VIBRATION DIAGNOSTIC TECHNOLOGIES FOR HELICOPTER MRO

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Abstract

To provide predictive way of maintenance and repair operations, the effective diagnostic tools must cover the most critical helicopter units, including engines, transmission and structures. Advance Passport Vibration Diagnostic technologies is developed to meet these requirements, including qualitative and quantitative assessment of damages. Helicopter diagnostic passport comprises Vibropassport for rotating units, and Modal Passport for fixed and rotating (blades) structures, which is considered as a basic passport platform. The paper presents the development and application of this approach using experimental data from numerous tests on test benches, rigs and real helicopters. The number of diagnostic parameters for assessing the condition of the object under study, varying depending on the type of helicopter, is determined. The composition of the measurement system and technical requirements to it are presented, including: the number and type of sensors for the engine, main gearbox, transmission, tail gearbox, fuselage and blades. The paper discusses Passport Approach of advanced Vibration Diagnostic (PAVD) technologies capable of diagnosing helicopter components in the field, and a roadmap for their adaptation to a specific type of helicopter.

1. INTRODUCTION

Predictive maintenance is a technique that uses condition-monitoring tools and methods to support the performance of a structure or a unit of equipment during operation (Ref. 1). Condition based maintenance (CBM) is performed until the dataset indicates that performance has decreased, then a partial renovation or overhaul has to be made. To provide predictive way of maintenance and repair operations (MRO), the CBM must cover all helicopter units, including engines, transmission and structures. In practice, the capabilities of existing systems are limited with respect to engines and transmissions. Engines condition is estimated using on-board condition monitoring units (CMU) that typically measure vibrations along with other parameters. For instance, GE Aerospace monitors the engine condition by parameters of oil temperature and pressure, fuel consumption and vibration at rotor speed (Ref. 2). There are attempts to expand the range of vibration measurement for monitoring some bearings (Ref. 3) for turbofans and new avionics modules (Ref. 4) have been developed for the CFM56-7B. The transmission units of helicopters are monitored better thanks to health and usage or vibration monitoring systems (Ref. 5, Ref. 6). Such systems may monitor vibrations of transmission units, like gears and drive train, while other critical units, like main and tail rotors or planetary stage of a main gearbox remain out of control (Ref. 7). As for aircraft structures, they are surveyed only by non-destructive techniques (NDT), like eddy current, ultrasonic, etc. (Ref. 8) and its application in field conditions are limited. Thus, currently used diagnostic methods cover only part of helicopter aggregates, leaving the critical units of the helicopter unmonitored, and are not yet capable of providing predictive maintenance of the entire helicopter.

For helicopter main units operation, the preventive system taking into account flight hours continues to be applied (Ref. 9). In practice, the condition of the power plant units of the helicopter, which is supposed for repair, depends not solely on flight hours but also on the operating conditions (Ref. 10).The technical state of units affects the logistics of spare parts required for overhaul, as well as the volume and timing of repair work. Currently, the list of replaced units for ordering and the work planning become known after disassembling the helicopter and fault detection. The period between the decision to send a helicopter for overhaul and the completion of defect detection in the workshop can be months. The cost of repairs and their duration, which sometimes exceeds a year, can be reduced if the need for replacement and repair depth is assessed in advance in the field. The condition of a helicopter structures in the field is assessed using visual inspection and, sometimes, NDT. Depending on the inspector qualifications, NDT make it possible to identify defects in idle units and in places accessible for inspection. If the damage appears in a place inaccessible for inspection or it could be detected only in a working unit, NDT cannot detect such one. To provide predictive maintenance of helicopters, methods are needed that are capable of not only detecting defects in the working unit, but also assessing their scale to decide whether replacement is necessary. Such methods must be capable for application in field conditions, and be able to account variations between serial samples of the same type, and the influence of external conditions. These requirements, including quantitative assessment of damages and exclusion of human factors, are met by Passport Approach of advanced Vibration Diagnostic technologies (PAVD).

The capabilities of this approach for diagnosing the operating helicopter units have been practically validated including the use of the operating helicopter (Ref. 11). The PAVD applied in the demonstrator allowed quantifying the seeded faults in rotating and stationary helicopter structures. This trial PAVD application to the helicopter units' has confirmed the opportunity to detect latent defects in the field using similar methods and potentially to reduce the maintenance and repair costs. To apply PAVD for an ordinary helicopter, it is necessary, firstly, to create diagnostic passports for its units, and secondly, to use special test and measurement technologies applicable in the field.

