# ADVANCED VIBRATION DIAGNOSTIC SYSTEM AS THE PART OF HELICOPTER TECHNICAL MAINTENANCE

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**Abstract**

This paper considers different aspects of advanced vibration diagnostic system development, validation, promotion and application. Authors discuss the list of tasks for such system from the helicopter technical maintenance and repair point of interest. Main problems and possible solutions are considered, including uniform diagnostic platform for board and ground systems, life cycle traceability for helicopter aggregates, single survey diagnostics etc. The general view on advanced system is presented, based on the state-of-the-art and advanced techniques of vibration diagnostics and SHM. Resolution levels for helicopter power unit aggregates are considered based on solutions of the high-resolution diagnostics collected under VibropassportTM brand. Authors discuss operating demonstrators of diagnostic techniques as well as application cases as the main tools for advanced system promotion and market entering.

## 1. THE TASKS FOR ADVANCED VIBRATION DIAGNOSTIC SYSTEM

Condition based maintenance (CBM) is the dominant for development of helicopter technical operations and it renders on principal requirements for advanced helicopter diagnostic system. Other parts of helicopter life cycle such as manufacturing, overhaul and even utilization do also provide specific requirements for diagnostics. Taking both into account, the following tasks for advanced diagnostic system to be considered:

- Monitoring of power unit and transmission aggregates of a helicopter, including drive train, main gearbox, engines, main and tail rotors in flight operation;
- SHM of most damageable parts of a helicopter, including blades, tail boom, landing gears;
- High resolution diagnostics of aggregates on production and overhaul stages, as well as in operation in case of monitoring parameters abnormality,
- Capability to manage technical state of principal helicopter aggregates in field conditions, including rotors balancing and engines tuning;
- Common diagnostic, data and information platform for on-board (as part of HUMS), portable ground-based and stationary expended vibration diagnostic systems for each helicopter type;
- Applicability of portable VDT on non-equipped by HUMS helicopters, including:
  - o quick and easy installation and dismantling of measurement equipment on board within technical maintenance checks in field conditions for survey,
  - o no screws locking, dismantling of aggregates and violation of regulatory documentation;
  - o transportability of VDT set by air or other way;
- Fleet vibration data concentration and analysis based on monitoring and diagnostic center that maintains interactive vibration data base (IVDB), including:
  - o data concentration from operation (both HUMS and VDT) and stationary systems,
  - o IVDB links to both operators and manufacturers of helicopter, engine and other aggregates;
  - o regular update of diagnostic parameters thresholds based on operational and manufactural data;
- Monitoring and diagnostic services for helicopter operators:
  - o data concentrating and storing as well as thresholds update,
  - o monitoring of helicopter aggregates parameters,

- o single survey diagnostics on call,
- o full monitoring and diagnostics of operator's helicopter fleet,
- o fleet tendencies analysis based of diagnostic parameters and development of recommendations for manufacturers and MRO.

The monitoring and diagnostic system conforming to above requirements is not limited by flight safety tasks, but becomes part of helicopter technical life cycle including production, operation and utilization. What is the current situation and what is lacking?

## 2. PROBLEMS AND SOLUTIONS FOR ADVANCED DIAGNOSTIC SYSTEM

Problems of existing diagnostic systems are typical for all helicopter aggregates so, here below it is considered on an engine as an example.

### 2.1. Uniform diagnostic platform and life cycle traceability

The existing vibration diagnostic systems, both stationary and board ones carry out limited set of tasks. Most systems at manufacturer test rig are limited to run exceedance check of integrated vibration parameter of an engine. In case of exceedance, a typical system may indicate one of rotors as the sources of high vibration only.

In flight operation an alarm issued by HUMS, when integrated parameter exceeds threshold in flight, warns the crew about emergency. By means of ground station, the helicopter operator monitors vibration data of transmission mainly in order to detect a failure threatening to flight safety and to repair it on time. So, existing HUM based systems contribute to flight safety and to cost reduction of technical maintenance. However, this contribution is limited both by capabilities and by number of equipped helicopters.

Aiming at different tasks, stationary and board systems apply different concepts and diagnostic techniques. Therefore, these systems are not related directly and data exchange is very complex.

To conform to advanced diagnostic requirements the system needs unified platform of measurement, data collection and development techniques for any stage of engine's life cycle. Common techniques and parameters would allow smooth data exchange between all diagnostic systems and provide traceability of engine's condition during its life cycle starting from manufacture till utilization.

### 2.2. High resolution diagnostics

The main approach of state-of-the-art HUMS is finding abnormality in operation of aggregates that is determined using vibration parameters trend. Algorithms of abnormality identification use multiple observations during long operation therefore it may not detect a failure immediately after its appearance. So, there is a time lag between a failure and its indication by ground station of existing HUMS. Simplified models of vibration formation are another problem, because actual HUMS may not detect small scale faults. Therefore, these systems have a low resolution, high risk of false alarm and finally the lack of credibility to vibration diagnostics from helicopter operators.

Advanced diagnostic system must have a high resolution of each aggregate state that has to be experimentally validated. The high resolution diagnostics may not be substantiated on mathematics only and needs extensive research study. Based on experimental and theoretical researches, the appropriate vibration models were built up and then its adaptation to specific aggregate type was provided. The new techniques of data development and diagnostic parameters computation follow and then they are experimentally verified. These verified parameters allow evaluate each engine or helicopter aggregate and even its specific units, like bearing, compressor stage, oil pump, gear etc.

### 2.3. Single survey diagnostics

It is important, that advanced diagnostic system may allow state identification using single observation. It is necessary both for an engine tested at engine shop and for helicopter engines at a maintenance check even if it is a first test. Single survey diagnostics could become reality if any diagnostic parameter has common relative scale of state for all aggregates of the same type. In other case a scatter of individual vibration parameters would reduce resolution of a diagnostic technique because of expanded tolerances of thresholds.

