MODAL PASSPORT APPLICATION FOR DYNAMIC PROPERTIES VALIDATION AND STRUCTURAL HEALTH MONITORING OF HELICOPTER BLADES

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Abstract

The paper considers experimental techniques for research of modal properties of rotating helicopter blades. Sensors of vibration deformations and operational modal analysis techniques are chosen as the optimal tools for evaluation of modal properties of rotating blades. As a complex approach to the study of structural modal properties and its further usage the concept of modal passport is proposed. Authors discuss the setup and technical solutions of the experimental system for determining the modal properties of helicopter blades in statics and rotation. The stages of data processing obtained by the experimental system are described, including preliminary reduction of the periodic component, application of Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA) algorithms as well as formation of a typical modal passport of the blade. The samples of experimentally determined mode shapes of vibrations and deformations in statics and rotation are considered, as well as the analysis of various factors influence on the modal parameters of the blade. The modal deformation shape parameter, which has a diagnostic value and allows detecting even small changes in the mechanical properties of the blade, is outlined. Authors conclude about OMA techniques capability for deformation sensors application for determination of modal parameters of rotating blades. There are conclusions also about benefits of modal passport approach and its application for structural health monitoring (SHM) of helicopter structures, including blades.

1. INTRODUCTION AND THEORY

Nowadays, the study of structural properties using vibration (modal analysis) is widely used for experimental validation of the mechanical properties of helicopter structures. Main rotor blades as the critical structures of a helicopter require modal parameters evaluation at different stages. At the design and certification stage modal analysis is used for the applied model validation and for check of dangerous oscillatory processes, like resonances or a flutter. The modal techniques may allow controlling of structural properties stability of the manufactured blades using modal parameters (frequency, shape, and damping) and comparing it to the etalon.

EMA techniques are applicable at manufacture stage of structural parts but both EMA and OMA - in after-sales service. Currently, for structural studies the EMA techniques are mostly used. These techniques imply the test excitation on the blade and the measurement of its response in the set of Degree of Freedoms (DOFs). The traditional and most common EMA applies the harmonic method of excitation, for instance by a shaker. More rapid assessment may provide another EMA technique called the roving hammer technique (RHT). The wideband excitation provided by hammer's impulse reduces the time required for testing of an object [1]. Further development of techniques to study the modal properties of helicopter blades is going on in different directions, mainly developing response measurement systems, for example, Autonomous Wireless Sensor Network [2], embedded accelerometer arrays [3], optical Fiber Bragg Grating and classical strain sensors [4]. Successfully applied for static tests above applications face difficulties in determination of modal properties of operating and especially rotating structures. For this purpose, OMA techniques application grow up quickly, because not requiring test excitations on the object and use only its dynamic response,.

The principle of OMA is discussed briefly below. Vibrational data from an object is gathered as time series data $x(t)$. This $x(t)$ is unique for each sensor, i.e. DOF. Say there is $i = 1,2...N$ DOFs in the measurement, so there are N $x(t)$ data vectors. The goal of OMA is to obtain a set of modal parameters (frequency, mode shape and damping), which together fully describes dynamic characteristics of an object. OMA considers several modal parameter estimation techniques that process $x(t)$ by different ways, but all OMA techniques have principal requirements for measurements that are:

- The excitation has to be random and flat in frequency domain (white noise),
- Spatial distribution of excitation has to be even across the object.

The Fast Fourier Transforms (FFT) of the vibrational output $x(t)$ is $X(\omega)$, which can be expressed as

(1) $X(\omega) = H(\omega)F(\omega)$

where $H(\omega)$ - is frequency response function (FRF) of a system and $F(\omega)$ – is the applied force.

In OMA $F(\omega)$ is not measured, so the only way to obtain $H(\omega)$ is to apply the assumption that $F(\omega)$ is a white noise. As the frequency spectrum of a white noise is flat, so

(2) $X(\omega) \sim kH(\omega)$,

i.e. measured time signals mimic the FRF of the system. Factor k denotes a constant force and has to match the physical units. So, that measured data is not actual FRF, but only an approximation of the latter. There are modal parameter estimation techniques that use time domain (Stochastic Subspace Identification (SSI) algorithms [5,6]) and others - frequency domain (for instance, Extended Frequency Domain Decomposition (EFDD) [6,7,8]).

Due to ongoing development of OMA methods, it became possible to evaluate the modal properties of rotating structures not only during testing, but also in operating conditions [9-11]. For instance, modal properties dependence on rotation speed may be provided by testing the blades within operational range. The study of modal property dependence of rotation speed have to be provided by the condition that other operational factors, for example, pitch, air temperature, helicopter flight speed, etc. remain constant. Here below we discuss OMA approach for assessment of modal parameters during bench testing (earlier considered in [12-14]) as well as its possible application for structural health monitoring (SHM) of helicopter blades in-flight.