The paper discusses PAVD technologies capable of diagnosing helicopter components in the field, and a roadmap for their adaptation to a specific type of helicopter. This work considers PAVD adaptation to the engines, transmission components and main rotor blades as the most critical helicopter units.

2. PASSPORT APPROACH TO VIBRATION DIAGNOSTICS

With the "passport" approach, the condition of the particular unit is assessed using one or more diagnostic parameters (DP) with a reference scale. The DP of any unit is determined by unit's vibration model that describes both mechanical interactions and modal properties that are common for all samples of such unit. For example, the nature of dynamic loads in a running bearing and its transmission to the housing are the same for most bearings. The situation is similar with models of compressor stage or gears vibration. Applying this approach for assessing the unit condition of a particular helicopter, it is possible to use the DP scale and the thresholds common to all units of the same type. Both scale and thresholds of any DP are determined by experimental testing a representative set of samples. An algorithm for calculating the normalized DP and the DP's dependence on operational factors are based on the physically based vibration model. For interactions in each type of rotation unit there is a specific generalized model, whereas the structural vibrations describes the modal model. The diagnostic passport is the platform that includes vibration model of the unit, the model-based algorithms for calculating one or more DP, the thresholds and influence functions of DPs. For rotating machines and mechanisms, the term Vibropassport™ is used, and the Modal Passport is applied to fixed and rotating helicopter structures. To provide the quantitative condition estimates required for predictive maintenance, both passports are based on high-order impulse-spatial vibration models. Reflecting the impulsive nature of interactions in rotating machines, nonlinear models of Vibropassport characterize vibration in a wide frequency range. The order of the Modal Passport models is determined by the set of spatially oriented degrees of freedom (DOF), reflecting the shapes of structural natural modes, and providing high-order resolution. Figure 1 shows a diagram illustrating the structure of a helicopter vibration diagnostic passport.

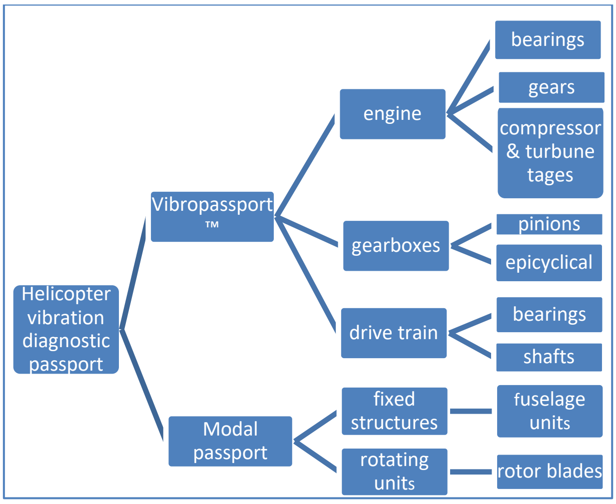


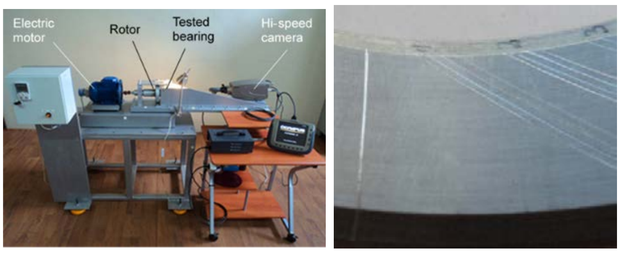
Figure 1: Helicopter vibration diagnostic passport

Though generally vibration models of similar units of different machines are related generally the same, they differ in kinematics and vibration paths. Therefore, the vibration model requires adaptation to the specific type of units or structures.

2.1. Rotating machines

The DPs of Vibropassport reflect the functional state of the helicopter power system, including engines, gearboxes and drive train. Each DP, based on the vibration model, quantitatively (on a normalized scale) assesses the state of the unit estimating the housing response to dynamic mechanical or fluid flow interactions. For example, the condition of a compressor or turbine stage is estimated using the structure of vibration excited by impulse loads from the blade wakes on the spatial guide vane. Gear vibration is modelled by a phase-pulse sequence of loads from teeth meshing, which are nonlinearly transformed passing the gear bearings. Vibropassport of the engine has the most complex composition, as it combines several groups of DPs characterizing gears, rotor bearings and aggregates of the flow part. The latter allow evaluating an aerodynamic irregularity and unsteadiness of compressor and turbine stages, as well as of gas flow downstream the combustion chamber.

