UDK: 621.312.22.094.64
COSATI: 01-03, 20-11

Measurement and Analysis of Vibrations on the Helicopter Structure in Order to Detect Defects of Operating Elements

Slobodan Stupar[1)]
Aleksandar Simonović[1)]
Miroslav Jovanović[2)]

A practical example of the measurement and analysis of vibrations on helicopter structures in order to detect defects on operating elements is presented in this paper. A comprehensive methodology of vibration testing is presented in this article and implemented in order to determine the correct operation of rotating components. A particular attention is given to the analysis of longitudinal and vertical vibrations on the helicopter fuselage in the frequency domain for different flight profiles. The vibration measurement and analysis on specific locations on a helicopter structure resulted in a timely technical review of a relevant component and a disclosure of the damage on its surface. The proposed methodology of measurement and analysis can be implemented on different types of aircraft in order to extend their life expectancy.

Key words: **helicopter, aircraft structure, fuselage, reductor, aircraft vibrations, vibration measurement, frequency range, flight test, Fourier transform.**

Introduction

VIBRATIONS in helicopters arise mainly from the sources such as the rotor system, the tail rotor, the engine and the transmission, leading to fatigue damage of structural components, human discomfort, difficulty in reading instruments and reduced effectiveness of weapon systems [1]. The vibration measurement and analysis is a very powerful condition monitoring technique which is becoming more popular as common practice in helicopter industry. Generally, helicopters do not break or fail without some form of warning, indicated by an increased vibration level [2]. The increasing level in the vibration signature of a helicopter can provide a variety of information about the conditions on many structure components and parts. Vibration measurement on different structural locations can be mighty working tools for the detection of potential structural damage or parts failure [3].

Surprisingly, vibration reduction efforts during the original design of most helicopters were not significant until 1990s. Too often it remained for later and costly flight-test programs to identify vibration problems and to suggest fixes – for example, the addition of vibration absorbers or, if necessary, even structural modifications [2]. Nowadays, the possibility and the ability to define structural loads and vibrations are one of the most important requests in the design and modification process on helicopters with aims to reduce the cost of the flight test process and to satisfy international standards in the area of structural and human vibrations [4].

Helicopters are continuously subjected to periodic loads and vibration environments that initiate and propagate fatigue damage in many components. Current helicopter maintenance practice requires a large number of parts to be monitored and replaced at fixed intervals. This constitutes an expensive procedure that adds considerably to helicopter maintenance costs. The solution of this problem is the development of Health and Usage Monitoring Systems (HUMS) which have to detect incipient damage in helicopter components, predict remaining life, and create the conditions for moving from scheduled based maintenance to condition based maintenance [5].

This paper presents the measurement of vibrations on a Gazelle helicopter with the aim to recognize and define the minimum necessary data for the detection of potential failure elements of systems in operational service. The fault detection capability of this method will be presented using the fast Fourier transform (FFT) of the time domain signal and the pass in the frequency domain.

Sources of vibrations on helicopters

Vibration sources in the helicopter are different and originate from: main rotor, tail rotor, engines and other rotating systems such as hydraulic pumps and air forces acting on the fuselage.

The frequency of vibrations caused by the main rotor is at integer multiples of the rotor RPM - 1 per revolution (1/rev) is the rotor RPM, then 2/rev, 3/rev, etc. In addition to the main rotor, other sources of vibrations are the engine/fan system, the main rotor transmission/drive-shaft/gear system, the tail rotor and its transmission system and loose components that are a regular or external part of aircraft. Examples are out of balance rotor blades, loose tail

1) University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, SERBIA
2) Technical Test Center, Vojvode Stepe 445, 11000 Belgrade, SERBIA

fins, loose engine shaft mounts, unsecured canopy, the landing gear system or external weapons or cargo systems.

In addition to dynamic coupling, significant amount of aerodynamic interference or coupling exists between the main rotor, the airframe and the tail rotor structures. The flow around the fuselage affects the aerodynamics of the main rotor and the tail rotor. The downwash from the main rotor changes the aerodynamics of the fuselage, the tail rotor and the horizontal tail and stabilizers. Under certain low speed conditions, the vortex wake from the main rotor impinges directly on the tail boom that gives rise to fuselage vibrations at the blade passage frequency.

