UNIFIED MONITORING AND DIAGNOSTIC SYSTEM OF A HELICOPTER: THE CONCEPT AND THE OPERATING DEMONSTRATOR

Aleksey Mironov, Pavel Doronkin, Ivars Unte
info@ddcentrs.lv, D un D centrs (Latvia)

Abstract

The presented paper analyzes the situation with condition and health monitoring of a helicopter, including engines, transmission and structures. Authors discusses the concept and the operating demonstrator of unified condition monitoring system of a helicopter that is weight and cost effective. The concept considers unification of methodical and technical solutions, including application of specific sensors for costs and weight reduction. To validate the solutions chosen and to demonstrate its workability the demonstrator of unified MD system was built using the operating helicopter Ka-26.

1. HELICOPTER CONDITION MONITORING

Most on-board aviation systems use vibrations for condition monitoring according to regulations, like [1]. Typically for helicopters, the HUMS (Health and Usage Monitoring Systems) or VHM (Vibration Health Monitoring) systems provide monitoring of vibration parameters. Such systems monitor vibrations of main and tail gearboxes as well as bearings of tail shaft [2]. Although the HUMS and VHM have been proven to be effective, they have so far missed transmission defects [3]. Many typical failures of gearbox epicycles, main rotor or its blades are not observable by such systems at all.

Monitoring of aviation engines is provided by Condition Monitoring Units (CMU) that measure different parameters, including vibration. In GE's Prognostic Health Management program, for example, engine health is monitored by oil temperature and pressure parameters, fuel consumption and vibrations at rotor speed [4]. Customer service of other engine manufacturers [5, 6] slightly differs but the set of vibration parameters is still limited by vibrations at rotation speed. Aiming to condition based maintenance some engine manufacturers [7] extend the range of measured vibration parameters, for instance for bearing diagnosis. To allow such extending the manufacturers of avionics release new modules [8]. For instance, the ACMS module [9] implemented on CFM56-7B turbofan provides tracking of vibration peaks and detection of 3rd and 4th bearing vibrations. Unlike the latter, the typical CMU of helicopter engine monitors the vibration parameter at rotor speed that responds to large-scale faults only and may not provide diagnosis in-depth. Thus, state-of-the-art board systems allow transmission/engines monitoring but due to limited functions cannot yet provide predictive diagnostics of helicopters.

Unlike partially monitored transmissions and engines, the critical helicopter structures (like rotors or tail boom) are still out of permanent monitoring. Historically, the engine/transmission manufacturers develop the monitoring system and they are not interested in structural monitoring. The helicopter manufacturer, on the other hand, has no competence in on-board monitoring so, applies non-destructive techniques (NDT) only. The NDT, like ultrasound, eddy current, X-ray and others [10, 11] are used for helicopter structures during the maintenance check or the overhaul. In between such stops the structures remain unobservable for hundreds flight hours, while some latent defects may grow and increase risk of damage. Health Monitoring of aircraft structures allows reducing the maintenance and operational costs, which are about 25 percent of the direct operating cost of the helicopter [12], especially in the case of the ageing helicopter. To reduce above risks the permanent monitoring of helicopter structures is required both on ground and in flight.

Among the different approaches applicable for structural monitoring the modal analysis techniques look the most attractive, because it uses direct relation between mechanical and modal properties of structures. Monitoring the modal parameters of the structure these techniques allow detecting the changes of mechanical properties. For instance, in [13] the change of modal parameters of the composite structure was successfully used for damage detection. For the helicopter rotor blade the authors in [14] propose a network of autonomous wireless sensors that allow structural monitoring. The combined sensor's network was realized in [15] using both accelerometers and innovative optical Fiber Bragg sensors to study capabilities of load monitoring and damage detection. Author in [16] uses data acquisition from so called "smart layers" that are based on sensor networks distributed in the structure. In [17] the same author focuses on "hot spots", i.e. the spar areas where the cracks occur more often.

Looking for ways to monitor operating structures more and more researchers are choosing Operational Modal Analysis (OMA) methods that use only the output signals of vibrated structure (without actuation control). Due to above the OMA provides the main benefit for operating structures that do not need to be stopped for inspection. Downside, the OMA based monitoring requires an extensive sensor system, the number of which can be in the hundreds. There are different approaches to modal identification from ambient response, one of which [18, 19] considers versions of frequency domain decomposition. OMA applications in aviation are considered widely last decades, for instance [20] for the Paris MS760 airplane case, [21] for helicopters and [22] for helicopter blades. Successful trials make the OMA techniques the most promising approach to structural health monitoring (SHM) of operating objects. However, to apply the OMA based SHM system to a helicopter, a solution to some challenges must be found.

The global issue is the necessity to build up the SHM system in a helicopter in addition to existing CMU and HUMS/VHM. If to apply traditional tools of modal measurements (accelerometers with dedicated measurement channels) the SHM system may meet limitations in mass, sizes and costs. For instance, the DLR presented the system for modal parameters estimation of an aircraft using its taxiing [23]. The system that contains accelerometers, cables and equipment took up a lot of space, is heavy and its costs may run into the millions.

Other technical issue is the OMA application to rotating structures (rotors and blades) that is even more problematic, as there are additional complains with embedding the sensors network and with power supply.

There is also the methodical challenge of OMA application related to different factors that influence the modal parameters of helicopter structures. A helicopter operates in a wide range of operational (rotation speed, payload, flight speed) and ambient (temperature, wind etc.) factors, so the SHM system must account the above. For instance, discussing the experimental case of Ariane 5 launcher, authors [24] using OMA algorithm take into account the influence of changing mass (fuel consumption) on modal properties.

Therefore, the multiple challenges hinder the practical application of OMA based SHM system to helicopters.

To conclude the analysis, it can be said that actual board systems, like CMU and HUMS/VHM allow partial monitoring of the engines/transmissions but the helicopter structures remain out of control. The promising OMA techniques capable to structural monitoring require the additional board system with huge number of sensor and measurement channels. Such an increase in size and cost may make monitoring impractical. As a possible solution, the authors consider a unified helicopter vibration monitoring and diagnostic (VMD) system. The purpose of the study is to develop the concept of VMD system and to validate it applying the system demonstrator based on the operating helicopter.

2. UNIFIED VMD SYSTEM CONCEPT

The term “unified” means optimal combination of common and specific solutions for monitoring both structural and engine/transmission units of a helicopter. The unified methodological and hardware approach of this system uses dynamic signals for condition monitoring of each helicopter part. The system idea is based on relations between the technical state of rotating machines or structures, from one side, and its dynamic behavior, from other side. Vibration signals reflect the dynamic behavior of helicopter units, allowing condition monitoring.

Methodically, the principles of diagnostic (dynamic) passport allow the universal approach. The set of diagnostic parameters is the core of the passport created for each helicopter unit. Each diagnostic parameter is related to the technical and operational properties of the unit (or its component) and estimated using vibration data. The diagnostic passport contains typical and individual parts. The typical one includes known vibration diagnostic information that is common to all units of this type, while the individual part allows computing the actual diagnostic parameters of the specific operating unit and estimates its technical state.

Commonly, the typical part of diagnostic passport (for the specific helicopter unit) includes:
1) the set of diagnostic parameters characterizing the state of the unit,
2) the algorithms of diagnostic parameters computation from vibration signals,
3) the typical influence functions of operational and ambient factors on the diagnostic parameters,
4) the thresholds of diagnostic parameters for typical states,
5) the signal data recording procedures, considering typical operation modes (engine operation modes, flight profile stages, etc.)
6) the typical diagnostic report of the helicopter type.

Each diagnostic parameter of the passport has its normalized scale, in which the thresholds of typical states are defined. The algorithms provide computation of diagnostic parameters using measured vibration signals and the data about operation and flight modes that influence the unit’s vibration. For machines, the operating mode has the most impact, so the measured diagnostic parameter is compared with this mode thresholds. For structures, mainly the external conditions (temperature, wind direction and speed) affect the dynamic properties, therefore the measured diagnostic parameters of the structure are recalculated to reference conditions using typical influence functions of above factors. If the diagnostic parameter exceeds the threshold (typical for such units), it becomes the primary sign of the particular unit abnormality.

