synchronized contextual variables. The software includes three parts: pre-processing of vibration signals, automatic learning and detection test.

The data base provided by RSL contains, for each of the four aircrafts, vibration signals recorded with 18 sensors belonging to specific groups, RPM and sampled values of 6 contextual variables (CV). All these data are synchronized for each of the recordings. Moreover, a table of pointers for each of the 6 sensor groups is available: the pointers reflect the internal structure of the corresponding rotating part of the helicopter.

Pre-processing consists in extracting pertinent data and features for the self-learning algorithm and detection tests, it includes 6 steps:

- Elimination of segments at the beginning and the end of each recording to eliminate defects related to recording start and stop.
- Re-sampling of vibration signals with respect to the shaft rotation cycle.
- Definition of the frequencies of interest. A pointer generates three (or more) harmonics.
- Selection of 6 to 10 time intervals for all the recordings.
- Computation of the vibration power spectral density (PSD) and mean CV value on each intervals for synchronized vibration/CV recording of a sensor.
- Computation of the energy value at each frequency of interest.

Automatic Learning is based on a statistical model of PSD values of the frequencies of interest for recordings without failure. The PSD value y at a frequency of interest calculated on an interval of a sensor recording is decomposed as $y = g(CV) + D$ in which CV represent the 6 synchronized contextual variables. g is called the contextual dependence function (CDF), it is defined on the space of contextual variables and g(CV) is the part of the PSD which can be predicted by the contextual variables. D is the residue of the decomposition, it is a random disturbance.

Automatic learning comprises two successive learning parts: determinist learning for CDF estimation and random part for the probability distribution estimation of D.

Detection test

A statistical fitting test method was proposed for failure detection from vibration recordings and synchronized contextual variables. The statistical model for vibration recordings without failure is given by $y = g(CV) + D$ as indicated above, with the CDF g and the probability distribution of D estimated by automatic learning. The joint probability distribution is also considered in the statistical test since the random disturbances D of different sensors of a same group are not a priori independent.

The test is performed with the null hypothesis “vibration without failure” and the alternative hypothesis “presence of failure”.

For recordings of a sensor group, all the PSD values y at the frequencies of interest of each sensor and CV on the intervals are calculated. If the pair (CV, y) is *statistically compatible* with the learned model the recordings are considered normal (without failure), otherwise a failure is detected. Vibration recordings of different sensor groups are processed and detected separately.

The signals of the database supplied by RSL have been tested and diagnosed with the software developed by ENSC. The diagnostic software was also tested by Eurocopter and RSL.

A first version of the software was delivered in April 2008. A second version was delivered in October 2008. The methods and test results are described in the report “Multi feature diagnosis by automatic fusion of vibration classifiers”.

1.5.9 Tools targeted for fleet scale analysis (WP3.4)

The objective of WP3.4 was to enable fast detection and elimination of defective sensors in order to avoid using their recordings as inputs to HUMS.

An auto adaptive methodology has been developed to diagnose degraded sensors. A software tool automatically learns the main shape characteristics of any given family of curves grouping the recordings of one given sensor. After learning is completed, the software tool can then be used to compute, for any new sensor recording, the main shape distortions presented by the observed curve and thus to generate a risk coefficient for possible sensor failure. The tool can also be used to evaluate the degree of normality of the continuous part of any spectral curve displaying spectral energies in terms of frequency.

The method includes three steps:

Pre-processing of signals

The vibration signature of a component is a function of its rotating speed. To uncouple rotating speed and vibration signature, the signal is re-sampled using synchronous sampling. Synchronous sampling means that the sampling interval is synchronous with the shaft rotation rather than time. Consequently, the resulting output has a fixed number of samples per shaft rotation rather than per second.

Extraction of descriptors by self-learning

The methodology focuses first on signal pre-treatments to systematically extract from sensors recordings a large family of computerized signal "descriptors". Then, by automatic learning from historicized sensor recordings, the algorithmic module computes an “empirical probabilistic model” able to emulate “normal" descriptors. This learning task is particularly efficient when the available learning database is of substantial size, which was the case in project ADHER. The learned "empirical probabilistic process model" (only based on historicized process data) can then autonomously compute a risk level, in terms of potential “abnormal signal", for descriptors extracted from any new sensor recording. The abnormality level is a risk estimate for the current signal to be abnormal. When applied on sensor recordings of vibration signals, this approach leads to the automatic computation of “production health indicators”, which provide Quality Risk Levels for each vibration variable monitored by a sensor.

Score and diagnosis

For each new signal recording provided by sensors, the diagnosis module can extract the adequate signal descriptors and then compute their risk levels. Whenever the current computed Quality Risk Level is higher than a fixed (adjustable) risk threshold, the quality diagnosis algorithm generates an alarm which can be displayed

The methodology and test results obtained are described in the report “Auto-adaptive elimination of degraded sensor inputs”.

1.5.10 Advanced software evaluation and testing (WP3.5)

The objectives of WP3.5 were to evaluate the self-learning software developed in the other WPs and to analyse the industrialisation feasibility of this software.

A preliminary vibration database for testing and evaluating the self-learning software tools was identified and organised in the testing-specific format. This database included real vibration data of a helicopters fleet that are not included in the database used for self-learning software tools development. The test database included data from time periods corresponding to both normal and abnormal behaviour of mechanical components. Two different sensor groups corresponding to main and tail gearboxes and two different failure modes corresponding to shaft unbalance and shaft misalignment were chosen for testing and evaluation. The 'normal' and 'abnormal' databases included respectively 230 flight hours from 6 helicopters and 120 flight hours from 4 helicopters. The number of failures for evaluation was chosen to be 5 (3 from main gearbox and 2 from tail gearbox).