Main rotor vibrations arise especially in forward flight. The rotor experiences varying fluid velocities and angles of attack at the advancing and retreating blade. Varying span wise distributions of lift and drag excite the blade bending modes. This results in alternating rotor hub loads, especially vertical forces and lateral and longitudinal mast moments. The occurring vibration frequencies are typically a multiple of the blade number and the revolution frequency [6]. Using more rotor blades and a smaller flapping hinge offset can help reducing vibrations.

In a high speed flight, vibrations can occur if the retreating blade suffers from strong dynamic stall while the advancing blade experiences transonic flow with the inherent shocks [6]. Another source of vibrations is the blade vortex interaction (BVI), especially in decent flight. Deficient blade tracking can be an additional source of vibrations, Fig.1.

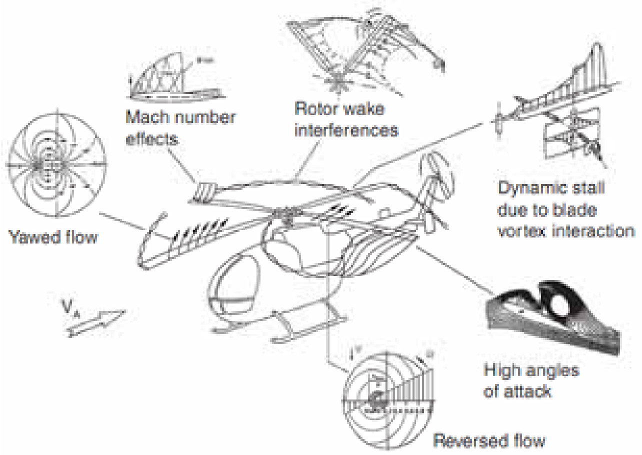

Figure 1. Aerodynamic effects associated with helicopter rotors

Spectral analysis and fault detection

The spectral (or frequency) analysis is a term used to describe the analysis of the frequency domain representation of a signal. The spectral analysis is the most commonly used vibration analysis technique for condition monitoring in geared transmission systems and has proved to be a valuable tool for the detection and basic diagnosis of faults in simple rotating machinery. Whereas the overall vibration level is a measure of the vibration produced over a broad band of frequencies, the spectrum is a measure of the vibrations over a large number of discrete contiguous narrow frequency bands.

The fundamental process common to spectral analysis techniques is the conversion of a time domain representation of the vibration signal into a frequency domain representation. This can be achieved by the use of narrow band filters or, more commonly in recent times, using the discrete Fourier Transform (DFT) of digitized data. The vibration level at each "frequency" represents the vibration over a narrow frequency band centered at the designated "frequency", with a bandwidth determined by the conversion process employed.

For machines operating at a known constant speed, the frequencies of vibrations produced by various machine components can be estimated; therefore, a change in vibration level within a particular frequency band can usually be associated with a particular machine component. An analysis of the relative vibration levels at different frequency bands can often give an indication of the nature of a fault, providing some diagnostic capabilities [7].

The frequency domain representation of a signal can be described by the Fourier Transform of its time domain representation

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \tag{1}$$

where: $X(f)$ - are Fourier spectra, $x(t)$ - represents a signal in time domain, f - is the ordinary frequency of the signal [Hz] and $j = \sqrt{-1}$ is the basis for complex numbers.

Most modern spectrum analysers use the Fast Fourier Transform (FFT), which is an efficient algorithm for performing a Discrete Fourier Transform (DFT) of discrete sampled data. The Discrete Fourier Transform is defined as:

$$X(m) = \frac{1}{N}\sum_{n=0}^{N-1} x(n) e^{-j2\pi\frac{mn}{N}} \tag{2}$$

where $x(n)$ denotes the input signal at time (sample) n, and $X(m)$ denotes the m spectral sample.

The sampling process used to convert the continuous time signal into a discrete signal can cause some undesirable effects, like aliasing, leakage, or a picket fence effect.

Methodology of vibration measurement during flight test procedures

Flight tests were conducted on a military Gazelle helicopter SA-342, similar to the one shown in Fig.2.

Figure 2. Gazelle Helicopter SA-342

The measurements were based on periodical measuring and analysing vibrations on specific locations on the helicopter structure. Practical methodology consisted of a few steps.

The first step was the determination of operating frequencies of all rotating systems and subsystems. The second step was a selection of a necessary number of locations on the external structure for measuring the level of vibrations on the ground with forming maps of proper conditions. The next step was choosing an interior location at the structure, which will be a specific point for all flight tests for determining conditions of helicopter properties and requirements for any corrective actions.