### 2.4. Automation

A human role in any diagnostic system has to be left for final solution about engine's state for authorized and skilled persons. However, actual diagnostic systems require participation of high-skilled staff in vibration components identification, verification of primary diagnostic indicators, and consideration of operation mode. Most of helicopter operators do not have proper systems and such specialists so, vibration monitoring data (in case of HUMS equipment) is typically transferred to producer's monitoring center. This means, that typical helicopter operator must purchase and maintain expensive equipment, spend resources on engine testing, remaining dependent on diagnostic center. Such relations require high confidence level from both sides: the center must be sure in correctness of data collection procedures and operator has to believe in the diagnosis. Unfortunately, based on many reasons, credibility in these relations is still low. The portable vibration diagnostic units operated by high-skilled experts have better effectiveness in operation, but its application is limited for e.g. rotor balancing and simple vibration survey.

The advanced diagnostic system registers all data automatically and does not require any skilled staff for that. Depending on system version, the collected data may be sent to IVDB or be developed in-situ using VDT if an operator has skilled and authorized personnel for providing diagnostic solutions. One of the main privileges of an advanced system is application of those vibration diagnostic techniques that allow automatic detection of latent failures signs and its indication without attraction of diagnostic specialists. The only solution to be taken by specialist is how long and on what terms the detected fault could be tolerated. An important role of monitoring and diagnostic center will remain for fleet data analysis, thresholds update and recommendations development, but will even expand as it will concentrate data from VDT servicing helicopters without HUMS.

### 2.5. System redundancy for further upgrades

Requirements to diagnostics and applied methods of HUMS determine sensor network configuration. Along the way of HUMS development during helicopter operation life the system's software could be upgraded even without additional certification. However, hardware, and especially sensors, could not be upgraded without full modification and subsequent certification. Limited upgrade capability makes actual systems aged in few years, which is the main problem of board systems.

Advanced vibration diagnostic techniques provide surveillance of practically any engine unit and even single part, if the collected data is sufficient. The term of sufficiency means here:

- The spatial vector of vibration signal to be measured (simultaneously in 3 orthogonal directions in each measurement point),
- The expanded dynamic range of transducers (130…160dB),
- The expanded frequency range (up to 40kHz and even more),
- The synchronous signals of engine rotor revolution.

Redundancy of the projected monitoring system allows its further upgrade upon new promising techniques occurrence. If a measurement part would be adequate the diagnostic system could be upgraded without necessity in certification after modification of a software part.

### 2.6. Common solution of an advanced system

In order to eliminate written above limitations and to monitor helicopter aggregates during all life cycle an advanced diagnostic system shall combine all above discussed solutions:

- The advanced system has terminal and central levels,
- The both board and ground components may represent terminal level of the advanced system, as well as stationary system on a test rig;
- The common methodology and unified software is the core of both system levels,
- The relative scale of diagnostic parameters and its unitary boundaries for whole fleet, providing:
  - high resolution diagnostics,
  - single survey diagnostic capability,
- The automatic data processing up to decision making,
- The united vibration data base maintained by the monitoring and diagnostic center that:
  - interacts with operators, manufacturers of helicopter and aggregates, MRO;
  - provides boundaries for diagnostic parameters based on data from all participants,

• The both autonomous and centralized variants of the system application are available depending on customer needs and capabilities.

So, at helicopter production or overhaul stage the terminal level is represented typically as an equipment set fixed to the test facility of a main gearbox, of an engine or other aggregates. In field conditions the onboard and ground parts of HUMS equipped helicopters will be on the terminal level, whereas other helicopters need autonomous portable measurement set that will be capable for application within technical maintenance. The terminal level will be related to central level as monitoring and diagnostic center provided with data base.

## 3. ADVANCED SYSTEM – HOW IT LOOKS

### 3.1. System configuration

In order to achieve desired capabilities the advanced helicopter monitoring & diagnostic system must obtain essential improvements in comparison with actual systems, including advanced measurement equipment and perspective vibration diagnostic and SHM techniques (Figure 1). For light and unmanned helicopters the specific portable diagnostic system should be created. Rotating HUM part and SHM part with wireless data transfer will upgrade main system to become advanced one. Helicopter SHM system including sensor network will become the new part of HUMS and will include both rotating and stationary parts. The rotating part will cover main rotor aggregates diagnostics, but the stationary one will allow monitoring of a tail boom and landing gears.

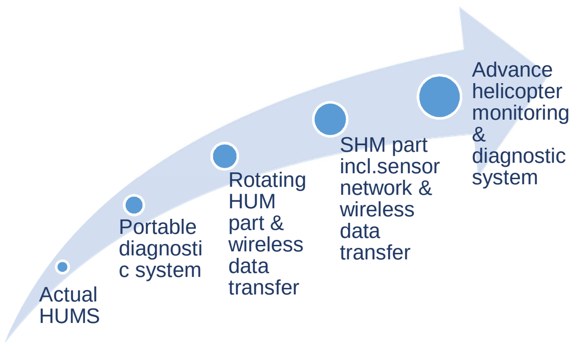



*Figure 1. A roadmap of advanced diagnostic system development.*

#### 3.1.1 Stationary part

State-of-the-art HUMS to be modified dramatically (Figure 2). As actual HUMS an advanced system have stationary DAU (1) in avionic bay receiving signals from stationary sensor network and from rotating data unit (2). Three-axial accelerometers replace single ones on a fuselage bottom (3), engines (4), oil fan (5), main gearbox (6) and tail gearbox (7). Only drive train of tail shaft (8) have two-axial accelerometers. Also tachometers (phase indicators) of engines, main and tail rotors relate to stationary DAU. Through embedded wireless receiver stationary DAU obtains data from rotating data unit.