The models of machine and structure vibrations differ significantly, so their diagnostic passports have different principles. The Vibration Passport (VP) characterizes the technical state of specific operating unit (engine, gearbox, etc.) using methods of vibration diagnostics. The Modal Passport (MP) applies OMA techniques to monitor the health of helicopter structures, whether fixed (fuselage) or rotating (blades).

The unified VMD system providing both VP and MP application has the on-board and the ground parts (Figure 1).

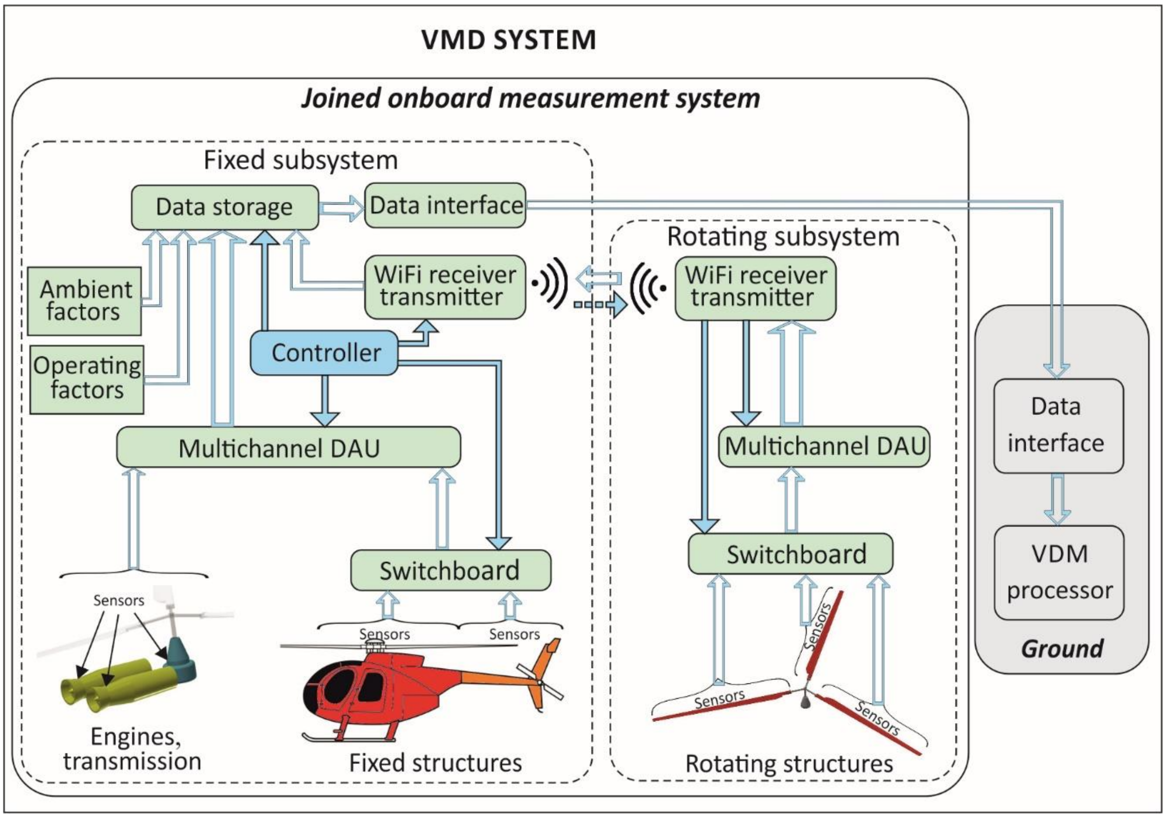


Figure 1.Block diagram of unified helicopter VMD system.

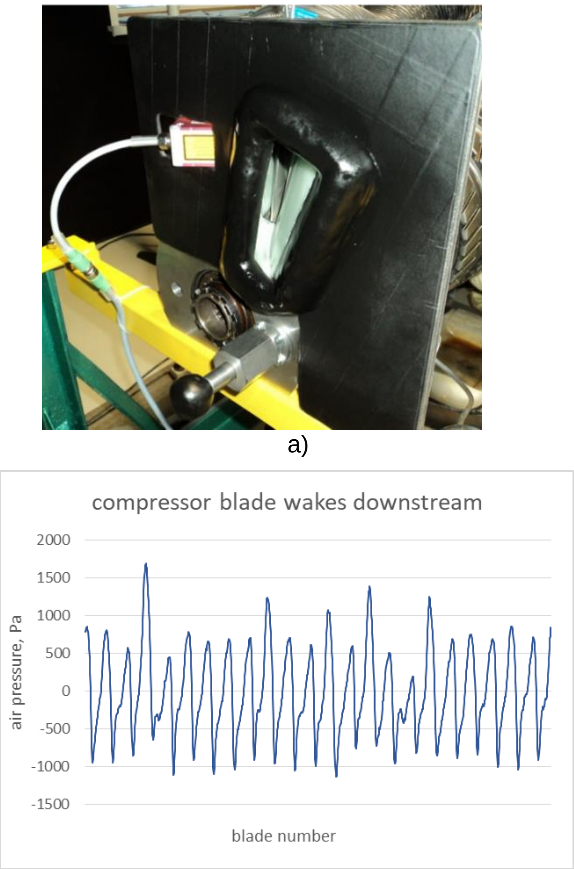
The onboard system controls the measurement, storage and transfer of dynamic signals of machines and structures. The onboard system includes fixed and rotating measurement subsystems. The fixed one uses two sensor types: accelerometers for machines/mechanisms and piezoelectric films for helicopter structures. Accelerometers mounted on the engines and the transmission units are connected to dedicated measurement channels of Data Acquisition Unit (DAU), while piezo films wired to switchboard that serially connects it to DAU. The rotating subsystem has only piezo films connected to rotating switchboard. The controller of fixed and rotating subsystems manage the channels switching in flight in accordance with the recording procedures that uses operating factors as inputs. The data measured by rotating subsystem is transferred wirelessly to the data storage, which accumulates also the data of fixed subsystem and the inputs like operating and ambient parameters. The controller manages the switchers and DAU of both subsystems according to flight data recording procedures. All the data recorded during the flight are the input data for processing by the ground part of VMD system.

The consolidated data management reduces weight and costs of the onboard system. First, the controller with the switchboards cyclically relay signals of hundreds sensors to only tenths measurement channels of fixed and rotating DAU. Second, the fixed DAU measures signals from both helicopter machines and structures. Third, the single data interface provides data transmission to the ground system part for further development.

2.1. Vibration passport

The VP is the tool for engine and transmission monitoring and diagnosis using the specific diagnostic parameter for each of the units. Vibrations of aviation jet engine have complicated composition of periodic and random components and heavily depends on structural and operational factors. So, the extensive studies are conducted to develop the diagnostic parameters of basic engine units such as compressor or turbine stages, rotor bearings, gears, etc. Firstly, the model is developed for each engine or gearbox unit that describes dynamic loads caused by physical interactions, and the vibration response measured by a sensor. Based on the model the set of diagnostic parameters are developed to monitor the unit's condition. The next is the algorithms development for computation of these diagnostic parameters. Both models and algorithms are verified using numerical modelling and the special test facilities based on a jet engine or gearbox units.

Some illustrations of above studies follow. Figure 2a illustrates the removable part of the test rig for researching the circumferential aerodynamic irregularity of compressor blades, and Figure 2b shows the profile of blade wakes downstream. The evident irregularity of blade wakes is one of multiple factors considered by the model of aerodynamic vibrations. This model, from one side, considers specific sequence of aerodynamic impulse interactions with dual deterministic and random nature. From other side, the model describes the broadband structure of the sensor response, caused by both modal properties of the casing and by spatially distinct vanes.