The first two steps are defined as an appropriate relationship in vibrations (level of amplitude) between the systems, which operate at the same frequency. In case of impossibility to define a fault with the testing procedures given in the third step, it is possible to repeat testing on the ground from the second step, but this procedure can check out the helicopter from operational service for a period of time.

The flow chart of the described method for the diagnostics of components health on the Gazelle helicopter is shown in Fig.3.

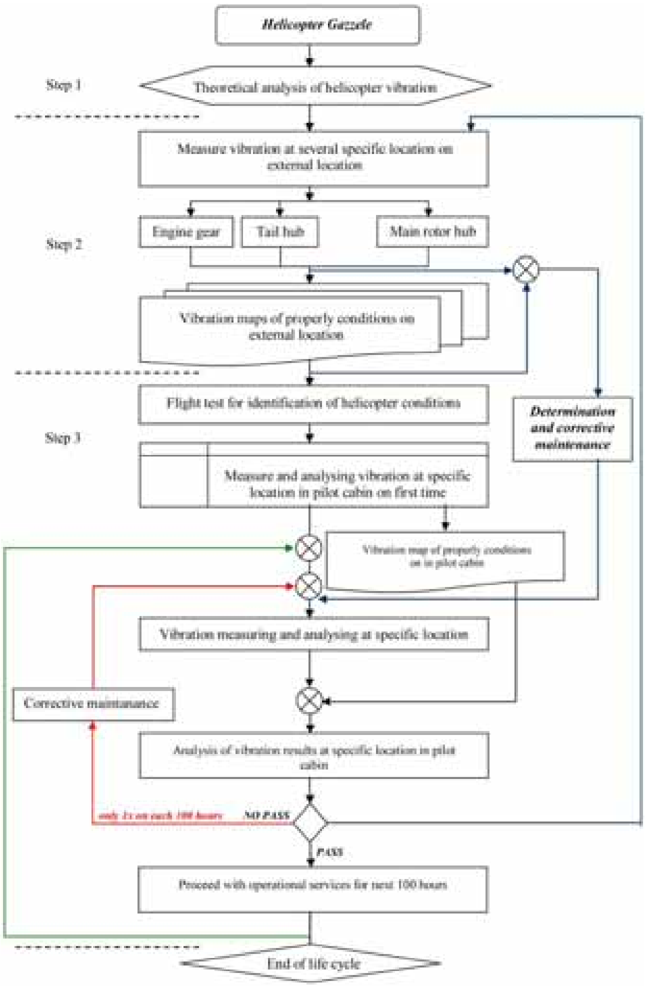

Figure 3. Flow chart of the vibration diagnostics method

The flight for testing vibration conditions at every 100 hours was approved by the Technical Test Centre in flight test schedules. These schedules were prepared and based on the need to involve all the limitations of the Gazelle helicopter. These schedules are created to ensure that the exercises and limitations in the amplitudes of vibrations are correctly based on a corresponding vibration map for flight.

An accelerometer was used to measure the acceleration as a vibration amplitude. Since the majority of general helicopter rotating parts operate in the range of 2-100 Hz, acceleration is commonly used for vibration measurements and analyses.

Test setup and procedures

The flight test was conducted with the following equipment configuration:

- 12 channels NetdB12 – 01 Metravib digital analyzer and data collector for measuring vibrations and noise in real time,
- 5 accelerometers, B&K type 4393
- 1 tachometer.

The recording configuration was equiped with several accelerometers on different positions and helicopter directions. The positions of the accelerometers are given in Table 1 and in Fig.4.

Table 1. Positions of the accelerometers for flight testing

Chanel	Direction	Position
1.	longitudinal	Runner of the pilot seat (forward)
2.	vertical	On the forward part of the pilot seat floor – below runner
3.	vertical	On the forward part of the pilot seat – above runner
4.	vertical	On the rear part of the pilot seat floor – below runner
5.	vertical	Runner of the pilot seat (rear)

Figure 4. Equipment installed on specific locations in the cabin floor for flight testing

The profile of each flight for this testing consisted of the following elements:

- Low speed maneuvers with ground effect,
- Climb at altitude Hi=3000 m,
- Acceleration at altitude Hi=1000 m,
- Deacceleration at altitude Hi=1000 m,
- Turns at altitude Hi=1000 m with different velocity.