Replacement of single accelerometers to tri-axial ones provides spatial vibration vector measurement in wide frequency and amplitude range allowing deep diagnostics of all aggregates of helicopter power unit using advanced vibration diagnostic techniques:

• The accelerometer mounted on a fuselage bottom (3) at vertical axis of a helicopter being used together with other accelerometers provides monitoring of landing gear functionality and fuselage integrity,

• The accelerometers and tachometers of engines supply data for monitoring of:

- o engine mounts serviceability,
- o aero & mass unbalance of a compressor and a turbine,
- o each compressor & turbine stage aerodynamic uniformity (blades aerodynamic capabilities failure caused by wear or damage) and compressor instability (surge margin lose);
- o hot gas path uniformity (gas temperature unevenness downstream of combustion chamber),
- o bearings & gears;

• The accelerometers of the oil fan (5) and main gearbox (6) using main rotor phase indicator allow its state monitoring as well as its balancing considering aero imbalance;

• The accelerometer and a phase indicator on a tail gearbox (7) provide gearbox and its bearings monitoring as well as tuning of the tail rotor,

• The accelerometers of the drive train (8) provides monitoring of shaft and bearings,

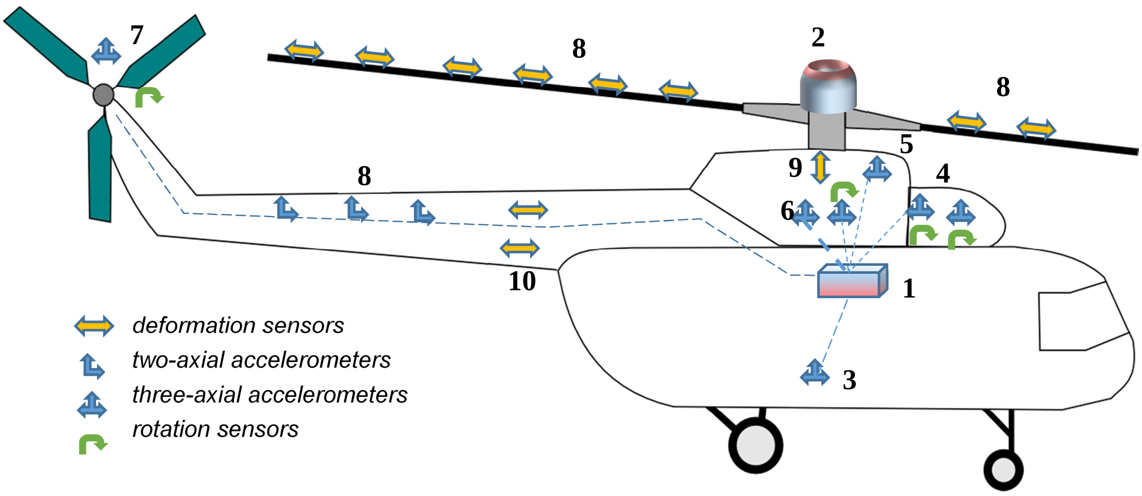



*Figure 2. Allocation of advanced diagnostic system components.*

SHM part of the advanced HUMS includes a sensor network (10), that is allocated around a helicopter. Depending on system's purposes, sensors could be allocated in each part of a helicopter, but they should be placed at least along the tail boom as the most critical structural part. Data from the sensor network provides a wide dynamic range signals allowing application of perspective Operational Modal Analysis (OMA) approach application for integrity monitoring of tail boom structure. Above approach uses multiple responses of allocated sensors for structure's modal properties estimation. In due course modal properties of each structural part is closely related with its mechanical properties that allows monitoring of its integrity and early detection of failure.

### 3.1.2 Rotating part

The rotating part of HUMS provides monitoring of main rotor and has both sensing and measurement parts. As shown on Figure 2, rotating sensing network consists of embedded dynamic deformation sensors (8) on each blade and same sensors on main rotor shaft (9) as well. Rotating DAU (2) provides signal multiplexing, conditioning, analogue-to-digital conversion and wireless data transmission to the stationary part (1). Principal scheme of board measurement system including rotating and stator parts are shown on Figure 3. *Board measurement structure*.

The measurement controller manages serial interrogation of dynamic deformation sensors of each blade and a shaft cyclically. Interrogation of specific blade sensors is determined according to algorithm of multi-patch OMA approach. Shaft's sensors are measured simultaneously. Wireless data transmitter sends DAU measured data to principal measurement unit located in avionic bay of a helicopter.

In order to supply a power for the rotating measurement system, an autonomous harvesting unit to be included in the system. The rotating and