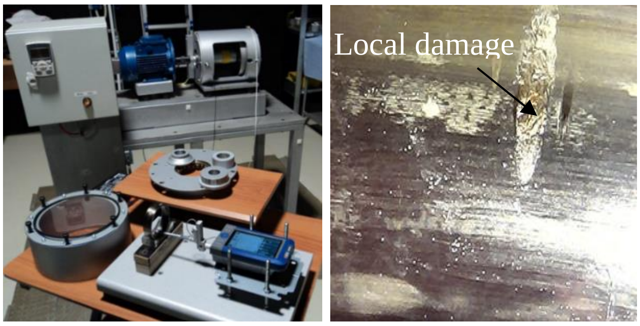


a)

b)

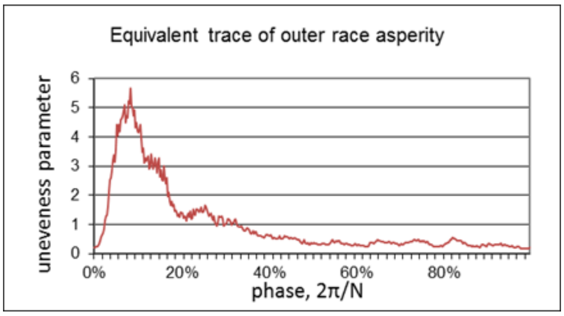
Figure 2.Test rig for the study of compressor blades aerodynamic irregularity (a), blade wakes profile (b).

Multiple powerful sources of vibrations (mainly gears and blades) complicate vibration diagnostics of engine's bearings. The advance model of bearing vibrations based on experimental studies allows its condition monitoring even with powerful background vibrational noise. The bearing's transfer function is the core of the model that considers both the random nature of impulse rollers-rings interactions and its modulation by quasi-deterministic loads from the rotor. The algorithms using the transfer function provide the adaptive technique of bearing diagnostics. Figure 3 shows the test rig for bearing vibrations research (a), the typical damage of the bearing outer ring (b) and the trace of this damage on the diagram of the diagnostic parameter (c).



a)

b)



c)

Figure 3.Test rig for bearing vibration research (a), damage of the bearing outer ring (b), damage trace on the diagnostic parameter diagram (c).

Epicyclical gears as components of main gearbox are the most complicated for condition monitoring. The study of such gears interactions has been carried out using the test rig shown in Figure 4a. Vibration modelling, including the typical damages, was based on the testing with seeded faults, for instance the damage tooth of sun gear (Figure 4b). The developed spatial-pulse model of epicyclical vibrations allows diagnosing damages, like the single damaged tooth or wear of all teeth.

a)

b)

Figure 4. Test rig for vibrations study of planetary gears (a), seeded fault of sun gear (b).

Both modelling and experimental studies allowed defining the general spatial-pulse approach to vibration modeling of most machine units, including stages of compressor or turbine, bearings and gears. Based on the developed vibration models, the basic diagnostic parameters were determined that are common to typical engine /transmission units. For each of above diagnostic parameter the basic algorithms were developed and verified experimentally.

For the specific type of jet engine or gearbox the *typical* VP may be formed using basic diagnostic parameters and its algorithms. For such purpose, these parameters and algorithms require a tuning stage, in which the kinematic, structural and operational specialties of this type are considered. The typical VP also includes the thresholds of healthy and typical damage states.

The *individual* VP of the particular engine or gearbox allows both monitoring and diagnostics of any of its unit. For in-depth diagnosis the individual VP does not need the history of the diagnostic parameter as the computed diagnostic parameter is compared to threshold of typical VP. For example, the VP [25] diagnoses compressor stages, bearings and gears of the particular engine using its single operational test. The VP of the main gearbox provides monitoring and diagnostics of its epicyclical gears [26]. High sensitivity of the VP approach to damages is ensured due to the signals from 3-axial accelerometers that are measured in the ultra-wide frequency (up to 30-40 kHz) and dynamic (110-130 dB) ranges.

The developed and verified basic diagnostic parameters of VP proved to be effective for different jet engines. Some systems applying VPs are used for vibration diagnostics of serial engines during bench tests. For instance, in case of high vibration the diagnostic system checks the technical state of helicopter turboshaft units using the VP diagnostic parameters [27]. Existing onboard measurement modules, like HUMS units, may essentially simplify application of VP based helicopter system.

2.2. Modal Passport

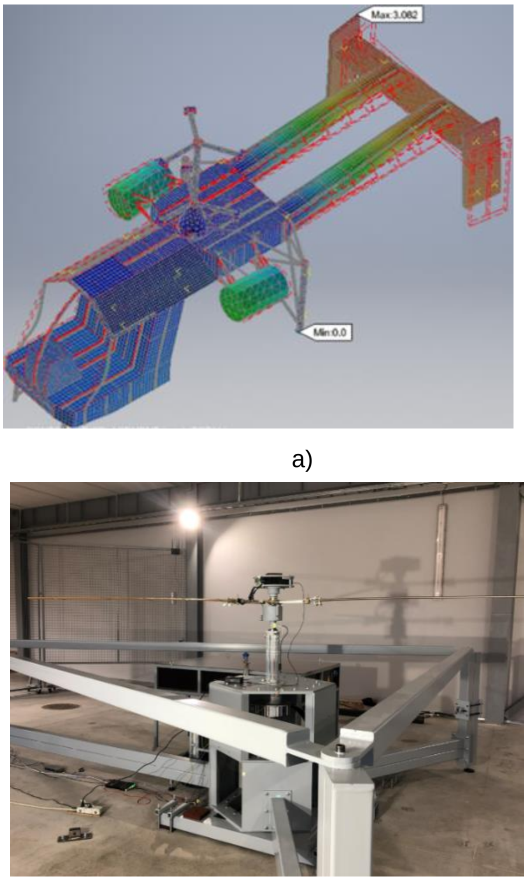
Contrary to the VP already in use, the MP approach is on its development stage. The MP applies the modal properties of helicopter structures for monitoring both fixed and rotating units. Mechanic and aerodynamic excitations cause the dynamic response of helicopter structures that characterized by the set of *M* natural oscillation modes. There are three basic modal parameters characterizing any m^{th} mode [28]: two scalar values - frequency f_m and damping d_m as well as the eigenvector $|s_n^m|$ describing the modal shape. The eigenvector has *N* measures provided by signals of sensors. The OMA techniques allow estimating the modal parameters using the data of multiple vibration sensors placed throughout the helicopter structures. The basic measure for monitoring is the change of modal parameters between an actual and reference states. The structural MP includes the modal parameters of the set of identified natural modes and the diagnostic parameters. The latter, for instance Modal Parameter Variation Integrated (*MPVI*), quantifies the integral change of modal shapes of all modes that included in the MP of the structure. If the MPVI of the structure exceeds the threshold, it is the indication of abnormality.

Ambient conditions (temperature, loads, humidity etc.) affects modal properties of operating helicopter structures that may cause errors of modal estimates. Therefore, the MP applies the influence functions that describe the modal parameter dependence on ambient factors. For instance, to monitor rotating blades, the modal parameters measured in flight are recalculated using the typical influence functions of such factors as rotation speed, temperature and payload. Applying such functions the MP reduces the risks of target miss or false alarm. The influence functions to become part of the typical MP are studied preliminary using modelling and specific testing procedures.

2.2.1. Typical MP

The development stages of typical MP differ from VP preparation. There are common algorithms and the commercial software for computing the modal parameters (frequency, damping, shape). The main effort is directed towards modal identification, because each helicopter type has the specific structure and different modal configuration. Therefore, each helicopter unit should be modelled, tested and its modal properties identified. Also, the influence functions, thresholds of typical states and the data recording procedures have to be defined.

The modal identification stage considers computing and identifying the modal parameters $(f_m, d_m, |s_m|)$ of the helicopter structures in determined frequency range. This range depends on the structure's configuration and requirements to the SHM system resolution. The modal modelling and dynamic testing of helicopter structures are the key tools of identification stage. Frequencies and shapes of modelled modes, like the sample on Figure 5a, contribute to modal identification of experimental data. The sample of the rig for rotating blades testing presented on Figure 5b.



a)

b)

Figure 5. One of modelled mode of helicopter fuselage (a), the test rig for rotating blades testing (b).