While typically accelerometers are used for data collection about blade vibrations, also another type of dynamic sensors may be used, for instance strain gauges or film piezoelectric sensors. The signal generated by such sensor is proportional to the relative stretching or compression of the blade's surface area under the sensor. The use of deformations instead of displacement is based on the assumption (3)

(3) $\varepsilon_s = y_s'' \cdot h$,

where *h* – the distance from the neutral axis to the stretched layer, *y* – transverse displacements of the neutral axis of the beam of the surface layer.

Equation (3) describes approximately the relationship between the deformation of the surface layer of the beam and its displacement in the same cross-section (assuming a rigid beam at pure bending). As the height of blade's front edge (h_f) more than the rear one (h_r), the deformations of the rear edge of the blade is much less according to the (3). For ease of comparison between vibration and deformation shapes, the values of the rear edge normalized deformations are recalculated accounting the difference in profile height along the front h_f and rear h_r edges

(4) $\bar{\varepsilon}(x)^c = \bar{\varepsilon}(x)\, h_f / \, h_r$

The concept of a *modal passport* [15] is considered as an integrated approach to modal properties recording and structural health monitoring (SHM) of blades. *Typical* modal passport (the set of typical vibration modes) serves for complex description of typical properties of the blade type. The typical modal passport of operating blades includes the matrixes of modal parameters (frequency, damping and shape) and is valid within wide range of operating conditions. The typical modal passport considers the *equivalent* blade, which modal parameters are equal to averaged parameters of blade ensemble of the same type. As modal properties of individual blade differ from averaged values the typical passport contains both averaged modal parameters and its confidence intervals. Typical passport is multidimensional. As many operational factors influence on blade modal parameters, to describe its dependence of each specific factor the typical passport has separate dimension.

Figure 1 graphically illustrates 3D example of modal passport that illustrates, how blade modal parameters depend of normalized rotation speed. To determine such modal properties, the tests of the rotating blade are conducted in operational range of rotation speed from static (0%) to the maximal (125% of nominal). The modal parameters are computed applying OMA techniques consequently to data of deformation signals on each rotation speed. The vertical axis of diagram presents the eigenvector (modal shape) and the eigenvalues (frequency, damping coefficient) computed for each of 13 modes set aside on sloping axis. The left vertical "slice" formed by the vertical axis (of modal parameters) and the sloping axis (mode number) reflects modal properties of a blade in static position (0% rotation speed). Any other vertical slices to be lined up along horizontal axis in depend of normalized rotation speed.

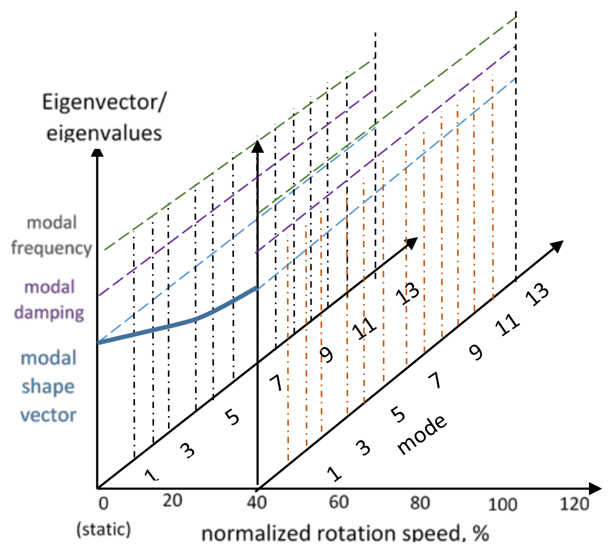


Figure 1. Graphic illustration of typical modal passport structure

The slice crossing the horizontal axis at 40% reflects modal parameters of the blade at 40% of nominal rotation speed. Each slice of the typical passport has the same structure as the static one; however, parameter values of the same mode vary between slices. The blue curve line relating modal shape vectors of zero and 40% speed illustrates modal shape dependence on rotation speed. On the top of rotation speed blade modal parameters depend of other operating or ambient factors (pitch, flight speed, temperature, etc.), so actual typical modal passport must describe the dependence of blade modal parameters to all above factors. The typical passport is based on representative blades sampling of the same type.

Individual modal passport of the particular blade has the same structure and dependence of operational factors as the typical passport. However, variance of individual mechanical properties causes modal properties deviations from typical ones. That is why modal parameters of particular blade differ from parameters of the typical passport. From one side the individual modal passport is compiled using individual properties of particular blade from its static test, and from other side, using operational factors dependences determined by the typical passport. The only limitation of such approach is that deviation of individual modal parameters (obtained in statics) does not exceed confidence intervals of the typical passport. Therefore, the typical passport provides opportunity to create individual passport for each specific blade based on its static test. Individual modal passport of the blade allows two important things:

- prediction the changes in the modal properties of the blade in depend of operational factors,
- SHM of each rotating blade by detecting the blade's modification cleared from influence of operational factors.