The testing and evaluation results showed that the software performed well in detecting shaft problems and that improvement on false alarm rate should be obtained.

The feasibility of industrialisation of the self-learning software was analysed with an approach based on the experience of RSL in developing HUMS for helicopters. The system requirements and limitations were analysed. A rough estimation of required resources was done.

The work performed and results obtained in WP3.5 are reported in the document "Results of self-learning software testing".

1.5 Results

A set of results was obtained in compliance with the project scope, goal and scientific objectives. They have been qualified by the consortium as *'good'* or *'promising'* in the light of further investigations and industrial applications. The main project outputs are:

- End user needs/requirements and specifications for failure diagnosis and maintenance of helicopter gear boxes;
- Extensive test results and data from laboratory gearboxes;
- Advanced signal processing techniques applied to vibration and AE recordings;
- Identification of diagnosis parameters extracted from data processing and performance assessment of these parameters;
- Comparison of diagnosis indications from ODM, vibrations and AE;
- Identification of contextual parameters (oil temperature, speed, load) effect on recordings;
- Analysis and explanation of ODM behaviour;
- Data from tribological analysis of gear contact mesh conditions in laboratory gear tests;
- Modelling and analysis of gear mesh distress indicators from gear tests;
- Comparisons of tribological analysis data and distress indicators with condition monitoring signal analysis;
- Large base of vibration data recorded during flights of several helicopters in a period spanning over several years. Recordings include data from healthy and faulty situations;
- Methods to analyse large quantities of multi-sensor vibration data and to diagnose healthy/faulty situations. The methods use several techniques for data mining, automatic elimination of degraded recordings, data structuring, data aggregation, modelling of flight contextual variables, self learning based on healthy situations and diagnosis;
- Software tool prototypes to implement the processing techniques and the diagnosis method;
- Performance assessment of the developed methods and supporting tools;

- Assessment of potential operational benefits of the project results and feasibility analysis of the industrialisation of the developed methods and software tools in the context of helicopter maintenance;
- Preliminary plan for using and disseminating the project knowledge.

2. Dissemination and use

All the ADHER results listed in section 1.5 are considered by their owners to be either ‘Confidential Knowledge’ or ‘Proprietary’ (concerning collected data). This status is related to the owners’ exploitation strategy which is based on building upon the project results within the owners and other partners own lines of activities. Indeed, due to the high innovation level of some of the project outputs, the results are not mature enough and they need to be further developed or improved before being used in industrial or business applications.

The approach of the ADHER partners to public dissemination is to publish the general ideas and scientific approaches/methods and to keep confidential detailed descriptions, performance levels and software prototypes.

Dissemination of knowledge was based on three types of actions conducted through respectively a project web site, open publications and contacts with potential end users.

Project web site: www.adher-project.org

Papers and press releases

- Press release in eStrategies, UK Publisher, January 2008;
- T.H. Loutas, J. Kalaitzoglou, G. Sotiriades and V. Kostopoulos, ‘The Combined Use of Vibration, Acoustic Emission and Oil Debris Sensor Monitored Data coming from Rotating Machinery for the Development of a Robust Health Monitoring System’, presented in 4th INTERNATIONAL ASRANet COLLOQUIUM, 25 - 27 June 2008, Athens, Greece;
- Qiao H., Evans H.P. and Snidle R.W. “Comparison of fatigue model results for rough surface elastohydrodynamic lubrication”. Proc. IMechE Part J: J Engineering Tribology. 222, 381-393, 2008;
- Evans H.P. “Modelling mixed lubrication and the consequences of surface roughness in gear applications”. Keynote presentation, Nordtrib 2008, 13th Nordic Symposium on Tribology, Tampere, Finland, June 2008;
- Evans H.P. and Snidle R.W. “Comparison of fatigue model results for rough surface elastohydrodynamic lubrication”. Invited Presentation to Specialist Meeting at INSA de Lyon France on Rolling Contact Fatigue, August 2008;
- Press release in the EU Parliament magazine Research Review, November 2008.

Other papers have been submitted for publication in,

- T.H. Loutas, Sotiriades G., Kalaitzoglou I. and Kostopoulos V., Condition monitoring of a single-stage gearbox utilizing on-line vibration and acoustic emission measurements. Part I: Experimental setup, signal processing methodologies and diagnostic parameters, submitted in Applied Acoustics, September 2008;
- T.H. Loutas, Sotiriades G., Kalaitzoglou I. and Kostopoulos V., Condition monitoring of a single-stage gearbox utilizing on-line vibration and acoustic emission measurements. Part II: Experimental results, submitted in Applied Acoustics, September 2008;
- T.H. Loutas, V. Kostopoulos, G. Sotiriades, A. Kalaitzoglou, The combined use of vibration, acoustic emission and oil debris monitoring towards a more effective condition monitoring of rotating machinery, submitted in Journal of Acoustical Society of America, November 2008;
- Evans H.P., Snidle R.W. and Sharif, K.J. “Deterministic mixed lubrication modelling using roughness measurements in gear applications.” Under review, Tribology International, 2008.

Four more papers are planned by the partners to be submitted in 2009.

In addition, Eurocopter participated in the CIRI conference, in Montreal, Canada, in December 2007. The conference was about industrial risks in several fields. In this framework, risk management with new technologies and sensors allows improvement in predictive maintenance and new processes. EC presented several lines of work explored with the aim to achieve a Condition Based Maintenance solution, in particular the means used in project ADHER to improve oil analysis.

Contacts with potential end users

Eurocopter conducted several actions with end users of the company's products with the aim to promote the project, to present some results and to identify possible cooperation for work towards improved maintenance practices by building upon ADHER findings.