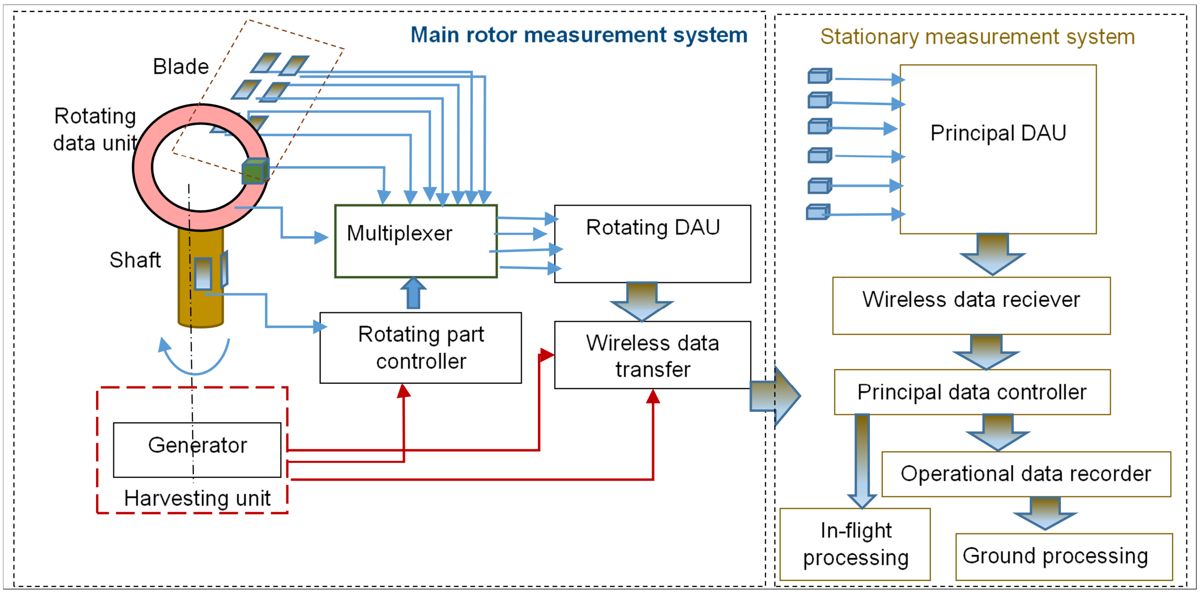



*Figure 3. Board measurement structure*.

stationary parts of DC generator are located on main rotor shaft and pitch control systems. The harvesting system supplies power to DAU, wireless transmitter and preamplifiers of sensors allocated along blades and shaft. The rotating HUMS also has own phase indicators mounted on each blade.

### 3.1.3. Signals management

The stationary DAU also applies serial interrogation of accelerometers groups aiming to reduce the number of expensive measurement channels. The principal data controller of HUMS manages data from both rotating part (received wireless) and stationary part. The data is going for in-flight processing to check alarm parameters and permanently for data recording.

Thanks to serial interrogation both stationary and rotating DAU have essentially less measurement channels than sensors quantity. Table 1 considers sensors allocation and measurement channels quantity of advanced system around a typical helicopter with 3-5 blades depending on its size.

**Table 1. Sensors in advanced HUMS.**

| Part | Sensor type | channels | allocation | Helicopter / blades qnty | | |
|---|---|---|---|---|---|---|
| | | | | light | med | heavy |
| | | | | 3 | 4 | 5 |
| Stationary | Accelerometers | 3-ax | engine 1 | 1 | 2 | 2 |
| | | | engine 2 | 1 | 2 | 2 |
| | | | MGB | 1 | 2 | 2 |
| | | | oil fan | 1 | 1 | 1 |
| | | | tail gearbox | 1 | 1 | 1 |
| | | | fuselage | 1 | 1 | 1 |
| | | 2-ax | drive train | 2 | 4 | 6 |
| | | total accelerometers | | 8 | 13 | 15 |
| | Deformation sensors | | tail boom | 12 | 20 | 24 |
| Rotating | | | main shaft | 2 | 4 | 4 |
| | | | blade (each) | 14 | 21 | 21 |
| | | total def.sensors | | 56 | 108 | 133 |
| | Rev./ phase indicator | | each blade | 3 | 4 | 5 |
| Stationary | | | engine 1 GG | 1 | 1 | 1 |
| | | | engine 1 PT | 1 | 1 | 1 |
| | | | engine 2 GG | 1 | 1 | 1 |
| | | | engine 2 PT | 1 | 1 | 1 |
| | | | main rotor | 1 | 1 | 1 |
| | | | tail rotor | 1 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| | | total phase | 9 | 10 | 11 |

For instance, the systems configuration on a medium size helicopter has 13 accelerometers, 108 deformation sensors and 10 phase indicators. However, minimum number of required channels (Table 2) are 15 in stationary part and 13 in rotating one. So, total number of measurement channels in advance system would not increase in comparison to the actual ones.

**Table 2. Measurement channels quantity for HUMS.**

| Helicopter type | light | medium | heavy |
|---|---|---|---|
| System part | min channels required | | |
| Stationary | 11 | 15 | 15 |
| Rotating part | 9 | 13 | 14 |

### 3.1.4. Portable diagnostic set

The portable diagnostic set may autonomously provide monitoring and diagnostics for such types of helicopters that do not have HUMS. Portable set includes a set of equipment:

- easy mounting vibration and additional rotation sensors,
- T-connectors for board tachometers taping,
- data acquisition unit (DAU),
- ruggedized laptop,
- tool set for easy mounting,

and software providing signals conditioning and transformation as well as data development, diagnostic parameters computation and exchange with monitoring and diagnostic center. Portable autonomous system applies techniques for monitoring and diagnostics of aggregates of helicopter power unit and transmission. A portable set represents a terminal level of advanced system for non-HUMS helicopters, just like a board system (HUMS) is a terminal level of actual HUMS.

Small preparatory works and vibration data obtained during engine test allow quick survey of helicopter aggregates diagnostics. Regular use of the portable system allows monitoring of above aggregates even on non-HUMS helicopters. Such portable system may be used for diagnostics of power unit and monitoring of helicopter structural parts. One portable system and skilled specialist may provide data collection for monitoring and diagnostic services for many helicopters.

### 3.1.5. Unification of an advanced system

Uniform methodical, software and information basis provide compatibility of both board and portable ground versions of the advanced system. The both systems use the same algorithms, partly software and most part of diagnostic parameters. That means three components of the advanced system: board, portable ground and diagnostic center could freely interact between each other using the same typical diagnostic parameters. By this way an advance system could cover all kind of helicopters whether it has the board system or not. Typically, only few percent of helicopters are equipped with board systems (HUMS) which operations may cause higher risks. The majority of helicopters do not have HUMS, due to economic reasons, so availability to perform its monitoring by portable systems becomes an important advantage for most of helicopter fleet.