2. MODAL PARAMETERS OF ROTATING BLADES: EXPERIMENTAL STUDY AND APPLICATION

The modal analysis technology of rotating helicopter blades includes, on one hand, the instrumentation for measuring and converting the signals of the blade dynamic response, and on other, the intellectual part, which implements modal analysis techniques and algorithms of its application.

2.1. Measurement system

Figure 2 presents the setup of the experimental system providing determination of the modal properties of a three-blade hinge-less rotor. The components of this system are considered also for prototyping the helicopter rotary blade monitoring system.

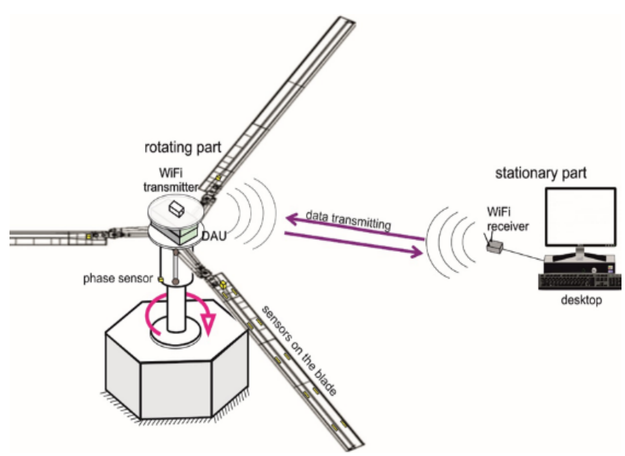


Figure.2. Setup of rotating blades measurement system

The rotating part of the system includes an integrated network of dynamic signal sensors (on one blade), connecting cables, the data acquisition unit (DAU) and the wireless data transmission module (WDTM). The sensors signals from the blade and from the rotor speed probe enter the inputs of the multi-channel DAU. The DAU module, rotating with the rotor, condition the sensor signals, filter and convert them to digital form. From the DAU output digital data enter to the WDTM and transmitted by the latter to the stationary part of the system.

The stationary part of the system includes the wireless communication module that receives data from the rotating part of the system and transfers it to the workstation. The workstation of the system, located in a safe place away from the rotating rotor, performs the functions:

• receiving and accumulating data from the rotor;

• data processing mode control (starting the data recording when a specified speed is reached, and stopping after a set amount of data has been received);

• computing of modal parameters by OMA techniques;

• recording of calculated modal parameters at specified operation modes,

• storing of accumulated data.

2.1.1. Rotating part

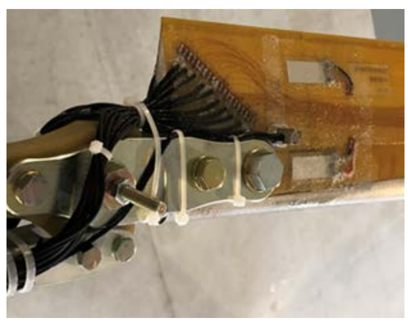
Figure 3 demonstrates the sensors location on the upper (a) and lower (b) surfaces of the rotor blade.

a)

Fig.3. Allocation of vibration deformation sensors on low pressure (a) and high pressure (b) surfaces of the blade.

Film piezoelectric sensors, that are deformation sensors, provide Information about blade vibrations. Piezo film sensors provide advantages over other types of deformation sensors. Firstly, unlike strain gauges, these sensors do not respond to static deformation, which eliminates the need for balancing and adjusting the gain of the measuring channels. Secondly, these sensors have small thickness and are almost weightless, therefore, practically do not affect the aerodynamics of the blade. Finally, vibration deformation sensors are much cheaper than acceleration sensors that are more mass and weight.

Vibration deformation sensors and their wires are glued to the top (low pressure) and bottom (high pressure) of the blade surfaces. The layer of glass veil and epoxy resin composite fix and protect sensors and wires. Sensors on upper surface are oriented along the blade axis (Fig. 3a) and serve to identify bending vibrations. For torsional vibrations, sensors located on high pressure surface are fixed at an angle of 45° to the axis (Fig. 3b). Due to the protective composite layer, the measuring system is integrated into the blade structure and is able to characterize the blade oscillations, with little or no effect on the inertial and aerodynamic loads acting on the blade. Located on the root part of the blade the connection block (Fig. 4a) connects the sensor wires with a flexible harness of cables, which relates the oscillating blade with the rotating DAU (Fig. 4b).