Test results and discussion

The first vibration test was performed in 2007 and the analysis of vibrations was conducted after each 100 hours or in situations of increasing vibrations based on pilot's sensibility. In accordance with the adopted methodology, the time domain and frequency domain were recorded from the first flight and adopted for the reference level of vibration investigation (Fig.5). The vibration map of proper conditions in the acceleration phase, one of the profile of flight, on which a decision about the helicopter condition is based, is shown in Fig.6. The results of average vibration levels are tabulated for the helicopter maximum velocity and hover for the accelerometers on channels 1, 2 and 3. in Table 2.

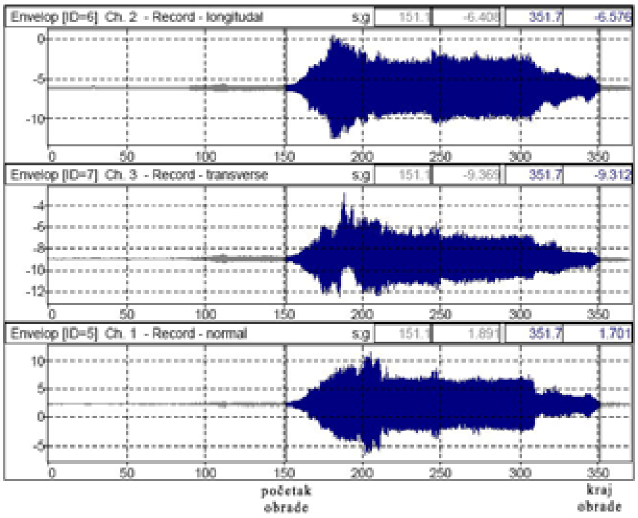

Figure 5. Time domain of the reference level of vibrations

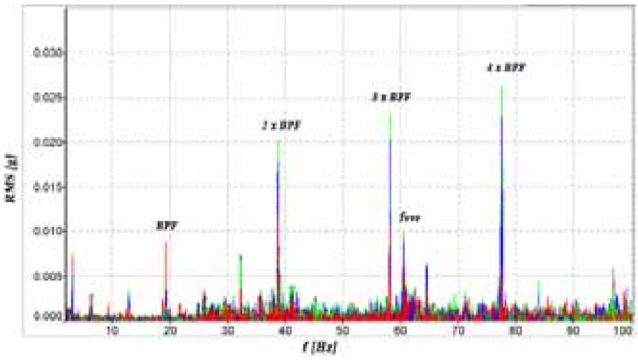

Figure 6. Vibration map of proper conditions in the phase of acceleration

Table 2. Vibration amplitude map in g's in different flight profiles

Profile of flight	*V* [km/h]	*f* [Hz]	Ch 1 [g RMS]	Ch2 [g RMS]	Ch 3 [g RMS]
Hover (H=10 m)	0	19.35	<0.0015	<0.0015	<0.0015
		38.70	0.0032	0.0059	0.0061
		58.05	<0.0015	<0.0015	<0.0015
		60.45	0.0074	0.0098	0.0106
		77.40	<0.0010	<0.0010	<0.0010
Vmax	240	19.35	0.0087	0.0050	0.0044
		38.70	0.0112	0.0186	0.0211
		58.05	0.0104	0.0213	0.0241
		60.45	0.0062	0.0091	0.0100
		77.40	0.0058	0.0243	0.0302

The flight test was conducted after 100 and 200 hours of operational service. After 100 hours, the change at frequency of 60.45 Hz was noticeable but it was lower about 6-7 % than the reference values of the vibration maps created from the first flight test. The results of testing after 200 hours were entirely different. The average FFT spectra from the second test (for channels 1, 2 and 3) are shown in Fig.7.

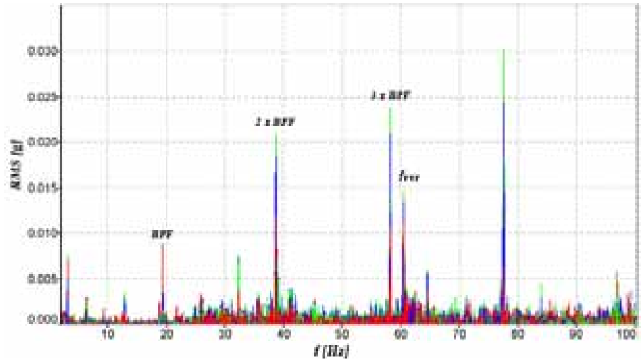

Figure 7. Vibration at specific locations in the cabin in the phase of acceleration

From these FFT spectra, from Fig.6 and Fig.7, it can be noticed that the biggest difference in amplitude levels is at a frequency of 60.45 Hz, which is an operational frequency of several helicopter elements. The percentage difference in the amplitude levels at a frequency of 60.45 Hz, between the adopted vibration maps and the second vibration check flight test, is presented in Table 3.