The structural testing considers series of *K* tests to reduce uncertainty. After computing the modal data measured in each test, the averaged modal parameters $(\bar{f}_m, \bar{d}_m, |\bar{s}_m|)$ are calculated. For instance, the equation (1) calculates the averaged eigenvector $|\bar{s}_n^m|$ of m^{th} mode from *K* tests

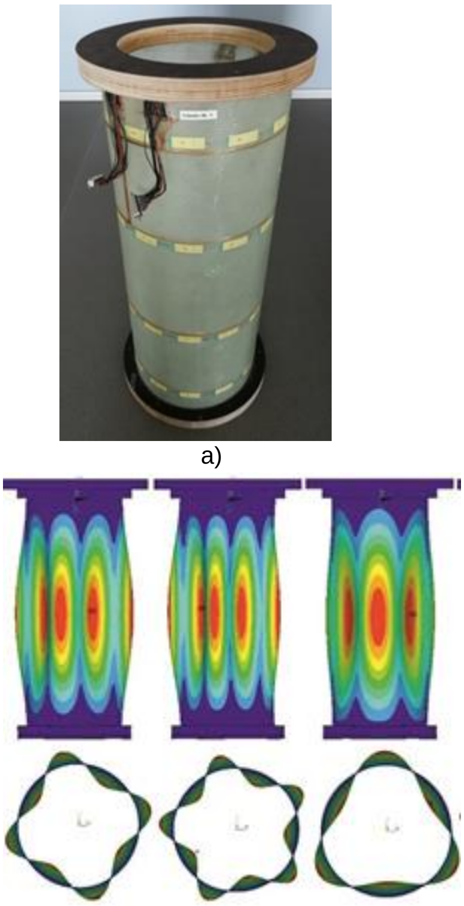
$$(1) \quad |\bar{s}_n^m| = \frac{1}{K}\sum_{k=1}^{K}|s_n^m|_k$$

The study of typical influence functions $F_m^p, D_m^p, |S_m^p|$ is another intense stage. These functions describe modal parameters dependence [29] on operating and ambient factors p_i in depend of its reference values $\bar{f}_m^0$, $\bar{d}_m^0$, $|\bar{s}_m^0|$

$$(2) \quad f_m^i = F_m^p(f_m^0, p_i);\ d_m^i = D_m^p(d_{m}^0, p_i);\ \ |s_m^i| = |S_m^p|(|s_m^0|, p_i)$$

To study influence of operating factors the different approaches are used. To research influence of common factors, like temperature, the specimen of similar structure and material may be used. For instance, instead of helicopter composite tail boom the test specimen of cylindrical shape may be used.

Figure 6a illustrates the composite specimen with embedded piezo film sensors prepared for experimental research of the ambient factors influence on modal parameters. Figure 6b shows some lobe mode shapes that FEM model of this specimen demonstrates.



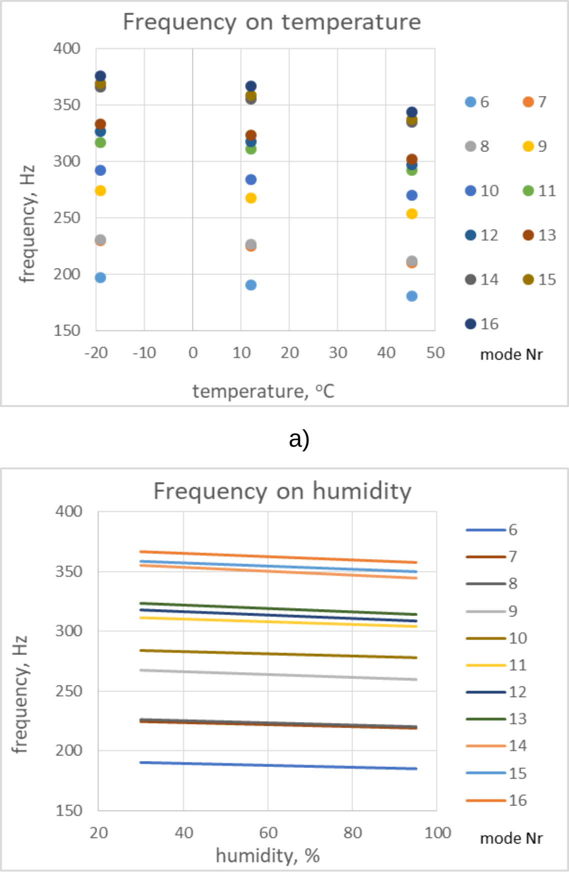
a)

b)

Figure 6. Photo of the composite specimen (a), FEM model lobe modes (b).

The study of operating influence functions requires natural tests. For instance, a centrifugal load is the most essential influencing factor for rotating blades and for its study the test rigs, like on Figure 5b, and natural helicopter test are used. Figure 7 illustrates the experimentally defined dependencies of modal frequencies of the composite specimen to temperature (a) and humidity (b) in the operational range.

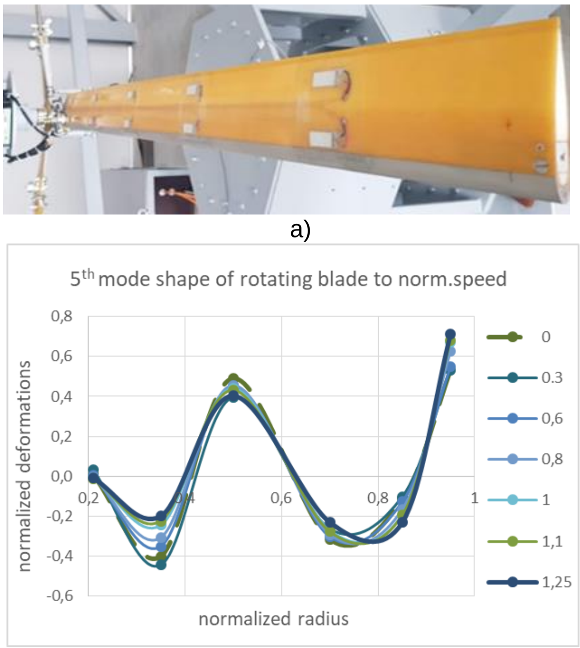
The vibration data measured in multiple points, like sensors on the blade (Figure 8a), allows studying the operational factors impact on the modal shapes in wide operation range. The diagram on Figure 8b demonstrates variation of the 5th blade flapping mode (defined along the normalized radius) in depends of normalized rotation speed (from 0 to 1.25 of nominal). After the influence functions of the specimen have been defined (in lab tests) they are verified on the actual helicopter blade and then included into typical MP.



a)

b)

Figure 7. Influence of temperature (a) and humidity (b) on the modal frequency of the composite specimen.



a)

b)

Figure 8.The composite blade with embedded sensors (a) and family of 5th flapping mode shapes of rotating blade in depend of rotation speed (b).

The stage of thresholds definition includes modelling and experimental study with seeding faults. The threshold of the modal parameter is normalized to its reference value so the threshold exceedance indicates a change of structural state. Each *mth* mode has thresholds for three modal parameters: frequency $[\delta f_m]$, damping $[\delta d_m]$ and modal shape $[|\delta s_m|]$. There are also thresholds of diagnostic parameters, like above mentioned $[MPVI_0]$. The sensitivity of the SHM system is estimated also at this stage taking into account the uncertainty of modal parameters computation [30]. For instance, the shape uncertainty $|\sigma s_n^m|$ for *m*th mode is calculated taking into account standard deviation for each of *N* eigenvector values measured in *K* tests

$$|\sigma s_n^m| = \sqrt{\sum_{n=1}^{N} \{\sum_{k=1}^{K} [|s|_k - |\bar{s}_n^m|]^2/(K-1)\}/N} \tag{3}$$

The final stage of typical MP preparation aims to optimize testing and measurement procedures in flight. Rotating helicopter parts induce multiple periodic components that affect the accuracy of modal identification. These components ratio varies in flight in depend of engines and rotor operation modes. The optimal procedure of signals registration in flight is developed to reduce influence of the flight and engine operation modes. Such procedure optimizes cumulative excitations ranges against modal frequencies within flight profile.

When the typical MP (for helicopters of one type) is developed, the structural health of particular helicopter may be monitored. The monitoring process includes data measurement in flight, computing the typical set of modal parameters, recalculating it applying the typical influence functions and comparing the modal parameters to typical thresholds.