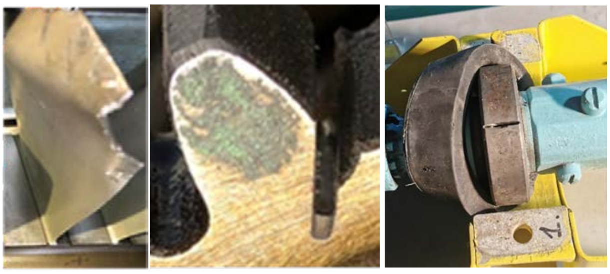
The study of vibration models was carried out in the laboratory on special bench installations that provide detailed analyses of dynamic processes. For example, the bearing test rig (Figure 2a) allows to investigate not only vibration but also the motion of bearing components (Ref. 12).



a b

Figure 2: The test rig for vibration research of rolling bearings

By carrying out tests with different types of damage to the raceways (Figure 2b) or balls/rollers, this research stage allows determining the DP thresholds. As the model of rolling bearing's vibration is mostly common for bearings of different sizes and even types, the normalized scale of diagnostic parameters can be similar. The test rigs of other typical parts of a jet engine allow investigating vibration, evaluating the effectiveness of the developed DP and its thresholds using test damages of different scales (Ref. 13 and Ref. 14). Figure 3 illustrates the seeded fault types embedded into the compressor blade (a), the gear tooth (b) and the transmission bearing (c).



a b c

Figure 3: Seeded faults of drive train bearing (a), compressor blade (b) and gear tooth (c).

Based on results of the test studies, normalized scales were established for all DP of the Vibropassport. Due to the commonality of vibration models, the DP may have common or close normalized scales and thresholds for similar units of different machines. Similarity of vibration models concerns not only bearings, but also compressor stages and gears of different machines. Common normalized scales allows applying the thresholds of one machine determined in laboratory to similar units of other machines. Another advantage of a common normalized scale is that in addition to monitoring it allows also quantification of a fault based on the single test of the operating machine.

After laboratory studies, the validation of Vibropassport techniques was carried out on full-scale objects, including bench tests of gas turbine engines and gearboxes.

a b

Figure 4: 3-axial accelerometers fixed with a bracket on the engine casing (a), on the main gearbox cover (b).

Figure 4 shows examples of three-axial accelerometers installation, marked with a white circle, on the engine (Figure 4a) and on the gearbox (Figure 4b).
Field tests of Vibropassport technologies were carried out on helicopters (Figure 5a), as well as on airplanes.

a b

Figure 5: Vibration registration while engine testing in helicopter using portable measurement set.

The case of latent damage detection of turbine bearing was the impressive story of the Vibropassport application in the field. Conducting the trial Vibropassport application for engine state monitoring during C check for series of aircrafts, the engine was identified whose DPs of the turbine bearing indicated abnormality. The DP of outer raceway and the DP of rollers exceeded the thresholds multiply that was estimated as fault prediction. This forecast was confirmed after several hundred flight hours, when the turbine bearing jammed. A view of the rollers of the jammed bearing is shown in Figure 5b.

2.2. Structural units

For structural health monitoring (SHM) of helicopter the Modal Passport assesses the condition using the parameters of natural vibrations, including modal shape, frequency and damping. Since modal properties depend on external factors, the Modal Passport also takes into account the ambient factors (mainly temperature) and operational factors (for instance, static load) using the influence functions. To describe the unit's state the Modal passport uses normalized vibration parameters in multiple degrees of freedom (DOF) distributed throughout the operating structure. For modal parameters estimation the Operational Modal Analysis (OMA) techniques are applied. Therefore, application of OMA methods requires equipping the structure by the sensor network and corresponding measurement system. The study and validation of the Modal Passport techniques were carried out initially on specially manufactured metal (Ref. 15) and composite samples (Ref. 16), then on the main rotor blade, and finally on the operating helicopter (Ref. 11). After modal parameters of the blade are determined, its dependence on static loads and temperature has to be studied. Such study considers testing the samples under variable ambient conditions and provides determining the influence functions allowing SHM (Ref. 17). The SHM demonstrator based on an operating helicopter with a coaxial rotor was used for in-situ studies of the Modal Passport parameters. The demonstrator was equipped with vibration measurement system in the fuselage and rotating blades with more than 300 measured DOF. A model of the helicopter showing the sensor locations on the fuselage and rotating blades is shown in Figure 6.

