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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF A GROUND RESONANCE PHENOMENON FOR THE ILX-27 UAV HELICOPTER

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Abstract

Ground resonance is an unbalance of the helicopter main rotor rotation caused by its asymmetry. Whilst the helicopter is in contact with the ground this asymmetry generates a divergent and often destructive oscillations of the helicopter structure. These oscillations are self-excited. This paper present results of both theoretical and experimental investigations of this phenomenon. They were dedicated to the new polish UAV helicopter ILX-27. The theoretical analysis were done with commercial software ANSYS using Finite Element Method. The virtual model of the helicopter model accurately reproduced the geometry of all elements of the helicopter and was easy to modify to simulate various kinds of damages. Calculations were done for the following cases: C1 – the helicopter standing on the ground with zero thrust of the rotor, C2 = C1 + helicopter with additional support of the rotor mast, C3 = C2 + thrust of the rotor equal to the total mass of the helicopter, C4 = C2 + fixing the helicopter to the ground, C5 = C2 + helicopter with additional mass. At the beginning the modal analysis for all cases was done – natural frequencies and modes of the structure were identified. Next, for selected cases, harmonic analysis was performed – the structure of the helicopter was loaded with concentrated harmonic forces. Finally the dynamic analysis gave time courses of blades and the hub center motions in the case of structural damages. All phases of simulations were correlated with ground tests of the helicopter prototype. This allowed to compare results of theoretical investigations. These results also supported tests of the prototype.

Keywords: *ground resonance, dynamics of helicopter structure, finite element method, simulation, ground tests*

1. Introduction

A helicopter is a rotorcraft, which can be subjected during its motion, to various types of vibrations [1-12]. When the helicopter is in contact with the ground, with its rotor running, a divergent oscillations of the rotor hub can occur. If the hub moves cyclically in the plane of rotation and its natural frequency is of the same order as the rotor speed the self-excited oscillations can be observed. These conditions appear on the ground, since the natural frequency of a helicopter standing on a shock-absorbing landing gear is often close or within the frequency range of the main rotor.

Cyclical motion of the hub in the plane of rotation is caused by lagging motion of blades. When out-of-phase lagging motion of particular blade appears its inertia forces react with the fuselage on its elastic landing gear and the fuselage starts to oscilate. In turn, oscillations of the fuselage produce motion of the hub, which further excites the lagging motion of the blades. The out-of-phase lagging motion may be caused by blast of wind, damage of damper etc. This is the source of an unstable behaviour of the helicopters.

Frequency of inertia forces is depended on the frequency of blades natural vibrations and on the angular velocity of the main rotor [1, 2, 4, 5, 7, 8, 10, 12]. Because this angular velocity changes during taxying or take-off the self-excited process, known as ground resonace, can appear for the helicopter staying on the ground. The ground resonance was encountered soon after the introduction of helicopters. A lot of accidents were caused by this phenomenon.

In a classical theory of the ground resonance for a one-main rotor helicopter [1-5, 7-12] only the following motions are usually considered: the lagging of the main rotor blades, the rolling of the fuselage about longitudinal axis and the displacement of its mass centre along lateral axis. This resonance is called the lateral ground resonance. Sometimes the "longitudinal" resonance is also considered but it is not so important as the lateral ground resonance. Aerodynamic forces are not included into consideration – an assumption is made that the main rotor rotates in vacuum. Many other simplifications are taken into account too. Only sometimes more complex models of the helicopter (including aerodynamic forces) are considered [6].

2. The ILX-27 helicopter

The ILX-27 helicopter was carried out by the consortium of three aviation institutions: Institute of Aviation, Air Force Institute of Technology, Military Aviation Works. The main purpose of this helicopter is the support for the army, navy or board guards special missions carried out in the difficult terrain (such as mountains and urban areas) or at risk of enemy fire. Usage of this helicopter depends on the type of installed devices and special equipment such as any kind of sensors. It may be used: – as the center of air reconnaissance, – for the transport of supply, – as the carrier of precision weapons, – for the evacuation reason of troops from areas at risk

It is assumed that it can operate in the area of natural or environmental disasters and it can be used for monitoring of engineering objects as bridges, railways, highways or other areas. Its planned performances are as follows: – max take-off weight 1100 kg, – payload 300 kg, – max speed 215 km/h, – max rate of climb 10 m/s, – ceiling 4 km, – range 441 km.