## 3.2. Methodical solutions

In order to realize the ambitious tasks, an advance diagnostic helicopter system must have principal novelties, based on sophisticated vibration models and breakthrough data development techniques. As the most important some novelties could be outlined:

- prospective solutions for high-resolution diagnostics of power unit aggregates and helicopter transmission,
- multi-patching approach of OMA application is the novelty for SHM of helicopter critical structures,
- data pre-processing transformation of rotating blades deformations for its condition monitoring,
- other Modal analysis techniques application for portable ground SHM system.

### 3.2.1. Solutions for high-resolution diagnostics

The experimentally verified physical models and advanced data development techniques serve as the set of tools for diagnostic parameters computation. Such set of tools developed by *D un D centrs* was called *Vibropassport*$^{TM}$ [1]. There are three groups of physical models in the basis of Vibropassport$^{TM}$:

- spatial impulse models for bladed aggregates and epicyclical gears,
- dedicated models of bearing dynamic forces and vibration, and
- models of mechanical properties relation to modal parameters of each helicopter structure.

The advanced diagnostic parameters allow estimation of current technical state of each particular aggregate or even its separate component of power unit and transmission. However, even very accurate computation of parameter is not enough for exact diagnosis if thresholds of above parameters are scattered.

The advanced diagnostic techniques use relative domain for parameters scaling that could be common for all individual engines of the same type and sometimes for other types. The vibration components that reflect excitation are the basis for normalization of other components that indicate the state. In relative scale thresholds of diagnostic parameters are concentrated, not representing vibration levels, but rather transformative features of the aggregate. Figure 4 illustrates resolution levels of an advanced system for typical power unit and transmission.

With regards to an *engine,* the advanced system is capable to detect latent faults even if vibration levels did not change. Aero- and mass unbalance, compressor stability, technical state of each bearing and gear, compressor and turbine stages could be controlled. This approach differs from actual HUMS, allowing fault detection of gas generator or power turbine entirely when vibration levels exceed threshold. High-resolution techniques expand diagnostics abilities also for *main gearbox*, where on top to typical techniques of actual HUMS, the advanced system would monitoring of epicyclical stages and its bearings as well. A *tail rotor* to be balanced without additional tests using parameters computed based on flight data only thanks to advanced balancing technique. Problems of drive train shaft become evident on very early stage because of spatial vibration vectors measurement.

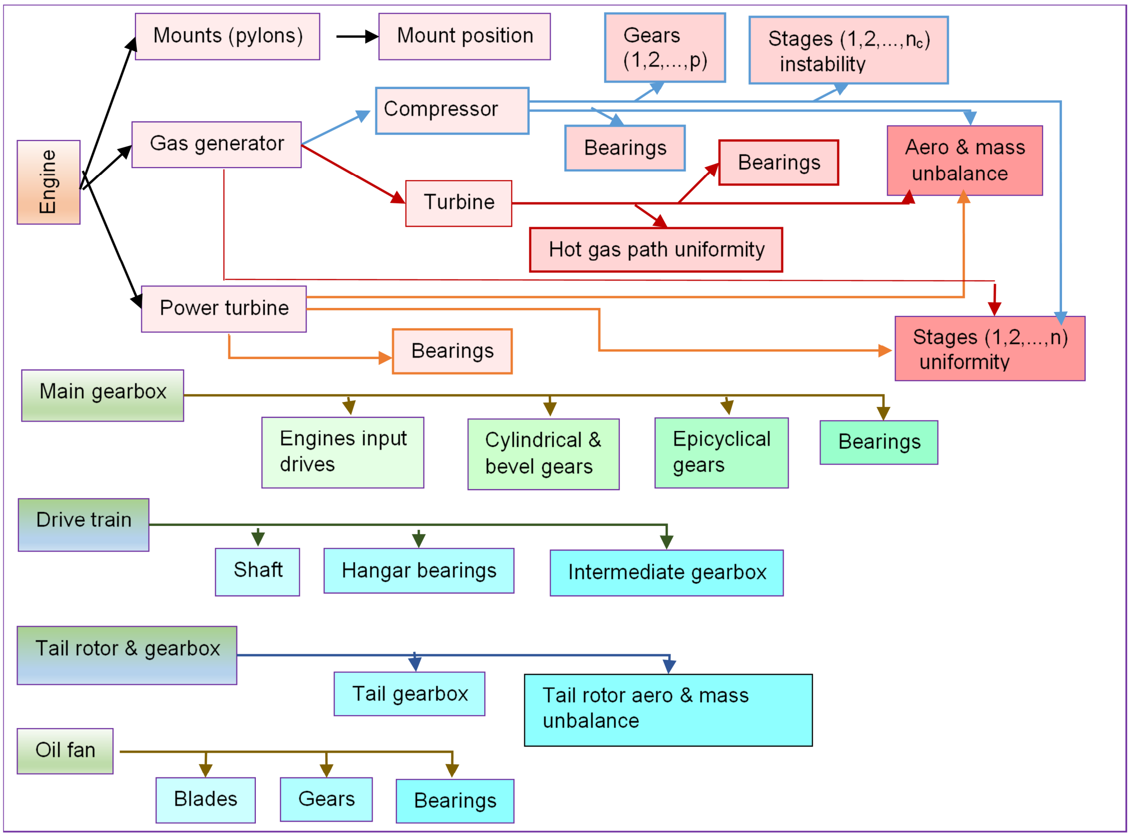



*Figure 4. Resoluti*

*on levels for helicopter power unit*

### 3.2.2. Multi-patching in OMA application

OMA techniques allow SHM of aircraft main structures, including stationary and rotating ones (like blades). Both monitoring of its integrity and early identification of developing failures are based on the relation between mechanical and modal properties of structural components. Typical modal parameters as frequencies, shapes and damping of structure's natural modes of oscillation provide efficient data for diagnostic parameters computation. To obtain these data two main tasks of modal analysis are to be carried out: efficient excitation and adequate measurement of structural response. OMA allows determination of modal properties of aircraft's structure using random excitation by airflow in flight. But this technique application requires the response to be measured in multiple points of the structure. So called multi-patching approach (serial measurements of sensor groups or patches) allows OMA realization using limited channels of the acquisition system.