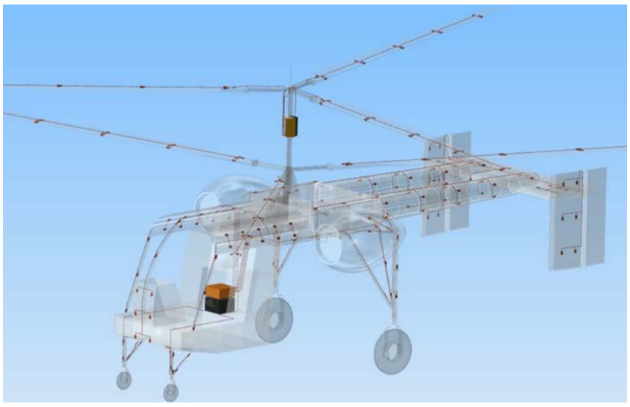


Figure 6: Film sensors allocation throughout fuselage and main rotor of the technology demonstrator.

In the course of modal studies, two technologies for determining the modal properties of blades have been validated. The first involves integrating a sensor network into the blade and measuring vibrations of the rotating blade that is excited by non-uniform and unsteady flow. This technology involves the use of piezoelectric film sensors (Figure 7a) and is intended for use as a part of the onboard SHM system of a helicopter.

a

b

Figure 7: Samples of blade measurement systems: with piezo-films (a), with 3-axial accelerometers.

The second technology is developed for modal testing of a non-rotating blade, removed from a helicopter, on elastic suspension in the field conditions. The blade is equipped with a removable measurement system, in which 3-axial accelerometers are used as sensors (Figure 7b). The special actuator mounted on the root excites the blade, simulating its interaction with the air flow.

The resolution of the Modal Passport technologies was evaluated using the operating SHM demonstrator. Location of the seeded fault on the helicopter tail beam indicated on Figure 8a and Figure 8b illustrates simulation of a gradually growing skin crack. Initially the cut with 1mm width and 20mm length was made, later the cut was increased up to 2x60 mm.

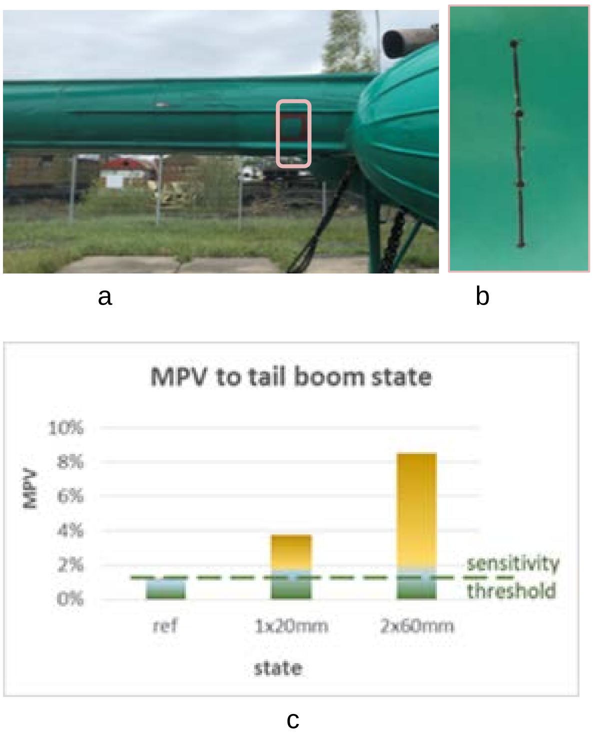


Figure 8: Helicopter tail beam test with seeded faults

The test results showed that even smaller size of the damage (1x20 mm) increased the diagnostic parameter MPV that exceeded the threshold of the reference state (green dotted line in Figure 8c). The damage growth (up to 2x60 mm) resulted in a corresponding increase of the diagnostic parameter MPV (Figure 8c), demonstrating its quantitative feature.