The design process was started in 2009. In 2012 two prototypes were completed. Fig. 1 presents one of them during ground tests. On 20 September of the same year, it flew for the first time on the range in Zielonka near Warsaw (Fig. 2). In the same year the prototype was also presented at the exhibition ILA Berlin Air Show (Fig. 3). Also in Poland, the helicopter was presented to the public during open public events and exhibitions.

The helicopter is modular, thus its reconfiguration (to perform specific tasks) does not require time-consuming work. It consists of three main parts: – the main gearbox and the engine are the central module, – the tail beam machines with drive shaft and the tail rotor gearbox, – the bow adapted to install various sensors and observation equipment. Both modules – the bow and the tail – may be easily detached from the central module [13, 14, 15, 16, 17]. The main rotor has three blades. Because of the low speed of the blades tips the helicopter is relatively quiet. Skids of the landing gear are capable to absorb impact energy during the touchdown. The additional outriggers are designed to cary payload of 200-300 kg (Fig. 4).

2. Description of the virtual model

One of the most important task od the design process was to estimate a risk of the ground resonance. Therefore theoretical investigations were done and the virtual model of the helicopter was carried out using Finite Element Method with commercial software ANSYS (Fig. 5). It allowed to omit most of simplifications listed in the introduction. This model accurately reproduces the geometry of all elements of the helicopter. It includes 3122 nodes, 2756 elements of 31 types. In Fig. 5 we have the rotor hub shown in details.

The virtual model is also easy to modify. One can change any element of the structure, its shaft, material properties. So, we have large computing capabilities. One can modify the structure of the helicopter components or simulate various kinds of damages. For instance, in Fig. 7 additional structural elements for the hub are shown. In the Fig. 8 the damage of one of blades is visualized.

Fig. 1. Ground test of the ILX-27

Fig. 2. Flight test of the ILX-27

Fig. 3. ILX-27 at the exhibition ILA Berlin Air Show (2012)

Fig. 4. External devices

Fig. 5. Virtual model of the ILX-27

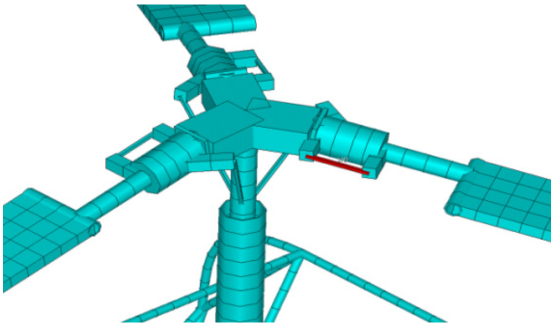


Fig. 6. Model of the rotor hub

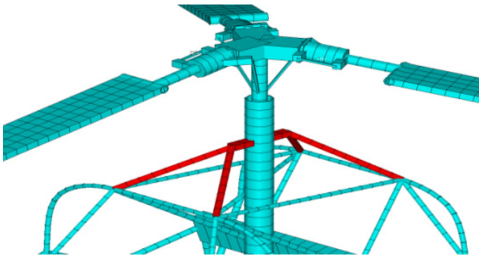


Fig. 7. Additional structural elements

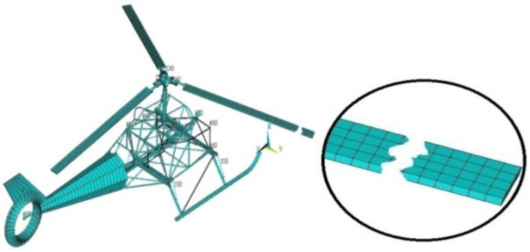


Fig. 8. Damage of the blade

Finally, on the basis of the virtual model, the mathematical description of the helicopter structure dynamics was carried out. This is symbolically shown as a system of nonlinear differential equations:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}\,, \tag{1}$$

where: **M** is the matrix of inertia, **C** – matrix od dumping, **K** – matrix of stiffness. **F** represents the external forces.

On the basis on material properties of all elements the mass of the virtual model is 1099 kg and it is equal to the mas of the real prototype. Positon of the center of gravity has also been identified. This position corresponds to the position of the center of mass of the real helicopter.

3. Results of the simulation

The described above virtual model was used to analyze the dynamic properties of the helicopter, especially to estimate the potential risks related to vibration of the structure. Three types of analysis were performed: – the modal analysis, – the harmonic analysis and the dynamic analysis.

