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INFLUENCE OF EMBEDDED DIAGNOSTIC SENSORS ON STRUCTURAL DYNAMIC BEHAVIOUR OF COMPOSITE ROTORS

Technological progress in the field of fibre and textile reinforced composites caused that these materials are increasingly used in the process of rotating machinery design including aircraft engines, turbines, etc. Reduction of mass and increase of strength of composite rotor elements by means of optimization of matrix and anisotropic reinforcement properties allows us to decrease dynamical forces and thereby to increase the machinery efficiency. This unique material optimization is impossible in the case of rotors made of classical isotropic materials. The application of the composite rotors with high reliabili-ty demands causes that it is important to evaluate their durability and to investigate phenomena related to the complex material degradation process and to the rotor failures. One of the ways of the failure detection and observation of its evolution is to apply a diagnostic system which use methods based on relations between features of diagnostic signals and the technical state of the machine. Diagnostic signals, e.g. vibroacoustic signals, can be observed and supplied on-line to the diagnostic system. Signal observation requires an application of suitable sensors, which should be mounted as close as possible to the place where the failure can occur. Among of different solutions, a big attention is paid to piezoelectric sensors, which are embedded in composites. Such type of sensors, especially in high-speed rotors, can cause unintended changes of their dynamical properties. In the article, a short overview of requirements for a diagnostic system at the different stages of life of a composite rotor was shown. Exemplary results of numerical modal analysis of a composite rotor disk with embedded piezoelectric sensors was presented. The aim of the experiment was to identify how the size and the number of piezoelectric patches effect on dynamic behavior of the disk at different values of rotational speed.

Keywords: **composite rotors, diagnostics, piezoelectric patches, modal analysis**

WPŁYW WBUDOWANYCH CZUJNIKÓW DIAGNOSTYCZNYCH NA ZACHOWANIE DYNAMICZNE WIRNIKÓW KOMPOZYTOWYCH

Postęp technologiczny w dziedzinie materiałów kompozytowych na osnowie włóknistej lub tekstylnej spowodował, że znalazły one zastosowanie w procesie projektowania i konstruowania maszyn wirnikowych, takich jak np. silniki odrzutowe, turbiny itp. Obniżenie masy i zwiększenie wytrzymałości wirników kompozytowych poprzez optymalizację własności i właściwości osnowy oraz matrycy pozwala na obniżenie poziomu sił dynamicznych, a tym samych na podniesienie wydajności i efektywności działania maszyny, co w przypadku wirników wykonanych z klasycznych materiałów nie byłoby możliwe. Stosowanie wirników kompozytowych o wysokich wymaganiach niezawodnościowych powoduje, że konieczne jest określanie ich trwałości i poznanie zjawisk leżących u podstaw powstawania uszkodzeń. Jednym ze sposobów detekcji uszkodzeń i obserwacji ich rozwoju jest stosowanie systemów diagnostycznych, w których wykorzystuje się metody diagnozowania oparte na relacjach diagnostycznych między cechami sygnałów diagnostycznych i cechami stanu technicznego maszyny. Sygnałami diagnostycznymi mogą być m.in. sygnały wibroakustyczne obserwowane i analizowane w sposób ciągły przez systemy monitorowania. Obserwacja sygnałów wymaga stosowania odpowiednich czujników, które powinny być zamontowane jak najbliżej miejsc, gdzie mogą wystąpić uszkodzenia. Spośród wielu rozwiązań dużym zainteresowaniem cieszą się czujniki wykonywane z materiałów piezoelektrycznych, które są wbudowywane w strukturę kompozytową. Zastosowanie tego typu czujników, szczególnie w wirnikach wysokoobrotowych, może mieć wpływ na ich własności dynamiczne. W artykule poza podstawowymi informacjami o procesie diagnozowania i wymaganiach dotyczących trwałości wirników kompozytowych przedstawiono przykładowe wyniki badań uzyskanych podczas prowadzenia numerycznego eksperymentu modalnego prostego modelu tarczy wirnikowej z wbudowanymi czujnikami piezoelektrycznymi. Eksperyment miał na celu określenie wpływu wielkości i liczby czujników na właściwości dynamiczne tarczy przy różnych prędkościach obrotowych.