2.3. Measurement and testing equipment

Diagnostic methods based on high-order vibration models require appropriate measurement and data transmission equipment. For rotating machines, three-axial accelerometers provide measurement of the spatial vibration vector in a wide (up to 20...30 kHz) frequency band. Such a wide frequency range requires high sampling rate of vibration signals and rotation phase. Accelerometers should be installed on the engines, gearbox and transmission units with easily mounted tooling for period of helicopter testing. The locations and method of installation are selected so as not to interfere with the helicopter's standard equipment. Rotational signals, which are used to calculate the DP of Vibropassport together with vibration signals, come from sensors that are part of the engine equipment. To minimize the influence of operational factors, diagnostics of helicopter rotating units is performed at fixed operating modes of the power system.

Unlike rotating machines, to determine the modal parameters of helicopter structures the sensor network distributed over the entire structure is used. Since the blades of commercially available helicopters are not equipped with sensors, they must be removed for field testing. The test of inoperative blades will require special rigging to suspend them and excite vibrations. Since OMA methods are used to estimate modal parameters, the vibration excitation method will have to fulfil the basic assumptions of OMA.

3. ADAPTATION OF PASSPORTS TO A SPECIFIC HELICOPTER TYPE

In order to diagnose helicopters of a particular type in the field, the platforms of Vibropassport and Modal Passport have to be adapted to specialties of this type’s power units and structures. Adaptation work is costly, so the feasibility of using PAVD in the field to be determined considering the cost-benefit ratio. Health assessment of fixed structures in the field is inexpedient, because during overhaul it is disassembled anyway and each aggregate of fuselage, landing gear, etc. is diagnosed by NDT methods. Besides, it would be too expensive to equip the whole helicopter with sensors. At the same time, it is desirable to assess the condition of engines and transmission in detail for determining the list of units that will need to be replaced during the overhaul. The same relates to the detection of hidden defects or deterioration of blades mechanical properties. If the required spare parts are ordered in advance the logistics could be cheaper and repair time shorter. Adaptation of both passport platforms includes tuning to the peculiarities of the design and operating modes of a particular type of unit. The stages of passports adaptation, that combining both analytical and experimental works are illustrated in the diagram (Figure 9).

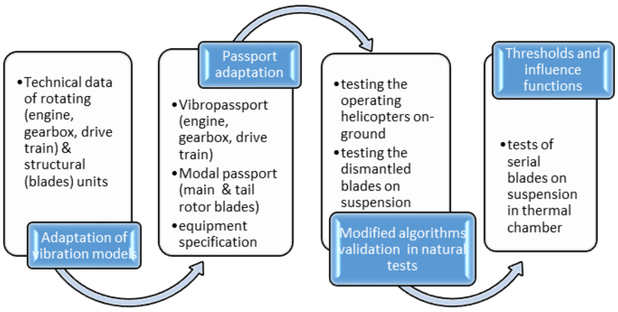


Figure 9: Stages of helicopter vibration diagnostic passport adaptation

Adaptation begins from collecting technical data of the diagnosed object being diagnosed that required for the vibration model tuning. For engine and other powertrain units, the numbers and sizes ratio are in interest, including the stage blades, bearing elements, fuel nozzles, gear teeth, etc. Using above data, vibration models are adapted to the kinematics of each unit. At the next stage the composition and quantity of DP are determined to provide diagnosing an each unit of the engine, gearbox and transmission. Then, the algorithms of each DP calculation are modified in accordance with the model. The adaptation of the Modal Passport starts from data collection about DOFs distribution throughout the structure (in this study – the main rotor blade only). The geometric model based on above data allows applying the OMA algorithms for computing the modal parameters of the blade. As Modal passport deals with identified natural modes, the composition of such modes is studied using numerical modelling and natural testing of the blade. Table 1 shows the approximate composition and number of DPs that may vary for different types of helicopters.

In the process of passports adaptation the requirements to the set of equipment for testing and measurement on the helicopter in field conditions shall be determined. These requirements include the type and number of sensors, the place and techniques of their temporary installation, the layout of cables and connection to the onboard channels of rotation signals, the portable kit of measurement equipment. The latter should provide signal measurements in two kinds of testing: the rotating units of operating helicopter and the actuated blade on suspension. The field set of equipment also includes the modal testing set for blades dismantled from the helicopter.