For ILX-27 the frequency of the rotational motion of the rotor is 8 Hz. The natural frequency of the lagging motion is 2Hz. Therefore from well known the ground resonance diagram (Fig. 9) we have, for the point *B*, that the ground resonance frequency is equal to 6Hz. If any of natural frequencies of the helicopter is close to this frequency it may be a source of risk of the ground resonance.

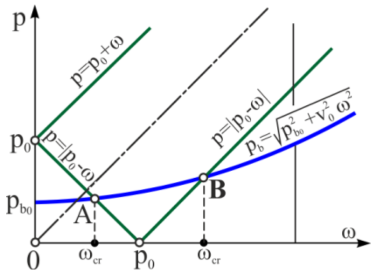


Fig. 9. Ground resonance diagram

Fig. 10. Test stand

3.1. Modal analysis

Calculations were done for the following cases: C1 – the helicopter standing on the ground with zero thrust of the rotor, C2 = C1 + helicopter with additional support of the rotor mast, C3 = C2 + thrust of the rotor equal the total weight of the helicopter, C4 = C2 + fixing the helicopter to the ground, C5 = C2 + the helicopter with additional mass. These cases of calculations were correlated with real ground tests (Fig. 10). Fig. 11 and 12 present exemplary modifications of the virtual model of the helicopter.

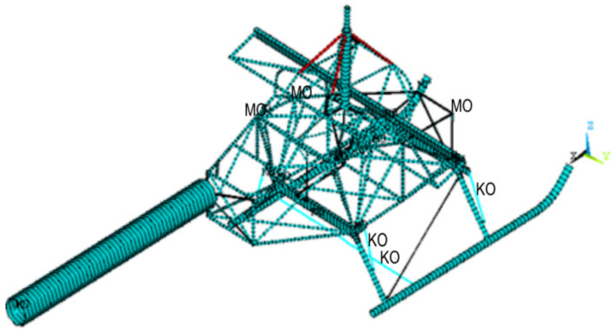


Fig. 11. Case 2 – additional support of the mast

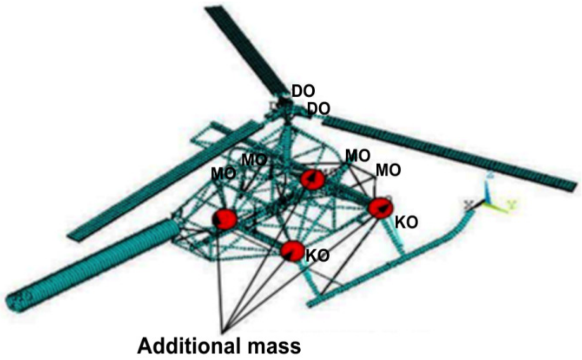


Fig. 12. Case 5 – additional mass

Performed modal analysis allowed to determine (on the basis of Eq.1) all eigenvalues and eigenvectors. Tab. 1 summarises natural frequencies for defined above cases of calculations. We can see that for the basic (primary) structure of the helicopter (Case 1) one of calculated frequencies is close to the 6 Hz. This mode represents bending vibrations of the tail beams and motion of the rotor hub center in the *ZY* plane (Fig. 13). Due to the proximity of the last frequency to the ground resonance frequency, the helicopter structure has been modified. This was done by stiffening the support of the rotor mast using additional elements (Case 2).We can see that there is not natural frequency of the helicopter close to the ground resonance frequency 6 Hz. Identification of natural modes were also performed.

Tab. 1. Natural frequencies of the ILX-27 structure

Case 1		Case 2		Case 3		Case 4		Case 5	
No	*f [Hz]*	*No*	*f [Hz]*	*No*	*f [Hz]*	*No*	*f [Hz]*	*No*	*f [Hz]*
1	1.56	1	1.07	1	1.78	1	2.09	1, 2, 3	1.1, 1.49, 2.06
2	1.79	2	1.1	2	2.92	2	2.11	4, 5, 6	2.36, 2.41, 2.79
3	3.21	3	2.57	3	4.1	3	2.37	7	3.33
4	**6.58**	4	3.32	4	13.43	4	2.97	8	11.9
5	8.29	5	4.05			5	**5.97**		
		6	8.29			6	7.41		

Next variant of calculations (Case 3) was done for the last configuration (with additional elements) but in this case the thrust is equal to the weight of the helicopter. It simulates the take-off moment. Simulations were performed because similar tests were also planned for prototypes. Because this is the UAV helicopter, the knowledge about of the potential resonance frequencies is very important. One can see that the closest natural frequency is almost the same as for previous case – it means that there is no risk of the ground resonance.