### 3.2.3. Pre-processing for SHM

SHM techniques of the advanced system need pre-processing transformation to divide raw data into random and deterministic components. Random component of in-flight vibrations is used for monitoring of structural properties estimation using OMA techniques. These techniques provide structural diagnostic parameters characterizing both stator parts (as tail boom) and rotating parts (as blades and other rotor components). Deterministic vibration component provides application of Vibropassport$^{TM}$ diagnostic techniques to rotating aggregates and its parts, like swash plate bearing, main gearbox satellites and sun gear etc. Such way of vibration data utilization creates opportunity to monitor technical state of whole helicopter from landing gears up to blade tips.

### 3.2.4. Modal analysis for portable ground SHM system

For SHM of helicopters which were non-equipped by a board system, the portable system applies so called testing techniques of modal analysis that use relation between dynamic and mechanical properties as OMA described above. The portable system applies technique different from OMA if there are no embedded sensors on the helicopter. The method of impact modal analysis (IMA) estimates modification of the structure's state using its modal properties. By this approach, a hand impact hammer excites surveyed structural part in multiple points of its accessible surface, but only one or two 3-axial accelerometers are used for response measurement. The IMA technique could be realized using the portable system that has appropriate set of easy mounted sensors and special hammer for dynamic impact.

## 3.3. Distance from actual systems to the advanced one

Some tasks and functions of considered above advanced helicopter diagnostic system may look like uncertain future. But at the same time, many components of such system already exist and operate in actual systems. For example, as for the hardware of an advanced system, there is already reliable HUMS board equipment as well as portable ground sets for non-HUMS helicopters.

As for the typical components of actual HUMS, the range of Honeywell products could be considered, for instance Honeywell's Onboard VXP health monitoring system [2], Health and Usage Monitoring (HUMS) portable systems or Honeywell 8500C+ Balancer or many others. To conform to technical requirements of the advanced system, only resolution and memory of such typical products shall to be increased. Even measurements on the rotor could be managed by actual equipment, like Curtiss-Wright Operational loads monitoring unit with circular form chassis [3]. The last one provides power supply to the multiple sensors on the rotating part using its battery and allows registration of signals. However, up to this moment such unit does not have harvesting system for flight operation and is limited in sampling rate and resolution. There are no actual HUM systems using 3-axial accelerometers and sensor networks for SHM on helicopters. Another component of actual HUMS - monitoring and diagnostic centers maintained by helicopter manufacturers - collect and develop vibration diagnostic data and already provide monitoring services and recommendations to MRO and helicopter operators. Although resolution level of those diagnostic services is not high up to moment, such operation develops new relations between market key players.

Globally speaking, both hardware and data management parts of state-of-the-art vibration diagnostic systems operate well and could be developed up to advanced technical requirements quite easy as soon as these technical requirements are specified. However, methodical components of actual systems are well behind on the path to advanced system. Advanced techniques need much more time for development as adequate models and data development algorithms become the product of expanded research study and trials only. So mainly, the rest of the way to an advanced system is measured by the distance between required diagnostic techniques and available ones. Below some application cases of advance diagnostic techniques are presented to demonstrate its availability.

# 4. THE WAY TO ADVANCED SYSTEM

## 4.1. The demonstrator of advanced system

A promotion of the advanced system reminds a road, where two trains must meet on a halfway. From one side a helicopter manufacturer needs to move with further validation and succcessful applications of his product, from another side a potential customer like MRO needs confidence in new techniques capabilities, its practical applications and his future benefits. Only practical approval in natural conditions or similar may convince the helicopter operator and support producer's efforts. The operating demonstrator of advanced vibration diagnostic techniques is one of the most effective tools for both of the above mentioned tasks. Specially built facilities conforming to requirements mentioned in p.2 and similar to solutions offered in p.3 may be the basis for research of advanced techniques as well as for certification tests and may act as techniques demonstrators for customers.

The demonstrators briefly described below does not need to look like helicopter, but have to functionally include most of helicopter operating units, as engine, drive train, main gearbox, main and tail rotors and some other aggregates (fig.6-12). Each of these units has own electric drive and are controlled in operation modes similar to actual ones.The measurement and data recording systems of each operating unit satisfy technical requirements of advanced diagnostic system. To conform to main tasks - demonstration and experimental research - the construction of each unit is tuned to provide easy state modification of the aggregate. For this purpose any unecessary aggregates mounted on the casing of the unit as well as pipelines and cables are removed, if they do not participate in object's vibration generation. Such preparation allows demonstration of seeded faults influence on Vibropassport™ parameters response. The demonstrator may also work for validation of any vibration diagnostic techniques that supposed to be applied on helicopter operating units.