Table 3. The percentage difference in the amplitude levels at a frequency of 60.45 Hz

Profile	V [km/h]	Ch 1 [g RMS]	[%]	Ch2 [g RMS]	[%]	Ch 3 [gRMS]	[%]
Hover >200 h	0	0.0065	47	0.0098	40	0.0106	33
		0.0093		0.0138		0.0142	
Vmax >200 h	240	0.0062	53	0.0091	45	0.0100	36
		0.0095		0.0132		0.0136	

Comparing the vibration values in Table 3, it can be seen that the increase of all vibration amplitudes at a frequency of 60.45 Hz after 200 hours results in a potential fault in the part of the system operating at a given frequency, without being connected with a complex aerodynamic field. The slope shaft, the inter gear box, the horizontal shaft, the binder shaft of the tail shaft and the tail gear box are the transmission parts which operate at 60.45 Hz. The oil and hydraulic pumps were not considered because the fluid pressure is within the allowed range, the functions of system lubrication and hydraulic controls system are satisfied in whole operational range.

In accordance with the vibration theory, the transmission elements were subjected to measuring and analysis [8,9,10]. Since all these elements are located on the exterior of the Gazelle helicopter, it was decided to perform their visual inspection. After this inspection, the inter gear box was changed and the new vibration check flight test was performed. The results from the flight test with new inter gear box were analyzed and it was concluded that the amplitude levels of vibration of new gear box was on the level above of adopted vibration map for proper conditions, but below the vibration levels from test confirmed at 100 hours flight test with old inter gear box. These conditions of new inter gear box were adopted as correct for further operational service.

The transmission inter gear box was disassembled and inspected. The gear wheel of the removed inter gear box was damaged. The condition of this gear wheel is presented in Figs.7 and 8.

Figure 8. The surface damage on the gear wheel of the inter gear box of the Gazelle helicopter

Figure 9. The surface damage on the gear wheel of the inter gear box of the Gazelle helicopter

Conclusion

An approach to temporary controlling low frequency structure vibrations has been validated in a flight test program on the Gazelle helicopter. This approach has been successful in detecting potential faults on helicopters.

The temporary and uncommon usage of this presented method on a helicopter can be reduced a possibility for involving the helicopter in operational services (after preventive maintenance) with potential damage. Potential damages on helicopter structure and systems can cause the serious faults, which can lead to quickly and disastrously destroying of the whole helicopter.

This method and procedures have proved to be very successful for the following applications:

- for processes of optimization, development and modifications of the helicopter structure with the aim of vibration reduction to satisfy international standards,
- for development and modifications of new air-borne armament systems, and
- good start position in the development of a permanent vibration monitoring system.

The illustrated methodology and measurement and analysis procedures of low frequencies vibration range on the Gazelle helicopter can be applied to all types of aircraft in operational service of the Serbian Air Forces.

References

[1] MILLOTT,T.A., FRIEDMANN,P.P.: *Vibration Reduction in Helicopter Rotors Using an Actively Controlled Partial Span Trailing Edge Flap Located on the Blade*, NASA Contractor Report 4611, USA, 1994

[2] FARRAR,C., LIEVEN,N.: *Damage prognosis: the future of structural health monitoring*, Philosophical Transaction of the Royal Society, 2007, Vol.365, pp.623-632

[3] ALI,M.K., YOUSSEF,M.F.H., HAMAAD,M.A., EL-BUTCH,A.A.: *A Study on Fault Diagnosis by Vibration Analysis at Different Loading and Speed Conditions*, 13th International Conference on Aerospace Science & Aviation Technology, Cairo, Egypt, 2010.

[4] JOVANOVIĆ,M.: *Analysis of low frequency vibration on structural connection elements of helicopter Gazelle*, Military Technical Courier, 2010, No.4, pp.17-36,

[5] JOVANOVIĆ,M., FILIPOVIĆ,Z., STUPAR,S., SIMONOVIĆ,A.: *An example of equipment subsystem for aircraft life extending model*, 4th International Scientific Conference on Defensive Technology, OTEH 2011, Belgrade, Serbia, 2011.