The next case (Case 4) is for the helicopter with modified structure. The helicopter is fixed to the ground. Such attachment to the ground is commonly used during tests, for instance tests of the engine or additional equipment. This protects the helicopter before the ground resonance. In this case the main rotor was reproduced in details – we have the hub and three blades with their hinges and dampers. One can see that the fixing of the helicopter fundamentally changes the natural frequencies. During this kind of tests the ground resonance can appear – one of frequencies (5.97 Hz) is close to the ground resonance frequency. This was the important conclusion for the research team.

The last modal analysis was made for the helicopter with additional masses, which are used to mount the helicopter to the ground (Case 5). This is one of methods used to fix the helicopter to the surface. These masses are of 30% of the helicopter mass. Analysis showed that there was not risk of the ground resonance.

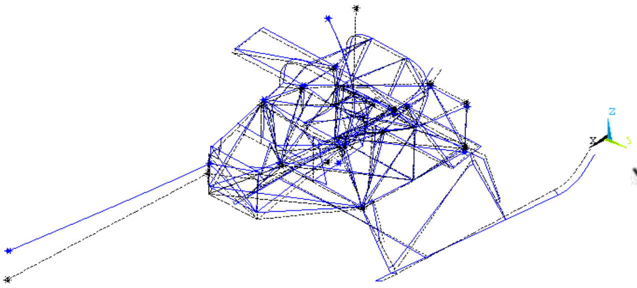


Fig. 13. Bending of the tail beam and motion of the rotor hub center in the ZY plane

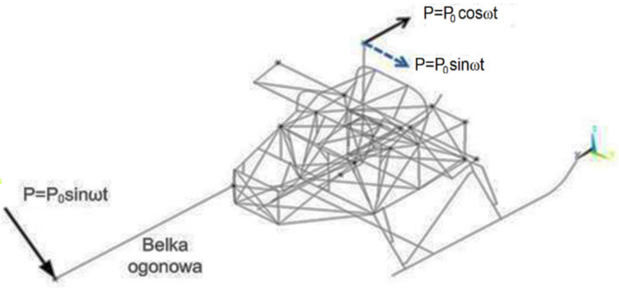


Fig. 14. Model of the helicopter for harmonic analysis

3.2. Harmonic analysis

Harmonic analysis were done on the basis of the Eq.1, but in this case the right-hand side of the equation was not equal to zero. The external forces were modeled as the harmonic oscillations applied to the center of the main rotor hub or to the tail boom (Fig. 14). Direction of the hub force was varied. The amplitude was 200 N for the hub force, and 100 N for the tail rotor force. Their frequency was changed from 0 Hz to 60 Hz. Calculations were done for the basic structure of the helicopter (Case 1) and for the structure with additional support of the rotor mast (Case 2). Fig. 15 and 16 presents the amplitude and the phase of the lateral motion (Y direction) of the main rotor hub center. We can see that:

- for the basic structure there is the risk of the ground resonance for the frequency of 6 Hz. It agrees with results of modal analysis.
- the additional elements supporting the mast significantly reduces the amplitude of oscillations – we can compare blue and green lines.