2.2.2. Individual MP

The individual part of MP provides structural monitoring of the particular helicopter. To compute modal parameters the MP uses flight data measured at defined operational modes and various ambient conditions. The thresholds are defined at reference conditions, like hover flight and International Standard Atmosphere. Therefore to compare the measured modal parameters with thresholds the individual MP recalculates the computed modal parameters to the comparable ones. To bring the flight modal parameters $(f_m^i, d_m^i, |s_m^i|)$ to comparable ones [26], the MP applies typical influence functions $F_m^p, D_m^p, |S_m^p|$

$$\hat{f}_m = f_m^i/F_m^p(p_i); \quad \hat{d}_m = d_m^i/D_m^p(p_i); \tag{4}$$

$$|\hat{s}_m| = |s_m^i|/|S_m^p(p_i)|$$

As the typical MP includes the set of *M* modes the individual part estimates the change of each one. The normalized change of *m*th modal parameters is estimated as difference between comparable (4) and reference values

$$\delta f^m = \hat{f}_m/\bar{f}_m^0 - 1 \tag{5}$$

$$\delta d^m = \hat{d}_m/\bar{d}_m^0 - 1$$

The modal change (5) is recognized as meaningful if it exceeds the uncertainty of the modal parameter. For scalar modal parameters (frequency and damping) the difference is compared with the threshold added by uncertainty of this parameter

$$\delta f^m > [f_m] + t * \sigma f^m \tag{6}$$

$$\delta d^m > [d_m] + t * \sigma d^m$$

where the t=1…3 defines the probability (68%…99,7%) of an estimate.

The geometrical sums of frequency and damping meaningful changes (6) are the scalar diagnostic measures of modal change

$$\delta f_\Sigma = \frac{1}{M}\sqrt{\sum_{m=1}^{M} \delta f^m} \tag{7}$$

$$\delta d_\Sigma = \frac{1}{M}\sqrt{\sum_{m=1}^{M} \delta d^m}$$

For normalized eigenvector (describing modal shape) the meaningful change is estimated for each *n*th comparable element (4) considering its computation uncertainty

$$|\delta s_m^n| = |\hat{s}_m^n| - |\bar{s}_m^{n0}| > [|\delta s_m^n|] + \mathrm{t} * |\sigma s^m| \tag{8}$$

The modal parameter variation of *m*th mode is calculated using (8) as

$$MPV_m = \frac{1}{N}\sqrt{\sum_{n=1}^{N} |\delta s_m^n|} \tag{9}$$

Then MPVI as integral measure of helicopter structural (modal shape) change is computed using (9)

$$MPVI = \frac{1}{M}\sqrt{\sum_{m=1}^{M} {MPV_m}^2} \tag{10}$$

Thus, the individual passport makes it possible to detect changes in the state of the structure by a comprehensive set of modal parameters.

3. OPERATING DEMONSTRATOR OF THE SHM SYSTEM

The demonstrator of a unified VDM system was built on the working helicopter in order to validate in practice the feasibility of monitoring techniques. The considered study is devoted mainly to application of SHM part of the demonstrator, so main objectives are:

- the practical check of demonstrator’s feasibility and affordability for SHM,
- the performance check of the joint measurement and data transfer system on the operating helicopter,
- the study of the ambient and operational factors impact on the modal properties of helicopter structures,
- development of the data recording procedures in flight,
- practical assessment of the system's sensitivity to seeded faults of operating helicopter.

3.1. Demonstrator of unified VMD

The basics of the SHM demonstrator is the joint signal measurement system and the "passport" monitoring methodology. The operating Kamov-26 coaxial helicopter (Figure 9) becomes the technical platform of the demonstrator. The signal measurement system of the demonstrator implements most of the functions supposed for the unified VMD system presented above on Figure 1. Only the functions of in-flight data accumulation and of automatic control of measurement procedures are missed in the demonstrator. The operator, instead of the controller, remotely controls the signals commutation according to the measurement procedure.

Figure 9. The helicopter Kamov-26

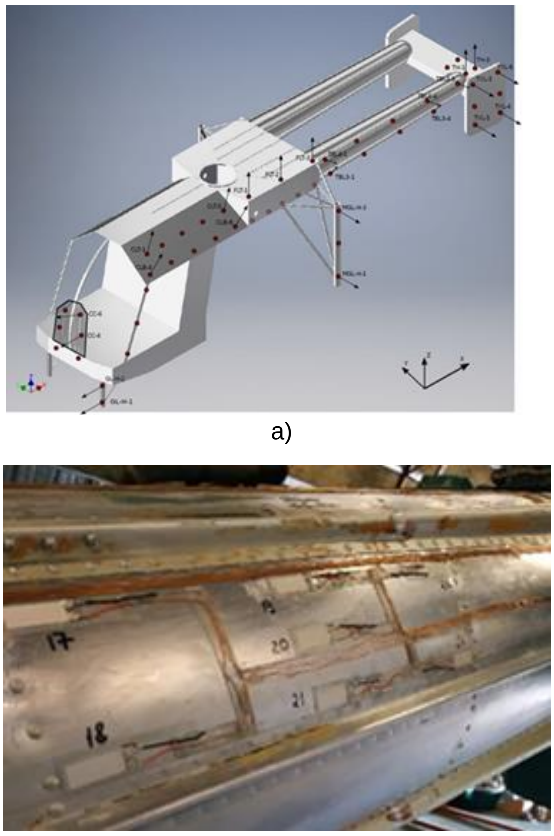
a) b)

Figure 10.3-axial accelerometer (a), piezo electric film (b).

The onboard system has fixed and rotating subsystems. The fixed one measures and collects signals from all non-rotary helicopter parts including engines/transmission and structural units of the fuselage. Three-axial accelerometers (Figure 10a), mounted on each engine and on the main gearbox provide vibration signals in wideband frequency range. These transducers are connected to the main DAU, located in the helicopter cockpit. Signals of these sensors are supposed to be used by the VPs of engines and main gearbox for condition monitoring and detailed diagnostics.

The simple, light and cheap piezoelectric film sensors are chosen to measure vibrations of structural units (Figure 10b) to overcome technical and economic challenges of OMA based SHM [31]. Electrical signal of the piezo film, glued on the structural element, is related to surface strains and dynamic behavior of its neutral axis. Reflecting variation in time of the neutral axis curvature, the sensor provides data for modal identification. The piezo films with a thickness comparable to a paint coat allow it's embedding into helicopter structures while minimizing the size, weight and costs of sensor network. Another benefit of piezo film within the unified system is that the same measurement units of onboard equipment measure signals of both accelerometers and piezo films. Such universality simplifies consolidation of the measurement system. The compact and inexpensive piezo films network as well as the united measurements contribute to affordability of unified VDM helicopter system.

The demonstrator includes fixed and rotating subsystems. The SHM part of the fixed subsystem includes the network of 194 piezo films that characterizes dynamic behavior of the helicopter structures. The sensors are located throughout the helicopter (Figure 11a), including the fuselage body, landing gears, tail boom and stabilizer [32]. Preparation of the sensor network is illustrated on Figure 11b, where piezo films and wires are installed on the preliminary cleaned surface of the tail boom. The connector collects the wires of all sensors embedded into the tail boom and via interconnection cable relates to the common bus that unites sensors of all structural units into a common helicopter network. The sensor network aggregation allows disassembly of helicopter units for seeding the test faults and for surveying. The cables of helicopter units ends at the central fixed switchboard that is located together with fixed DAU in the cockpit. The operator remotely controls the switchboard that relates the groups of piezo films to 48 channels of the main DAU. Unlike the conceptual VMD system, the data measured by the system demonstrator is transferred to the ground station on-line without storing.

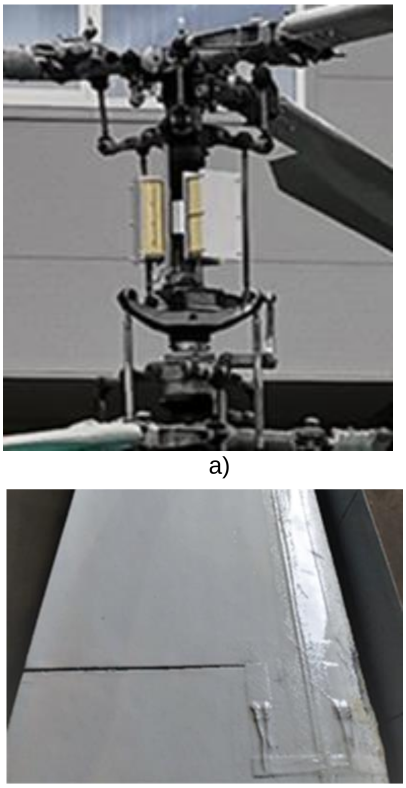


a)

b)

Figure 11.Piezofilms layout on the helicopter (a), sensors network on the tail boom (b).