### 4.1.1. Engine diagnostic system demonstrator

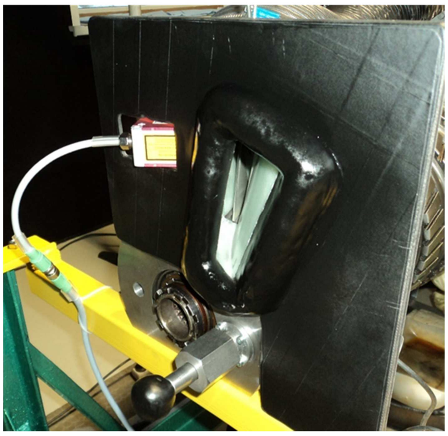
Preparation to the Vibropassport™ demonstration takes from few minutes till days depending on the engines part considered. For instance, diagnostic ability for uneveness of turbine flow duct could be arranged by prompt switching of air supply system through combustion chamber however, test fault implementation into the bearing could take a day or even more. The engine demonstrator is equipped by 3-axial acellerometers, the phase indicator, dynamic pressure and deformation sensors. There are also unique actuation system simulating impulse interactions between blades and vanes. The list of optional failures that may be simulated in the engine prototype is:

- ✓ Compressor or turbine unbalance
- ✓ Shadowed intake,
- ✓ Damaged blades or uneveness of blade rows of compressor stages,
- ✓ Reduced stall margin of separate compressor stages
- ✓ Uneveness of flow turbine upstream,
- ✓ Overlapping of turbine blade shrouds
- ✓ Damage of inner, outer ring or rollers/balls
- ✓ Damaged teeth of gears
- ✓ Misalligned gears.

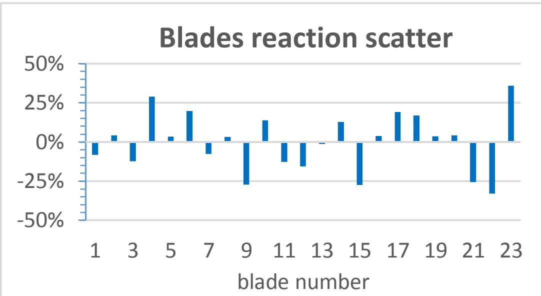
For tuning or calibration of testing damages and failures some auxiliary facilities are included to the demonstration set.

The test rig, that is a portable wind tunnel for scatter estimation of blades aerodynamic features (fig.6a) may be applied to a compressor blade row (assembled on a disc). This experimental facility allows estimation of each blade deflection in response to identical flow actuation. Difference of aerodynamic and mechanical properties causes variance of blade tip deflection. The test rig may also demonstrate to a customer the necessity to consider uneveness of components of engine flow duct. Fig.6b illustrates the scatter of blades mechanical reaction (deflection of blade tip) to identical aerodynamic loads of the worn blade row (1st compressor stage). The histogram shows -45%

… 35% variation of blades deflection caused by its properties scatter.



a)

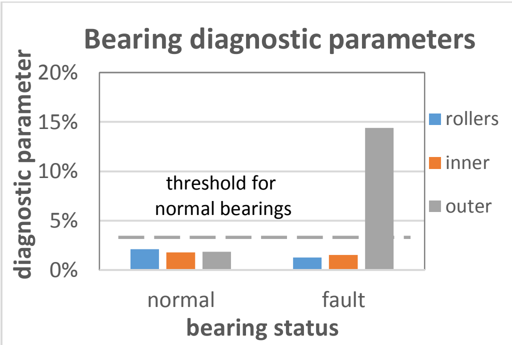



b)

Figure 6. Blades aerodynamic features estimation: a) – the test rig, b) – scatter of blades reaction to aerodynamic loads.

The specific bearing testing bench (fig.7a) provides tuning of bearing diagnostic technique. Implementing failures of different types and sizes it is possible to determine thresholds for diagnostic parameters for each bearing component: inner and outer rings, rollers/balls and radial air. As Vibropassport™ parameters have relative scale irrespective to the bearing size, experimentally determined thresholds could be applied for other bearing types. Figure 7b illustrates thresholds and actual values of diagnostic parameters measured within demonstrational experiment with testing faults implementation.

a)




b)

Figure 7. Bearing testing: a) – testing bench, b) – diagonstic parameter relation to bearing status.

The balancing rig (fig.8) plays its role in experiments and demonstrations related to aero- and mass imbalance modification.

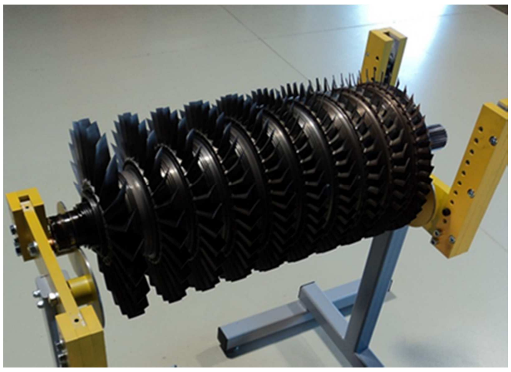


Figure 8. Balancing rig.

### 4.1.2. Demonstrator for drive train and tail rotor diagnostics

The drive train and tail rotor diagnostic demonstrator (fig.9) includes the actual drive train with supporting structure and the tail rotor. Supporting structure is able to simulate flight deformations of helicopter tail boom and its influence on operation conditions of the drive train. Depending on demonstration task the shaft or bearings could be defected or supporting structure could be modified to simulate operational conditions. All bearing supports of drive train are equipped by accelerometers and the tail gearbox is equipped by 3-axial accelerometer and indicator of rotation. Demonstration case of tail gearbox diagnostics could be carried out if artificial failure would be implemented. Also the demonstration of aero- and mass balancing of the tail rotor is available.

Figure 9. Drive train and tail rotor diagnostic demonstrator.