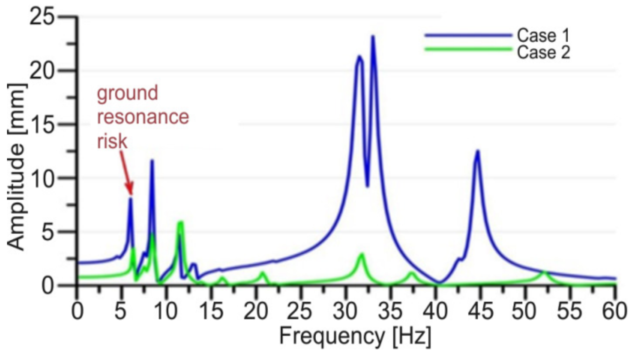


Fig. 15. Amplitude of the hub lateral motion

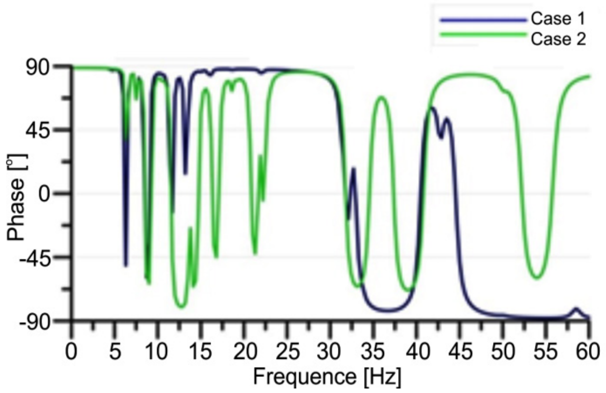


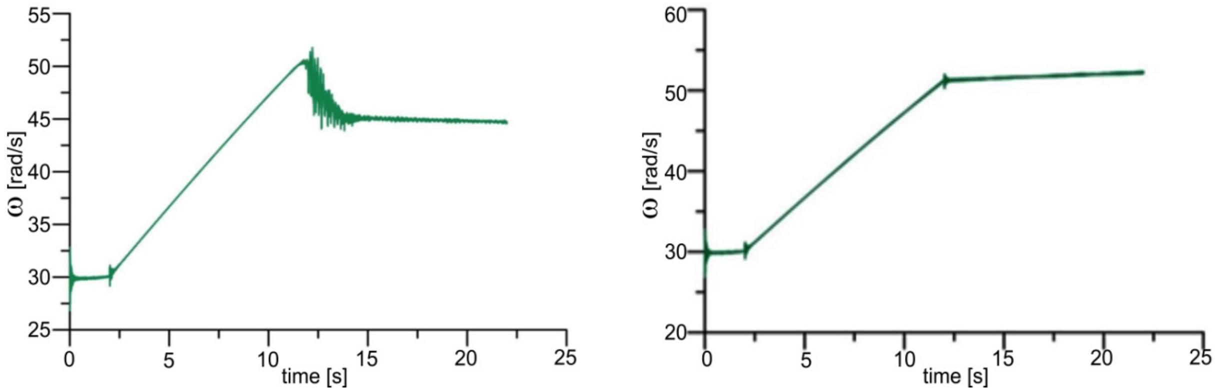
Fig. 16. Phase of the hub lateral motion

3.3. Dynamic analysis

Dynamic analysis were done for the variable angular velocity of the main rotor. In these simulations this velocity was changed in a continuous manner from 30 to 51 rad/s. The last value is the nominal velocity. It means that the rotor was untwisted. Calculations were done for the basic structure of the helicopter (Case 1) and for the structure with additional support of the rotor mast (Case 2).

Figures 17-19 show comparison of exemplary results for the basic structure of the helicopter (Case 1) and for the modified frame (Case 2). We have rotor velocity (Fig. 17), the lagging motion about vertical hinge of one of blades (Fig. 18) and the horizontal trajectory of the hub center (Fig. 19).

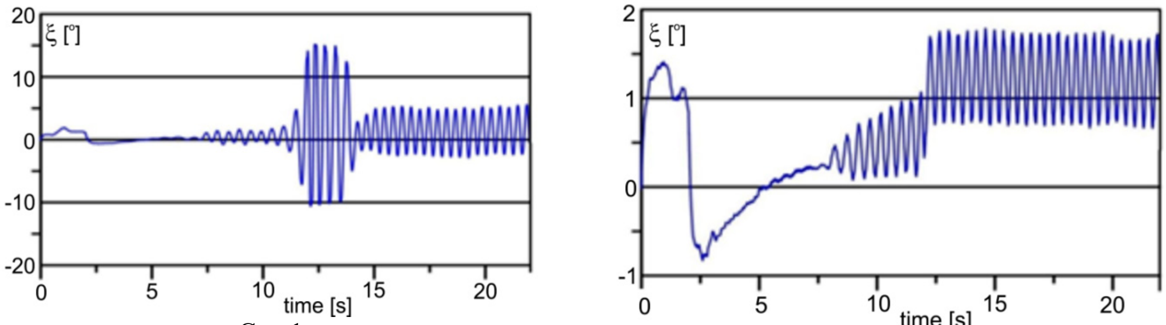
We can see that for the Case 1 there is a strong increase of the lagging angle. The same phenomena is observed for the motion of the hub center – it is particularly important in lateral direction because of ground resonance risk. The additional structure elements reduces amplitudes of all vibrations about eight times. This shows that reconfigured support of the rotor mast has to be implemented for the ILX-27 helicopter.