The rotating SHM subsystem is mounted on the upper main rotor. The data processing unit of rotating subsystem is mounted on the rotor's shaft as it shown on Figure 12a. The unit includes the switchboard, the 12-channel DAU with the battery for autonomous power supply and the wireless data transmitter. For actual helicopter's rotating subsystem the harvesting unit would be added that containing DC generator and a control unit [33]. Each rotor blade has the network of 15 piezo films located on the low-pressure surface and protected by composite layer (Figure 12b). Flexible protected cables connects sensors of upper rotor blades to the rotating switchboard. The remotely controlled switchboard serially connects signal groups to the DAU. There are also four piezo film sensors on the rotor's shaft that allows monitoring the shaft stresses. The data measured by rotating subsystem is transmitted wirelessly to the ground station.


a)

b)

Figure 12.Rotating subsystem: rotating DAU on the shaft (a), sensors on the blade (b).

The ground work station (VMD processor) receives data from the onboard systems (both rotating and fixed) and concentrates all data development functions. In actual research stage the demonstrator's activity is devoted to helicopter structures monitoring and Figure 13 illustrates the stages of modal data processing and damage identification.

Up to date the data processing in the ground system includes both automatically operating SW and manual operations. The techniques and SW for full automated processing are under development.

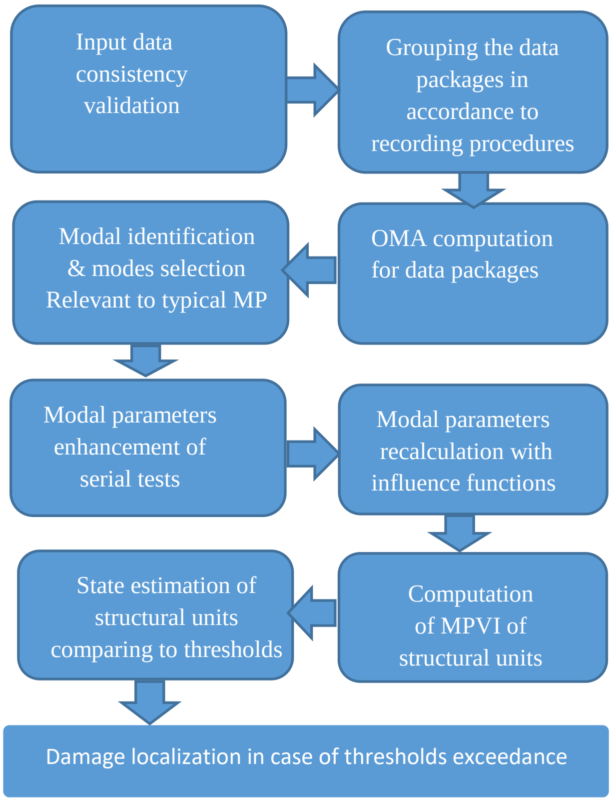


Figure 13. Modal data processing diagram.

3.2. Testing the SHM system demonstrator

The experimental study of the SHM system demonstrator includes three group of tests:

- the check of the on-board systems functionality,
- the structural dynamic and field tests of the helicopter structures,
- the tests with seeding faults to estimate the resolution abilities of the SHM system demonstrator.

3.2.1. Systems functionality

The functionality indicator of the demonstrator is trouble-free operation of all sensors and equipment units in quasi-flight operational modes of helicopter. The quasi-flight is the basic test mode and this means hover mode when helicopter's landing gear wheels are off the ground. Being chained to the ground anchors, the helicopter is dynamically balanced by the pilot, who controls pitch-gas. The results of helicopter serial tests confirmed the stable workability of the sensor network and the board equipment at all available operation modes. Also the consistency of the input data was verified and confirmed.

3.2.2. Dynamic tests

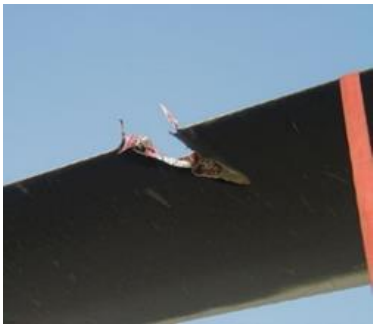
The structural dynamic and field tests were aimed at researching the dynamic (excitation and modal) properties of operating helicopter. The excitations (mechanical and aerodynamic) are studied to determine its main indicators: intensity and probability distribution in frequency ranges of interest. The defined excitation in different operation modes allows developing the signals recording procedures. The modal properties were studied for both: the separate structural parts (blades, rotor) and the entire helicopter. The combined application of modal modelling and dynamic tests allows modal identification of the helicopter structures. For modal properties research two basic techniques were applied. The Experimental Modal Analysis techniques consider excitation control and computation of Frequency Response Functions. These techniques were used to study the modal properties of separate helicopter structures. The OMA methods do not consider excitation loads therefore, they are applied to definition of modal properties of the fixed and operating helicopter. The quasi-flying test was the main type of helicopter field testing. As a result of dynamic testing the set of identified modal parameters became the basis of the helicopter MP.

3.3. Diagnostic resolution

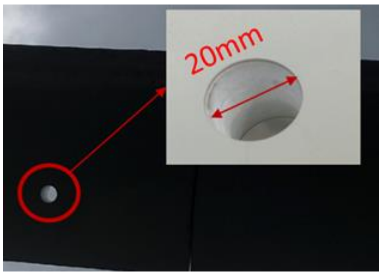
Diagnostic capabilities of the SHM demonstrator depend on sensitivity of the MP techniques to structural failures and uncertainty of data measurement and computation. As it was studied [29], the higher the order of structural model used by MP, the potentially higher the resolution of the SHM. The number of sensors (on the fuselage or on rotating blade) determines the order of the structural model. Therefore, the more sensors, the less failure scale could be detected. Practically, the number of sensors for each helicopter unit depends on technical capabilities. To estimate the sensitivity level of the MP technique, the numerical experiment for the blade model was conducted. The virtual hole was modelled in FEM model of the blade and the difference between modal parameters of “damaged” and reference states was calculated using equations (5-10). To diagnose the state the estimates of frequency change δf_Σ and modal shape change *MPVI* (discussed further in section 4) are compared with thresholds of the reference state.

For operational blade the threshold cannot be less than the uncertainty level of modal data obtained using the SHM demonstrator [30]. In accordance with eq. (3) the standard deviation of modal parameters measured in serial tests characterizes the uncertainty of the SHM demonstrator. As the study aimed to determine the lower limit of sensitivity of the SHM demonstrator, the smallest seeded faults were used that slightly affect the structural integrity [31]. Based on literature review [34, 35] two typical kinds of damage were chosen: in the rear blade part, like on Figure 14a and as a tail boom fatigue crack. The drilled hole in rear blade part (Figure 14b) and the skin cut in the tail boom of the helicopter (Figure 15) simulated the actual failures. To reduce influence of ambient factors the series of five retests was conducted for each structural state. The averaging of modal measures according to eq. (7-10) reduces uncertainty of modal parameters and arises sensitivity of the system. For health estimation the uncertainty levels of SHM data were computed for the blade and the tail boom of the helicopter.

The test series with blade included 20 tests at four structural conditions: two reference states (*ref1* and *ref2*) at different days and two damaged states (with hole): 20mm (*def20*) and 30mm (*def30*).



a)



b)

Figure 14. Blade natural damage (a), seeded fault (b).

The seeded faults (skin cut) of the tail boom was made in the root part (Figure 15a) between the alongside power elements looking for the minimal detected damage. There are illustrations of two seeded faults: first - 20mm length (1mm width) and larger one - 60m length (2mm width) shown on Figure 15b.

a) b)

Figure 15. Seeded faults in the tail boom: damaging zone (a), cut for 60мм (b).