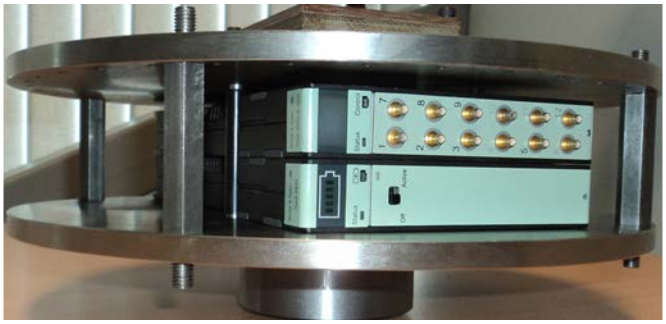


a)

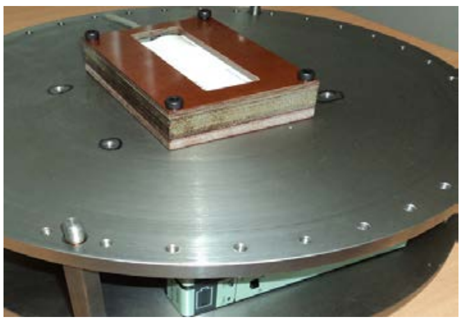
b)

Fig.4. Blade sensors cabling to the DAU.

At the other end of the cable harness there are coaxial SMB connectors connected to the DAU measurement input channels. Fig.5a. shows the type of DAU mounted in a balanced frame.



a)



b)

Fig.5. DAU mounted in the balanced frame (a) and wireless router on its cap (b).

Ruggedized frame, balanced before, carries out the inertial loads acting on the DAU and cables. From the DAU output, the data of deformations and speed in the digital form come to the router installed on the upper part of the frame (Fig.5b), from where the data are transmitted to the data receiving device of the operator's workstation.

2.1.1. Stationary part

The stationary part of system provides data monitoring (Fig.6), accumulation and storage.

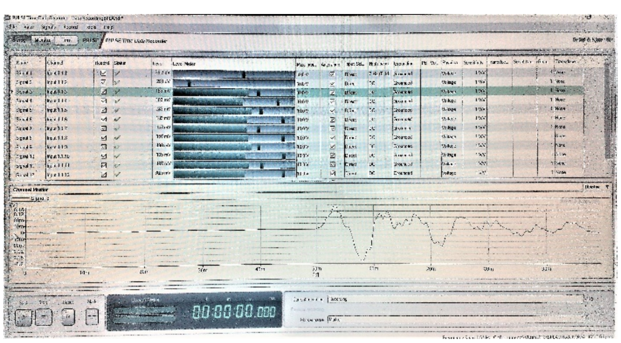


Fig.6. Measurement channels monitoring on workstation screen

The data accumulated from tests of rotating blades enter the intellectual part of the system.

2.2. Intellectual part

Commercial and original software provide three stages of data processing: conditioning, modal analysis and application of modal passport algorithms. The first two parts process the digitally presented physical signals from blade sensors, and the third deals with the estimates of the blade modal parameters.

To satisfy the basic assumption of OMA (about random nature of excitatory loads) the data of sensors to be preliminary developed. Blades rotation causes periodic variable inertial and aerodynamic loads that may increase the error of the modal parameters determination. Both types of excitation depend of operation mode. For instance, experimental study shows that at zero pitch the share of the periodic component in blades vibration energy at the nominal rotation speed is about 4-6%, but at 25% higher speed - grows up to 15-18%. Such periodic component has small effect on the accuracy of modal parameters computation. However, with pitch growth, especially cyclic one, the periodic component increases an error. That is why if the periodic share of vibration signal exceeds 20%, the special algorithm reduces the periodic component providing a permissible level of error in determining the modal parameters.

In the next step, OMA algorithms implemented with commercial software *Artemis* processes conditioned data (sensor signals) of each test. The set of modal parameters (modal frequency, damping and mode shape) is the result of this analysis. The set of extracted modes may vary from test to test caused by random combination of external factors so, tests of rotating blade are repeated.

On the last stage, the intellectual part analyzes the calculated modal parameters using the approach of the typical modal passport. From each test, it selects the parameters of *typical* modes only, i.e. the modes containing the typical modal passport. Typical modes correspond to two criteria: they are stably appear on nominal operation modes, and conform to the tasks of modal passport application. Modal Assurance Criterion (MAC) [16] computed as in equation (5) allow the typical modes selection and identification from number of modes obtained in each test.

(5) $$MAC_{cdr} = \frac{\left|\sum_{q=1}^{N_0} \Psi_{mqr}\Psi^*{}_{tqr}\right|^2}{\sum_{q=1}^{N_0} \Psi_{mqr}\Psi^*{}_{mqr} \sum_{q=1}^{N_0} \Psi_{tqr}\Psi^*{}_{tqr}}$$

where Ψ_{mqr} - modal coefficient for degree-of-freedom q, mode r of measured modal vector m,

$\Psi^*{}_{tqr}$ – modal coefficient for degree-of-freedom q, mode r of complex conjugate of typical modal vector t

N_0 – number of DOFs.

Modal parameters of the specific blade, which correspond to the typical passport and satisfy the MAC threshold, are included in the *individua*l modal passport of this blade.