Case1

Case 2

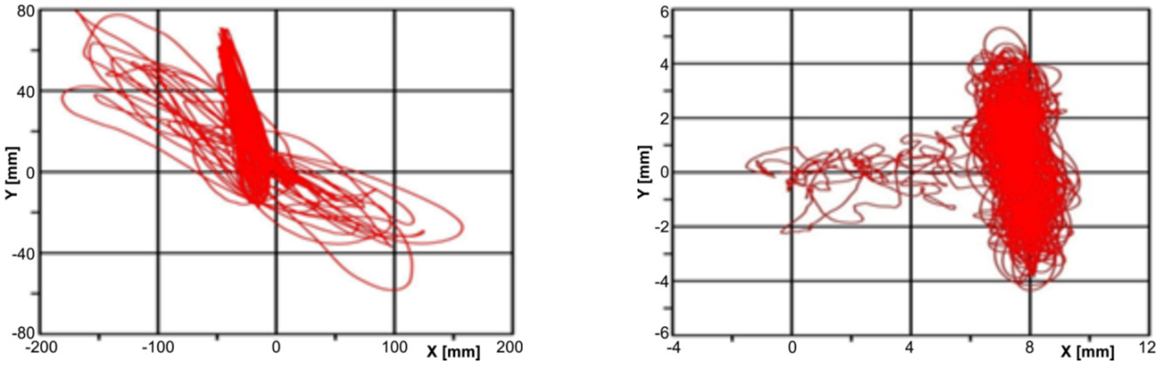
Fig. 17. Rotor angular velocity



Case1

Case 2

Fig. 18. Lagging motion of the blade



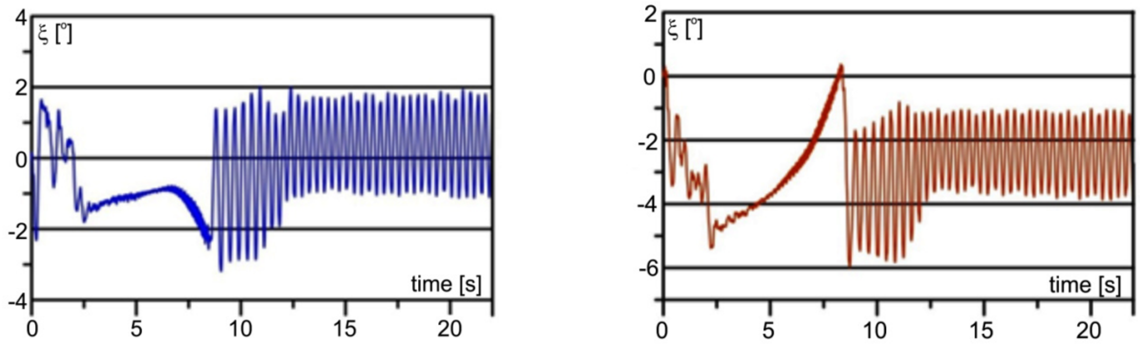
Case1

Case 2

Fig. 19. Trajectory of the hub center

3.4. Dynamics of damaged helicopter structure

The next simulations were dedicated to the damaged helicopter. Its structure was modified using the additional support of the rotor mast (Case 2). It was assumed that one of blades is damaged – the tip part of the blade is cut (about 2 kg) as shown in Fig. 8. The rotor was still untwisted – so it was still dynamic analysis. We can observe different motion for the efficient and damaged blades (Fig. 20). This damage also produces strong vibrations of the hub center, which can be potentially dangerous for the helicopter.



Efficient blade

Damaged blade

Fig. 20. Lagging motion

4. Conclusions

On the basis of the obtained results we can conclude that:

- the virtual FEM model of the helicopter is the powerfull support for its design, building and testing process,

- this model allows to map the full structure of the helicopter,
- modifications of the real helicopter structure are easy to simulate,
- this model allows to analyze vibrations of the helicopter structure,
- the ground resonance phenomena can be effectively simulated without any simplifications,
- real test conditions can be simulated using the FEM model.

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