The testing procedure for each structural state considered 5 cycles of helicopter operation with 10 min in quasi-flight mode. During the cycle the onboard system measures the signals and transfers the data to the ground station, where they are recorded for following development. The ground system provides post-processing in accordance with the MP algorithms, including signal data processing, modal identification, computation of modal and diagnostic parameters and finally diagnosis.

3.4. Discussions

The tests of the onboard SHM equipment confirmed operability of all its components in the working helicopter. The shielded sensor network provided signal measurement without visible traces of interference. The switching of signals to measurement channels took place without signal interruptions or bursts. The rotating DAU transfers the data to the main unit wirelessly in real time.

Analysis of the modal parameters from the specific test series allowed to determine typical influence functions for the fuselage and blades. The influence functions of structural units, computed using the testing data, have different behavior in depend of material and configuration. For example, for fuselage metal structures the ambient temperature played main role, changing more the global modal parameters (frequency and damping), and had less influence on the modal shapes. The solar radiation, which can cause a significant temperature gradient between the fuselage parts, may affect the modal parameters significantly. For composite blade structures, the static loads that is function of rotation frequency and pitch, mainly influence on modal parameters.

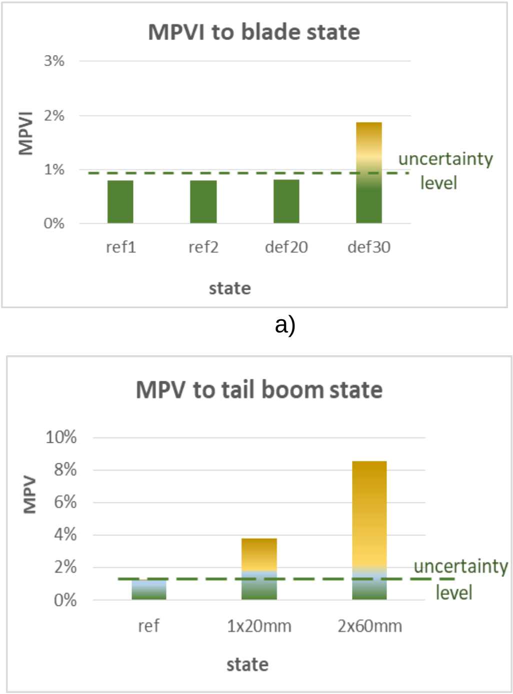
Aiming to optimization of measurement procedures, the helicopter excitations were studied. The research detected the dependence of vibration components on the helicopter's operational mode. As excitation (especially periodic) may cause the modal identification errors, the optimal procedure was developed for the quasi-flight mode of operational tests. The optimal measurement procedure considers the registration of signals at a certain combination of operational modes of the engines and the blade pitch.

Practical assessment of the system resolution is based on the results of numerical and tests analysis. The numerical model of blade defect allows estimating the change of modal diagnostic parameters caused by the seeded fault. The change of modal frequencies (δf_{Σ}) for the blade model was calculated according to equation (7) and the modal shape change *MPVI* – to equations (9, 10). The virtual 30mm hole (equivalent to removed 0,03% blade's mass) causes the integrated change of modal frequencies δf_{Σ} - 0,24% and for shape change *MPVI* - 2,5%.

For actual structures the system resolution also depends on uncertainty of measurements and computation. The estimation of the systems uncertainty is based on analysis of the experimental data and takes into account the implemented test procedures. In particular, the ratio between sampling frequency and measurement time, as well as the number of repetitive tests play a determining role. The modal shape parameters have decisive role for state identification so, the following discussion concerns the modal shape uncertainty. The uncertainty level that SHM system has for the blade modal shape estimation is about 1% and for the fuselage modal parameters - up to 2% of normalized scale. That means the SHM demonstrator would be capable to identify the seeded fault, if the MPVI exceeds above levels. As *MPVI* of numerical blade damage (2,5%) is higher than estimated level of the modal uncertainty (1%), it is assumed that the actual defect must be detected by the system.

The diagrams on Figure 16 illustrate the results of experimental tests with seeded faults. Columns indicates *MPVI* value in comparison with uncertainty levels (green dotted line). For the blade, the *MPVI* of both reference states (*ref1, ref2*) and of the smaller damage (*20mm*) remains below the uncertainty level. The *MPVI* of 30mm damaged blade (Figure 16a) exceeds the level, indicating the damage. The larger scale of tail boom damages more evidently demonstrates the *MPVI* effectiveness (Figure 16b) that multiply times exceeds the threshold.

So, the uncertainty level defined for measurement and processing procedures of the SHM demonstrator can be considered as the system's sensitivity thresholds. Thus, the results of numerical and natural tests proved applicability of the MP as a methodology and the SHM demonstrator as technical implementation of the unified VDM system for helicopter monitoring in-flight.



a)

b)

Figure 16. Diagram of diagnostic parameters: rotating blade (a), helicopter tail boom (b).

4. CONCLUSIONS

The concept of unified VMD system for helicopter is proposed as the optimal solution for condition and heath monitoring in flight. The concept considers the common methodological framework and a joint measurement system of vibration signals. The "passport" approach considers common methodology of vibration diagnostic techniques for both rotating machines (VP) and helicopter structures (MP). In the study, the emphasis was made on SHM systems operating in flight, as there is no such system existing to date. The joint measurement system is based on combination of new and justified technical solutions, including piezoelectric film sensors. For validation of unified VMD concept the operating demonstrator was built based on Kamov-26 helicopter. The MP for a working helicopter was created for the first time using the results of research study (FEM modelling and dynamic tests). The helicopter MP includes the set of identified structural modes, the influence functions, the measurement procedure and the thresholds of key modal parameters. The actual MP allows health monitoring of all helicopter structures in flight.

The full-scale sensitivity tests of the OMA based SHM system were conducted. Using data measured in quasi-flight mode the SHM demonstrator was able to identify the seeded faults in the rotor blade and in the tail boom. The results of the study confirmed the effectiveness of MP as the tool for condition monitoring of rotating and fixed helicopter structures in flight.

On the top of technical and methodical solutions the organizational efforts are necessary for further promotion of the VMD system. As the joint board system measures and collects data from engines, transmission and structures, the common interests of both helicopter and engine manufacturers must be found. For instance, the co-operation project could be effective, if the designer of avionics develops the board system under technical requirements of both engine and helicopter manufacturers. Within such project it will be easier for both manufacturers to master the passport approach: VP for engines and gearboxes, MP for helicopter structures.

ACKNOWLEDGEMENTS.

This research was funded by the European Regional Development Fund Project No. 1.1.1.1/20/A/016 “A prototype of typical structural health monitoring system of operating objects for condition based maintenance.”

REFERENCES

[1] UK Civil Aviation Authority. (2011). Intelligent Management of Helicopter Vibration Health Monitoring Data. CAA Paper 2011/01. https://publicapps.caa.co.uk/docs/33/2011_01RFS.pdf

[2] https://www.rotor.org/resource?ArtMID=493&ArticleID=7434

[3] EASA HUMS Research Developments (2014) http://aerossurance.com/helicopters/easa-hums-activity/

[4] https://www.geaviation.com/services/regional-business/onpoint

[5] ADAS/ADAS+ Upgrade Instructions for Continued Airworthiness TWIN-T-260-1 For Raytheon Model 200, 300, and 1900 Series, Pratt & Whitney Engine Services, Inc., Norwood, MA 0206.

[6] https://www.aviationtoday.com/2016/07/06/rolls-royce-taps-sita-onair-for-engine-health-monitoring/

[7] https://www.safran-electronics-defense.com/aerospace/military-aircraft/propulsion-system-solutions/health-monitoring-military-aircraft

[8] https://meggittsensing.com/aerospace/product/engine-health-and-condition-monitoring/

[9] [15] http://aviadeco.com/capabilities/engineering-services/cfm56-7b-advanced-vibration-monitoring/

[10] Jeong-Beom Ihn, Fu-Kuo Chang and Holger Speckmann (2001). Built-in Diagnostics for Monitoring Crack Growth in Aircraft Structures. Proc. of 4th Internat. Conf. on Damage Assessment of Structures (DAMAS) Cardiff/Wales, Key Engineering Mat., Vols. 204-205, 299-308.