### 4.1.3. Demonstrator for main gear box and main rotor diagnostics

The most complex demonstrator (fig.10) includes the main gearbox and the main rotor for on-line diagnostics of both. Electrically driven gearbox allows demonstration of ordinary and epicyclical gears diagnostics. The demonstrator has own harvesting system for power supply of data measurement and acquisition unit as well as sensor preamplifiers. The sensors embedded in the rotating blades provide comprehensive data about blades oscillations. Operational Modal Analysis techniques applied to above data allow identification of blades dynamic properties and detection of its modification.

Also the rotor shaft, sun gear of gearbox, inner rings of bearings could be monitored on this demonstrator of diagnostic techniques.

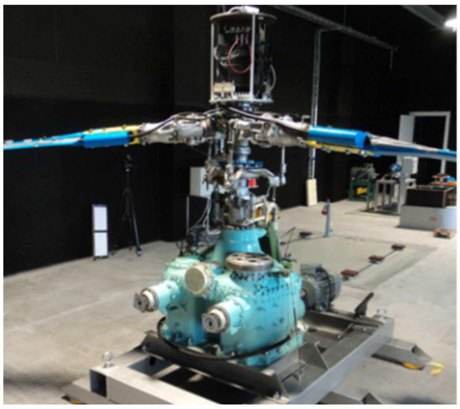
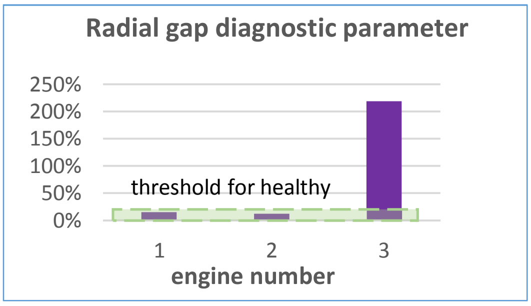


Figure 10. Main gearbox and main rotor diagnostic demonstrator.

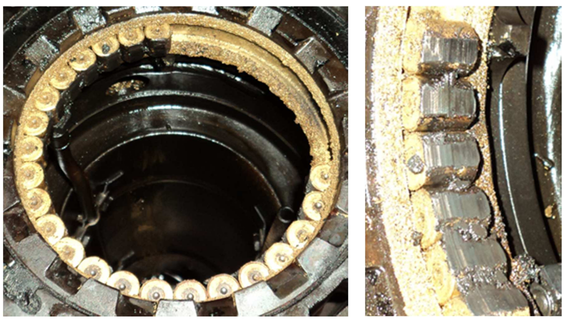
### 4.2. Success stories of Vibropassport™ application

The successful stories of advanced system application play important role for potential customer to realize the potential and benefits when such cases occur in natural circumstances.

For instance, aiming to monitor bearings condition Vibropassport™ technique was applied to turboprop engines within maintenance routines. Once, the diagnostic parameter surveying radial gap of bearings showed tenfold growth in the turbine bearing in comparison with threshold and other engines (fig.11). The recommendation for bearing replacement was not taken into consideration and 7 months later the engine collapsed (after landing).



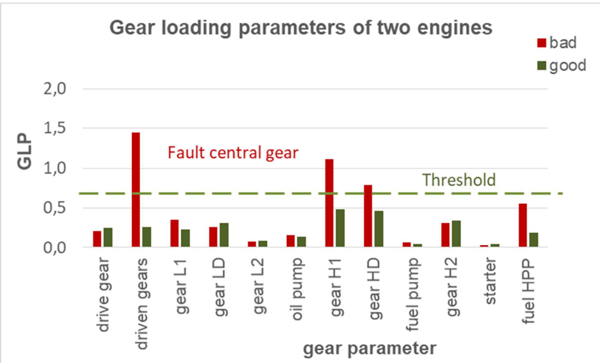

a)



b)

Figure 11. Bearing fault: a) - histogram of bearing radial gap parameter 7 months prior to collapse, b) – photo of the collapsed bearing.

One more case is the drive gear misalignment occurred at engine assembly in the engine shop. The system based on Vibropassport$^{TM}$ estimates operation quality of all engine gears during acceptance test. Diagnostic Gear Loading parameters (GLP) indicates how both interacting gears influence on dynamic loads of each gear. On the diagram (fig.12) green dotted line shows GLP threshold as average value around a fleet of this engine type. For normally operating gears threshold is about 0.6 – 0.7 and if GLP of some gear exceeds 1.0 it indicates the problem in this gear. Figure 12 shows GLP of all gears driven by gas generator for two particular engines. The “good” one has GLP of all gears below threshold (green bars), whereas the “bad” one (red bars) had exceedance of three central gears (driven gears, gear H1 and gear HD). Subsequent disassembly of “bad” engine allows discovering some violations of requirements to central drive assembly, like non-roundness, clearances etc. Actual tracks of diagnosed gears abnormal operation are shown on fig.12b.




a)

b)

Figure 12. Engine gears diagnostics: a) - diagnostic diagram, b) – photo of teeth damage.

### 4.3. Education for Customer’s motivation

Demonstrations of advanced techniques and success stories of its application could be not enough, if the customer does not acknowledge the needs in such system. The practice of advanced techniques implementation suggests essential efforts in education of customer’s specialists in regard to all aspects of advanced diagnostic systems. Only well-educated customer may analyze technical operation and technological processes to determine actual needs in diagnostics and formulate tasks to the system. Improvement in specialists’ skill aims to provide understanding the basic principles of latent failures detection using vibration diagnostic techniques, For instance, the damage detection of particular compressor blade may be discovered owing to modification of its wake in comparison to wakes of normal blades. Modified wake influences the series of pulsed loads to Guide vanes downstream actuating pulses of deformation or tension. Modification of pulse series changes corresponding vibration of the housing measured by the accelerometer. Understanding of vibration mechanisms may enforce customer’s credibility to vibration diagnostic techniques.

## 5. ACKNOWLEDGEMENT

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