Słowa kluczowe: **wirniki kompozytowe, diagnozowanie, czujniki piezoelektryczne, analiza modalna**

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INTRODUCTION

The raising demands on efficiency of modern rotating machinery on the one hand and the technological progress in the field of composite materials on the other hand caused that the application of parts made of fibre and textile reinforced plastics increases in the process of machinery design [1]. High specific strength and stiffness with possibility of controlling their properties through a reinforcement and matrix optimization are important advantages of these materials. In this way, a load-adapted thermo-mechanical property profile and the excellent resistance to chemicals can be achieved at the stage of material design.

Phenomena typical for the rotor operation (centrifugal forces, medium flow influence etc.) in combination with unexpected external excitations build a complex, dynamical state of load that can initiate various failure processes of rotor components. Since the progress of the failure in critical components of the machine can lead to a catastrophic damage, it is very important to apply an reliable diagnostic system, which enables on-line monitoring, diagnosing and prognosing faults and thus helps to make appropriate maintenance decisions. In general, diagnostic systems base on information carried by signals, which describe changes of observed parameters such as acceleration, strain, stress, temperature etc. [2-5]. The prerequisite for the application of such systems is the selection of appropriate signals that can be measured directly on the machine and their features, which are relevant to the specified diagnostic task.

The paper deals with some aspects connected with the use of sensors embedded in composite components of the rotor. The application of such sensors seems to be very promising as they can directly measure vibroacoustic signals as the response of the monitored part to operational excitations. However, it should be considered that these sensors also affect properties of the base material. Conducted research gives the estimation, how the dynamical behaviour of an exemplary disk rotor made of carbon fibre (CF) reinforced PEEK changes in consequence of piezoelectric sensor embedding.

DIAGNOSTICS OF COMPOSITE ROTORS

Any damage (e.g. micro-cracking, fibre failure, delamination, compressive failure) in a composite structure [6] begins always from a very tiny extent and gradually cumulates to some degree which causes variations in structural mechanical characteristics. The main purpose of a designed on-line diagnostic system is to recognize the significant increase of the damage and, wherever applicable, to predict the remaining safety margin (Fig. 1).

Elements of rotating machinery rotors are not readily accessible for damage detection using conventional techniques such as x-radiography, acoustic emission (AE) and ultrasonic testing. All these techniques have a common limitation in that continuous damage assessment cannot be made in situ during the machine operation.

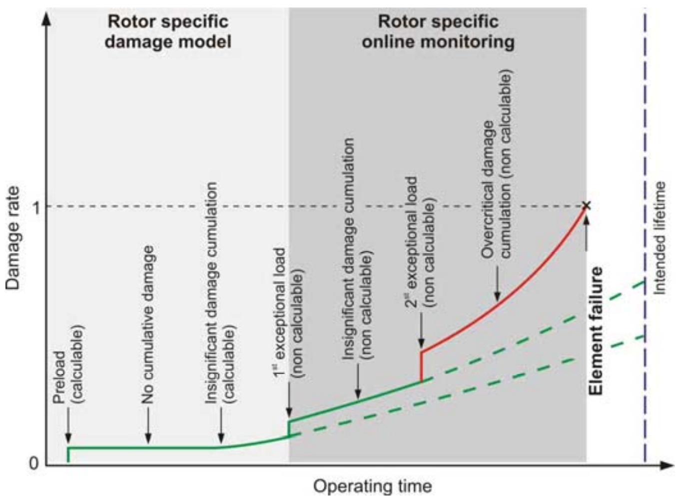


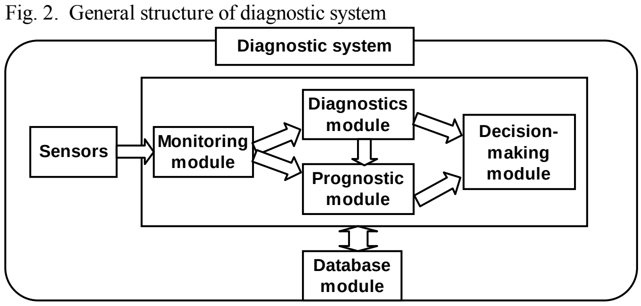
Fig. 1. Task-sequence of diagnostic system during composite rotor life cycle