3. PRACTICAL STUDY OF BLADES MODAL PARAMETERS

Here below the practical application of modal testing concerns the composite hinge-less rotor blades that involves both experimental and operational modal analysis techniques. For blades testing in a static position the EMA technique is applied that involves measurement of blade oscillations in reference DOFs as a response to controlled dynamic impacts in multiple DOFs. Using measured data the EMA provides computation of Frequency Response Functions (FRF) as response-to-impact ratio, which is used to determine modal frequency, damping and shape of each mode. As OMA techniques do not require excitation control these techniques determine the modal parameters of rotating blade.

3.1. Static tests

Static tests involve two stages with two consequently applied techniques.

The first one is one of EMA type - the roving hammer technique (RHT). This method considers consequent excitations in multiple DOFs and synchronous measurement of the responses to it in reference DOFs. The number and location of DOFs on the blade is preliminary determined based on maximal order of the modal blade model. The latter was assumed as the 5th order of bending and 3rd torsional modes. The equipment required RHT includes the signal measurement and recording system, the impact hammer with an integrated load cell and two tri-axial accelerometers located at the tip and on the root of the blade. Figure 7 shows the RHT test measurement setup, where the black dots indicate the locations of orthogonally directed force impulses by the impact hammer. The white circles indicate the locations of tri-axial accelerometers for response measurements. Commercial software *Modal Consultant* of Pulse Labshop platform relates the measured data to blade geometric model that reflects the location of the DOFs on the blade. After measurement is completed, this platform provides FRF and modal parameters computation. Modal frequency and shape are the principal parameters for measured modes identification.

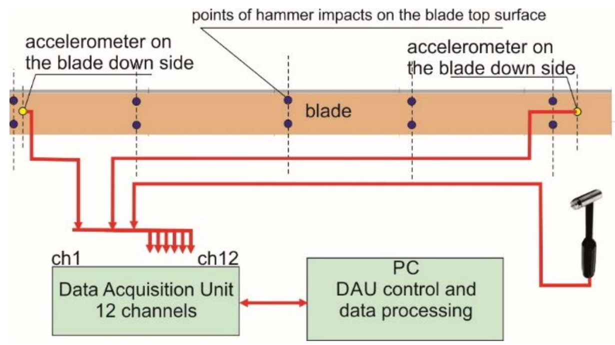
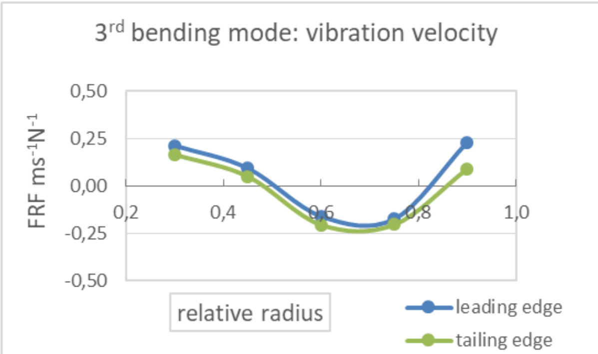


Figure 7. Measurement setup of blade testing by roving hammer technique.

The diagram of modal shape magnitudes relation on the relative blade radius makes modal validation more convenient. Fig. 8 as an example illustrates the FRF values ($ms^{-2}N^{-1}$) measured at DOFs that located along the leading and trailing edges of the blade. Figure 8a shows the FRF diagrams of the 3rd blade bending (flapping) mode, measured from sensors along the leading (blue) and tailing (green) edges of the blade. The second method of blade testing in statics is the implementation of the OMA with simulated random excitation of the blade and measurement of its dynamic deformations as the response. The rubber hammer helps to simulate the random excitation, blowing on the fixed blade support at randomly varying force, direction and frequency. The *Artemis* commercial software platform uses as response the measured dynamic deformation signals. Based on the geometric model *Artemis* provides the modal calculation in defined frequency range in terms of surface relative deformation. Fig.8b shows the diagrams of relative dynamic deformations of 3rd bending (flapping) mode. Comparison between FRF diagrams (EMA) and deformation diagrams (OMA) of the same modal shape contributes to validate modal identification on the stage of rotating blade testing. Such comparison of vibration (Fig.8a) and surface deformations (Fig.8b) shows that the curves have about 180^o shift.



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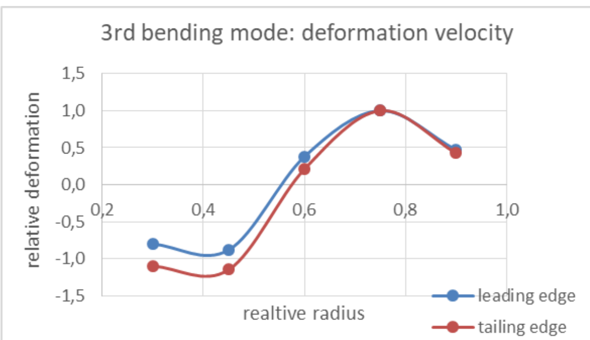


b)

Figure 8. Diagrams of magnitudes: FRF (a) and dynamic deformations (b).