[6] JOHNSON,W.: *Helicopter theory*, Dover Publications, New York, 1994.

[7] HARRIS,M.C.: *Shock and vibration handbook*, McGraw-Hill, 4th ed., 1996.

[8] TANDON,N., CHOUDHURY,A.: *A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings*, Tribology International, 1999, Vol.32, pp.469–480.

[9] KIRAL,Z., KARAGÜLLE,H.: *Simulation and analysis of vibration signals generated by rolling element bearing with defects*, Tribology International, 2003, Vol.36, pp.667–678.

[10] KAR,C., MOHANTY,A.: Vibration and current transient monitoring for gearbox fault detection using multiresolution Fourier transform, Journal of Sound and Vibration, 2008, Vol.311, pp.109–132.

Received: 20.02.2012.

Merenje i analiza vibracija na helikopterskoj strukturi sa ciljem otkrivanja defekta radnih elemenata

U radu je prezentovan praktičan primer merenja i analize vibracija na helikopterskoj strukturi sa ciljem da se otkriju potencijalna oštećenja radnih elemenata. Sveobuhvatna metodologija merenja vibracija je predstavljena u ovom članku i sprovedena sa ciljem da se utvrdi ispravan rad rotirajućih komponenata. Poseban osvrt je dat na analizi uzdužnih i vertikalnih vibracija trupa helikoptera u frekventnom domenu za različite profile leta. Merenje i analiza vibracija na određenim lokacijama helikopterske strukture, rezultiralo je blagovremenim tehničkim pregledom odgovarajuće komponente i otkrivanjem njenog površinskog oštećenja. Praktična upotreba predložene metodologije merenja i analize je moguće implementirati na više vrsta letelica u cilju produženja životnog veka.

Ključne reči: **helikopter, struktura letelice, trup letelice, reduktor, vibracije letelice, merenje vibracija, frekventni domen, ispitivanje u letu, Furijeova transformacija.**

Измерение и анализ вибраций структуры вертолёта с целью обнаружения повреждений рабочих элементов

Эта работа представляет собой практический пример измерения и анализа вибраций на структуре вертолёта с целью обнаружения возможных повреждений рабочих элементов. В этой статье представлен комплексный метод для измерения вибраций и осуществлён в целях определения правильности работы вращающихся компонентов. Особое внимание уделено анализу продольных и вертикальных вибраций фюзеляжа вертолёта в частотной области для различных профилей полёта. Измерение и анализ вибраций в определённых местах структуры вертолёта в результате дали своевременное техническое рассмотрение соответствующих компонентов и раскрытие повреждения её поверхности. Практические использования предлагаемой методики измерения и анализа могут быть реализованы в нескольких типов летательного аппарата для того, чтобы продлить его срок службы.

Ключевые слова: **вертолёт, структура летательного аппарата, фюзеляж летательного аппарата, редуктор, вибрации летательного аппарата, измерение вибраций, частотная область, испытания в полёте, преобразование Фурье.**

Le mesurage et l'analyse des vibrations sur la structure d'hélicoptère en vue de détecter les endommagements des éléments de travail

Dans ce papier on a présenté un exemple pratique du mesurage et de l'analyse des vibrations chez la structure d'hélicoptère dans le but de détecter les endommagements possibles des éléments de travail. Une méthodologie complète de mesurage des vibrations était présentée et réalisée en vue de constater le fonctionnement correct des composantes de rotation. L'attention particulière était prêtée à l'analyse des vibrations longitudinales et verticales du fuselage d'hélicoptère dans le domaine fréquent pour les différents profils du vol. Le mesurage et l'analyse des vibrations sur les locations spécifiques de la structure d'hélicoptère a comme résultat l'examen technique à temps de la composante correspondante ainsi que la détection de son endommagement superficiel. L'emploi pratique de la méthodologie proposée de mesurage et d'analyse peut s'appliquer pour plusieurs types d'aéronefs dans le but de prolonger leur durée de vie.

Mots clés: **hélicoptère, structure d'aéronef, fuselage, réducteur, vibrations d'aéronef, mesurage des vibrations, domaine de fréquence, essais en vol, transformation de Fourier.**