[11] Holger Speckmann, (2002), Structural Health Monitoring with Smart Sensors Approach to a New NDI Method. Proc. SPIE Conference on Smart Structures and Materials and NDE for Health Monitoring and Diagnostics, San Diego, California.

[12] Robert Hudec, Ladislav Janousek, Miroslav Benco, Pavol Makys, Vladimir Wieser, Martina Zachariasova, Matej Pacha, Vladimir Vavrus, Martin Vestenicky. (2011) Structural Health Monitoring of Helicopter Fuselage. COMMUNICATIONS 2/2013, pp.95-101. https://doi.org/10.26552/com.C.2013.2.95-101

[13] Andrea Sanchez Ramirez, Richard Loendersloot, Tiedo Tinga (2013). Helicopter Rotor Blade Monitoring using Autonomous Wireless Sensor Network. Proc. of the 10th Int. Conference on Condition Monitoring and Machinery Failure Prevention Technologies. The British Institute of Non-Destructive Testing, 775-782.

[14] Jonathan White, Douglas Adams, and Mark Rumsey (2010). Modal Analysis of CX-100 Rotor Blade and Micon 65/13 Wind Turbine. Proceedings of the IMAC-XXVIII. Jacksonville, Florida, USA.

[15] Krzysztof Dragan (2010) Structural Health Monitoring Approach to the Aerospace Structures, Fatigue of Aircraft Structures, vol.2010, no.2, , pp.14-18. https://doi.org/10.2478/v10164-010-0021-y.

[16] Krzysztof Dragan (2011) Structual Health Monitoring and damage detection of the helicopter main rotor blades with the structure integrated sensors. (2011). AIAC14 Fourteenth Australian International Aerospace Congress. 7th DSTO International Conference on Health & Usage Monitoring (HUMS 2011).

[17] Missoum Lakhdar ,Djermane Mohammed , Labbaci Boudjemâa , Abdeldjebar Rabiâ , Moudden Bachir (2013). Damages detection in a composite structure by vibration analysis. TerraGreen 13 Int. Conference 2013 - Advancements in Renewable Energy and Clean Environment, Energy Procedia 36, 888 – 897.

[18] Bart Peeters, Guido De Roeck, T. Pollet, L. Schueremans (1995). Stochastic Subspace Techniques Applied to Parameter Identification of Civil engineering structures. Proc of New Advances in Modal Synthesis of Large Structures: Non-linear, Damped and Non-deterministic Cases. (edited by L. Jezequel) Lyon, France, pp. 151-162.

[19] Rune Brincker, Lingmi Zhang and Palle Anderson, (2000). Modal Identification from Ambient Response using Frequency Domain Decomposition. Proc. of the 18th IMAC. San Antonio, TX, USA.

[20] M. Abdelghani, M. Goursat, T. Biolchini (1999). On-Line Modal Monitoring of Aircraft Structures under Unknown Excitation. Mechanical Systems and Signal Processing, 13(6), 839-853. doi:10.1006/mssp.1999.1248.

[21] S. Rizo-Patron, Jayant Sirohi (2017). Operational Modal Analysis of a Helicopter Rotor Blade Using Digital Image Correlation. Experimental Mechanics 57, pp. 367–375.

[22] Aleksey Mironovs, Deniss Mironovs, Modal Passport of Dynamically Loaded Structures: Application to Composite Blades. No: 13th International Conference "Modern

Building Materials, Structures and Techniques" (MBMST 2019): Selected Papers, Lietuva, Vilnius, 16.-17. maijs, 2019. Vilnius: VGTU Press, 2019, 750.-757.lpp. e-ISBN 978-609-476-197-3. e-ISSN 2029-9915.

[23] Marc Böswald, Jan Schwochow, Goran Jelicic, Yves Govers (2017). New Concepts for Ground and Flight Vibration Testing of Aircraft Based on Output-Only Modal Analysis. IOMAC 2017 - 7th International Operational Modal Analysis Conference, Ingolstadt, Germany.

[24] Simone Manzato, Bart Peeters, Jan Debille (2012) Tracking the Evolution of Modal Properties of a Solid Propellant Launcher During Static Firing Test. In: Allemang R., De Clerck J., Niezrecki C., Blough J. (eds) Topics in Modal Analysis I, Volume 5. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, New York, NY.

[25] Aleksey Mironov, Pavel Doronkin, (2022). Advanced Vibration Diagnostic System for Aviation Jet Engine. In: Kabashkin, I., Yatskiv, I., Prentkovskis, O. (eds) Reliability and Statistics in Transportation and Communication. RelStat 2021. Lecture Notes in Networks and Systems, vol 410. Springer, Cham. https://doi.org/10.1007/978-3-030-96196-1_16

[26] Aleksey Mironov, Deniss Mironovs, (2019). Condition Monitoring of Helicopter Main Gearbox Planetary Stage. In: Kabashkin, I., Yatskiv (Jackiva), I., Prentkovskis, O. (eds) Reliability and Statistics in Transportation and Communication. RelStat 2018. Lecture Notes in Networks and Systems, vol 68. Springer, Cham. https://doi.org/10.1007/978-3-030-12450-2_39.

[27] Aleksey Mironov, Pavel Doronkin, Alexander Priklonsky, Dmitry Podoryashy, A. Garipov, (2017). Advanced vibration diagnostic system as the part of helicopter technical maintenance. In: 43rd European Rotorcraft Forum, Milan, Italy 2, pp. 1547-1560.

[28] Aleksey Mironovs, Deniss Mironovs, (2019). Modal Passport of Dynamically Loaded Structures: Application to Composite Blades. No: 13th International Conference "Modern Building Materials, Structures and Techniques" (MBMST 2019): Selected Papers, Lithuania, Vilnius, pp.750.-757 e-ISBN 978-609-476-197-3. e-ISSN 2029-9915. https://doi.org/10.3846/mbmst.2019.091

[29] Aleksey Mironov, A. Priklonskiy, Deniss Mironovs, Pavel Doronkin, (2020). Application of Deformation Sensors for Structural Health Monitoring of Transport Vehicles. In: Kabashkin, I., Yatskiv, I., Prentkovskis, O. (eds) Reliability and Statistics in Transportation and Communication. RelStat 2019. Lecture Notes in Networks and Systems, vol 117. Springer, Cham. https://doi.org/10.1007/978-3-030-44610-9_17.

[30] Aleksey Mironov, & Pavel Doronkin. (2022). The Demonstrator of Structural Health Monitoring System of Helicopter Composite Blades. ICSI 2021 The 4th International Conference on Structural Integrity. Procedia Structural Integrity 37, 241–249.

[31] Aleksey Mironov & Pavel Doronkin. (2021). An Analysis of Sensitivity of the Monitoring System of Helicopters to Faults of their Blades. Mechanics of Composite Materials. 57. 10.1007/s11029-021-09948-z.

[32] Aleksey Mironov, Pavel Doronkin, (2021). The Demonstrator of Helicopter Structural Health Monitoring Technique. In: Kabashkin, I., Yatskiv, I., Prentkovskis, O. (eds) Reliability and Statistics in Transportation and Communication. RelStat 2020. Lecture Notes in Networks and Systems, vol 195. Springer, Cham. https://doi.org/10.1007/978-3-030-68476-1_20.

[33] Aleksey Mironov, Pavel Doronkin, & A. Priklonsky, (2016). Structural health monitoring of rotating blades on helicopters. Aviation, 20(3), 110-122. https://doi.org/10.3846/16487788.2016.1227554

[34] Kevin Hughes & James Campbell. (2008). Helicopter Crashworthiness: A Chronological Review of Research Related to Water Impact from 1982 to 2006. Journal of The American Helicopter Society - J AMER HELICOPTER SOC. 53. 10.4050/JAHS.53.429.

[35] Marco Giglio & Andrea Manes & Massimo Fossati & Mariani & Giani. (2010). Comparison of Fatigue Crack Propagation Behavior of Al 2024 and Al–Li 8090 Helicopter Fuselage Panels. Journal of Testing and Evaluation. 38. 10.1520/JTE101909.