Such a shift is consistent with above described expression (3), which considers the deformation mode shape as the 2nd vibration derivative. Thus, when identifying the vibration and deformation patterns in the static and in rotation, their relationship through the 2nd derivative is taken into account.

3.2. Rotating blades testing

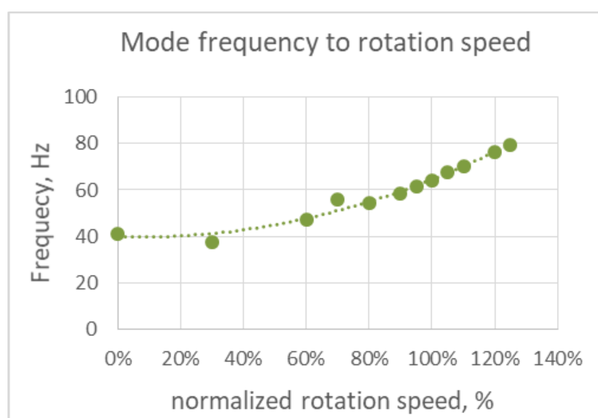
The modal parameters of rotating blades are determined by OMA techniques based on data from dynamic deformation sensors. Test conditions, including rotational speed, pitch, temperature and other factors, affect the modal parameters. For example, rotational speed and pitch, respectively, determine the centrifugal and aerodynamic loading of the blade. Variable loads, actuating blade vibration (within elastic deformations limits), have no effect on the blade modal properties. At the same time, the constant component of loads (centrifugal or lifting force) creates a pre-tension or pre-compression of the surface layers, affecting blade modal properties.

To study the influence of any operating factor on the modal properties the test series is carried out variating studied factor and keeping unchangeable other factors. For example, modal properties dependence on the centrifugal loads is investigated varying rotation speed with zero pitch of the blades. This minimizes the effect of the lifting force on the modal properties, so the centrifugal load remains the main influencing factor. If, however, the effect of the lifting force on modal properties is investigated, the tests are carried out at the same speed and only the common pitch changes. Some samples of practical study results of various factors effects are given below.

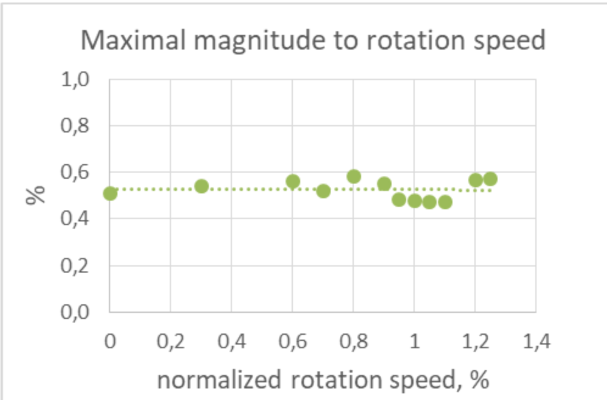
It should be noted the probabilistic demonstration of modal properties developing experimental data of tests series. Data development of each blade test may provide arbitrary variated number of modes however, only those modes to be selected for further consideration that match up with the blade typical passport.

3.2.1. Rotating speed influence

Rotation speed influence on the blade modal properties is carried out in the range from 0 to 125% of the nominal speed in the steady-state operating modes with zero blade pitch. The modal parameters dependencies on rotating speed are the results of this experimental study. Fig. 9 presents the samples of such dependencies of tested blade for considered above 3rd flapping mode. The modal frequency (Fig.9a) demonstrates small scatter and well known dependence close to parabolic one. The parameter of maximal deformation magnitude (Fig.9b) has small scatter and is independent of rotation speed because the algorithm of its computation considers normalization to modal energy. At the same time, the damping factor (Fig. 9c) scatters a lot and descends along rotation speed.



a)



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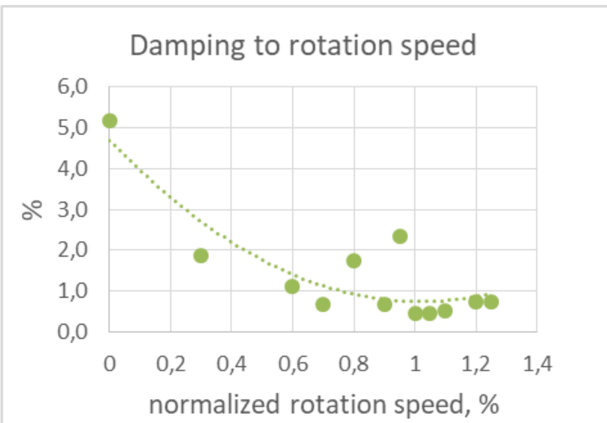
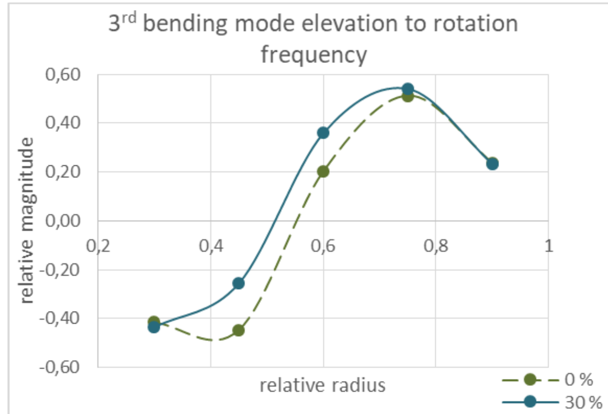