Table 1: Composition and number of DPs varying for different types of helicopters

Helicopter unit	Part	DP,pcs	Detected defects
Engine	gears	15-50	teeth wear, pinion fault
	gas generator	10-30	blades damages, stability margin reduction, injectors coking
	power turbine	2-5	blades damages & overlapping
	GG & PT bearings	20-30	races tear, balls & rolls problems
Gearbox (main & auxiliary)	epicyclical stage	4-6	uneven load distribution
	gears	6-30	teeth wear, pinion fault
Drive train	bearings	25-45	races tear, balls & rolls problems
Blades	Main rotor	30-50	delamination, strength loss, latent damage
	Tail rotor	20-30	

Table 2. Composition of the portable equipment set for PAVD field application

Equipment	type	pcs	technical requirements
Portable measurement kit	3-axial accelerometer	30-36	Frequency range, Hz 2…25000 dynamic, dB 130-160
	multichannel measurement module, number of channels	6-48	
	sensor's brackets		detachable
	connectors, cable harness	set	interference-proof, shielded
	Wi-Fi router	1	300mBit/s
portable computer	laptop	1	control and measurement software installed
Modal testing set	rigging for blade suspension	set	lightweight, transportable, non-damaging
	impact blade actuator	1	
transport-tation cases	shockproof, waterproof	2-3	airline luggage limited weight

Specific requirements for this equipment aim to provide the method of blade excitation that meet the

OMA requirements. The approximate composition of such equipment and brief technical requirements to it are presented in Table 2.

The set of the specified equipment must meet the requirements of portability and transportability to the test site in special shockproof and waterproof cases.

After the passports are modified and the portable set of equipment is ready, testing is carried out to validate the DPs under natural conditions and to determine thresholds of normal state.

At first, the DPs of the generated Vibropassport and Modal passport are validated on several working helicopters of chosen type. Based on the validation results, the analytically developed composition of the DPs may be modified. There are two basic validation criterions at this stage. First includes the sensitivity check of the measurement system for each monitored unit. For rotating units this is the check of the signal/noise ratio of all vibration components used for to compute the DP. For structural units, including blades, the sustainability check is proceeded for those modes that combines Modal passport. Second criterion is the check whether the DP value calculated from the test result corresponds to the normalized scale of the related vibration model.

For natural testing nominally serviceable helicopters are used, that is, those whose units have residual life and have no identified faults. After testing the helicopter's power plant, the blades are removed and tested using a modal testing set including the actuator and the rigging simulating free suspension. The results of DP validation are used to estimate standard deviation between the DPs of serial samples of the same type.

At the last stage, the threshold values of the healthy state are determined for all DPs and influence functions for the blades are determined. Thresholds of DP for a healthy state are established based on the standard deviation of DPs between serial samples. The case of such threshold exceeding is considered as indication of the abnormal unit. To reduce the influence of the operating mode, the threshold values of the Vibropassport DPs are determined at fixed operating modes close to the maximum. The DP thresholds of the Modal Passport are established for a reference temperature, for example corresponding to standard atmospheric conditions. Since the testing data in field conditions are measured at an arbitrary temperature, the influence functions allows accounting the temperature influence effect on DPs of the blade. Such functions are determined for DP of all natural modes included in the Modal Passport of the blade. The influence functions are calculated based on modal testing of the blades within the temperature operation range of chosen helicopter type. Such modal tests are carried out in a temperature test chamber allowing specific blade excitation mentioned above.

Adapted and validated Vibropassport of powertrain units and Modal passport of blade may be used for monitoring in the field detecting abnormalities of helicopter units.

4. CONCLUSIONS

The passport approach to vibration diagnostics (PAVD) enables assessing the condition of the principal units of those helicopters that lacks an onboard vibration monitoring system. PAVD diagnosing the helicopter in field conditions may be conducted without violation of regulatory routines through the single test of the operating power system and the removed blade set. PAVD permits the reduction of the duration and cost of the helicopter overhaul, as well as the monitoring of those helicopters that undertake critical missions but do not equipped by HUMS or its analogue. PAVD requires the adaptation of the existing platforms of Vibration Passport (for machines) and Modal Passport (for structures) to the specific characteristics of this particular type of helicopter. The adaptation of the basic passport platform to rotating units and structures of a specific type of helicopter can be carried out in several stages in accordance with the proposed roadmap, including an analytical phase and field tests. Field tests for Vibropassport adaptation to helicopter machines and mechanisms will be conducted using serial samples of helicopters of the chosen type. The Modal Passport adaptation will necessitate the testing of blades (dismantled), within the specified temperature range.

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