c)

Figure.9. Dependence of tested blade modal parameters on rotation speed: a – frequency, b – maximal deformation magnitude, c – damping.

Contrary to magnitude, the modal shape is sensitive to rotation speed. In case of newly designed blade, the modal shape dependence on rotating speed may be of interest, for instance to determine the optimum location for the anti-flutter load. The diagrams on Fig. 10 illustrate how the mode shape modifies in relation to rotation speed. For example, the deformation of the blade near the root (0.45 relative radius) at a speed of 30% reduced by half, compared to the stationary blade (Fig. 10a). Some shift of deformation curves could be seen around nominal rotation speed (Fig.10b).



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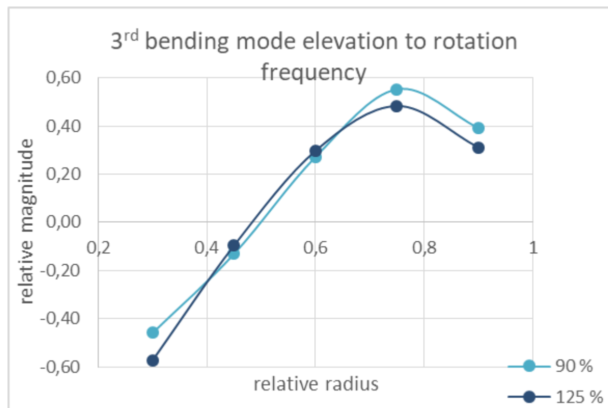

b)

Figure 10. Diagrams of modal shape of blade deformations (leading edge only) to relative rotating speed.

Very often modal frequency relation to rotation speed is in interest for potential resonances check. Such diagrams allowing also comparison of experimental and computational data (Fig.11).

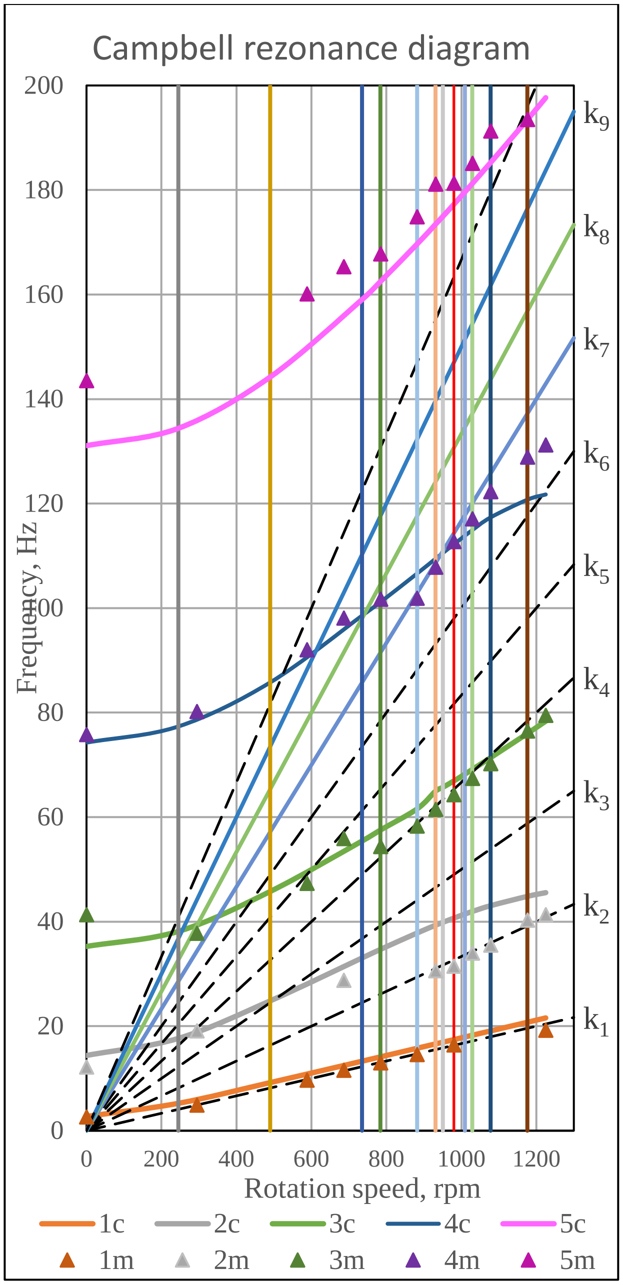

Figure 11. FEM computed and experimentally measured modal frequency dependence on normalized rotation speed.

3.2.2. Random factors influence

A typical modal passport should take into account the influence of random factors that cause the spread of modal parameters. In experimental study the effect of random flashlights is estimated by multiple repeating tests under constant external conditions. For instance, such study of the composite blade with a hinge-less bushing includes 12 tests at the same rotation speed (100% of the nominal speed) at zero lifting force. The estimated scatter of modal parameters are presented in Table 1 for three flapping modes (4th, 5th and 6th). Columns 2-4 of the table show standard deviation between 12 tests for three parameters: modal frequency f_m, the maximal magnitude of mode shape M_m and the integral parameter of the mode shape S_{int}. As can be seen from the table, scattering of these parameters is small and stacked at 0.2%...0.6%. At the same time, the damping factor (K_m) in column 5 varied at 11% ... 15%, demonstrating low accuracy of its determination by OMA techniques.

Table 1. Scatter between "healthy" tests

Mode number	f_m	M_m	S_{int}	K_m
1	2	3	4	5
4	0,6%	0,3%	0,2%	11%
5	0,4%	0,2%	0,2%	15%
6	0,3%	0,3%	0,2%	14%

Thus, the analysis of random factors influence on modal parameters shows, firstly, the possibility to determine some modal parameters with high accuracy.

3.2.3. Influence of structural changes

The sensitivity of modal parameters to structural modification is of interest from SHM point of view. The sensitivity is estimated by the significance of modal parameter change in response to the blade structural modification caused by change of design, defects implemented in manufacture or in service as well as FRP resin degradation. In this study, the following rule was fixed: If the change of modal parameter exceeds triple standard deviation of this parameter (Table1 columns 2 – 4), such change can be considered as significant. Light modification of the studied blade structure was caused by perforation of its tailing edge with holes of 4 mm diameter for the flutter-provoking weights installation. Such modification scale is comparable to a case when the blade with honeycomb tailing part absorbs water. Despite the small scale, the holes locally change the ratio between masses and stiffness and by such way influence the modal parameters. Columns 2-5 of Table 2 show changes of four modal parameters between two blade states (initial and perforated).The changes in modal frequency (Table 2 column 2), maximal magnitude (column 3) and damping (column 5) remain within scatter of blade initial state.

Table 2. Difference between healthy and faulty tests

Mode number	f_m	M_m	S_{int}	K_m
1	2	3	4	5
4	0,5%	0,2%	**0,7%**	-2,0%
5	0,1%	-0,2%	**0,8%**	12,8%
6	0,4%	-0,2%	**1,1%**	-2,5%

At the same time, the integral parameter of the mode shape S_{int} (Table 2 column 2) exceeds the limits of its scatter in initial state 3-4 times. Thus, the study confirms quite satisfactory sensitivity of the integral blade shape parameter.

Blade modal shapes are important for the task of SHM in flight. Even minor changes in the blade's mechanical properties due to material aging or impact of foreign objects may affect the mode shapes of the blade's deformation that can be detected in time using modal parameters. In depend of requirements to the scale of potential faults resolution the composition of modes for blade monitoring can be determined. Based on above composition the typical modal passport can be formed. Trial application indicates the lower-order modes, usually represented by bending and twisting shapes, provide monitoring of the blade global integrity. Higher order modes are more efficient to diagnose local defects, like bundling or layering.

Resuming, we may say some modal parameters have high sensitivity to blade structural condition that allows structural health monitoring of rotating blades.

4. CONCLUSIONS

The trial application of modal passport approach to study of composite blades properties allowed to draw the following conclusions:

- ✓ Embedded deformations sensors provide modal parameters measurement of rotating blade with minimal impact on aerodynamics;
- ✓ OMA techniques provides assessment of modal frequencies and shapes of rotating blade;
- ✓ State-of-the-art equipment provides measurements of vibration signals of rotating blades,
- ✓ The typical modal passport allows characterization the operating factors influence on blade modal properties,
- ✓ Granting operating factors dependences on modal parameters the typical modal passport allows:
    - validation of computational models in wide range of operational factors,
    - individual modal passport for each specific blade based on the static tests only (under further investigation);
    - improvement of production and in-service quality control of blades and structural parts,
- ✓ Blade modal passport may predict the changes of its modal parameters in depend of operating factors modification,
- ✓ Application of piezo film deformation sensors combined with OMA methods simplifies the study of blade modal properties, especially for light helicopters;
- ✓ The complex technology combining the advance equipment, the OMA techniques and the modal passport approach allows creating the SHM system for helicopter rotor.

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