Rys. 1. Zadania systemu diagnostycznego wirników kompozytowych w czasie cyklu ekspolatacyjnego

In order to monitore rotating machinery continuously diagnostics systems are used [2-4, 7]. In general, they consisting of (Fig. 2):

- Monitoring module (continuous signal acquisition and processing)
- Diagnostic module (fault detection, isolation and identification)
- Prognostic module (fault prediction)
- Maintenance supporting module

Fig. 2. General structure of diagnostic system



Rys. 2. Ogólna struktura systemu diagnostycznego

Present diagnostic systems are able to collect a lot of signals of process and structural parameters such a temperature, vibrations etc. and to inference on their basis. Over the time it was possible to acquire some general diagnostic knowledge [2, 4] concerning typical faults of rotating machinery equipped with conventional rotors (e.g. unbalance, bearing displacements, shaft cracks, rub etc.) that tailored for a given machine enables the diagnostic and prognostic modules to interpret patterns of diagnostic signal features. In the case of novel high performance rotors containing critical parts made of composite materials, it is necessary to enhance the existing diagnostic knowledge with features concerning specific, for these materials, damage evolution with associated dynamical phenomena.

On-line diagnostics can be realized on the basis of vibroacoustic signal analysis gathered by fixed sensors placed close to selected elements of the machine. These signals, such as absolute vibration orbits of the bearing casing or relative orbits of bearing journals, result from the interaction of all phenomena connected with rotating machine operation. Since, in this case, the identification of unknown signal components originating from damaged composite parts is complicated, the application of sensors embedded in the composite structure is desirable. Laminated composites can be equipped with following embedded sensors [8-12]:

- piezoelectric sensors,
- optical fibre sensor,
- shape memory alloys sensor,
- magnetoelastic sensors.

Recently, a special attention has been paid to the detection of composite damage using piezoelectric sensors/ /actuators. Detection of the damage can base on structural vibration responses excited and measured by integrated piezoelectric actuators and sensors.

INFLUENCE OF EMBEDDED SENSORS ON DYNAMIC BEHAVIOUR OF A COMPOSITE ROTOR

The application of embedded piezoelectric sensors/actuators in composite structure for on-line monitoring and diagnostic purposes is connected with a change of structural properties of the composite. Such modification of composite properties can affect the behaviour of whole rotating machinery and cause considerably increased vibration level. The high level of vibration in turn can speed up the degradation process of the composite structure. Thus it is important to investigate how piezoelectric sensors/actuators affect the modal properties of a composite rotor.

Description of a model

An object of the research was a multilayered composite disk with piezoelectric patches. The disk was made of 12 layers BD CF PEEK whose properties are shown in Table 1. Dimensions of the disk shows Figu-re 3a. The stacking sequence of the composite plate was θ = [0, 60, 90, 0, –60, 90]$_S$ as shown the Figure 3b, which causes a quasi isotropic behaviour in the plane.

The model of the disk was created using ANSYS Parametric Design Language [13, 14]. The meshing was conducted with the use of a mapped hexahedral finite element Solid 46 type. The disk was fixed along the edge of the centre hole and its rotation about the Z axis was simulated at different rotational speed ω = 0, 1000, 2000, 3000, 4000, 5000, 6000 rpm. For the needs of numerical experiments appropriate ANSYS scripts were prepared, which allow us to change automatically the model parameters.

TABLE 1. **Properties of the single layer BD CF PEEK**
TABELA 1. **Własności pojedynczej warstwy BD CF PEEK**

Young's modulus, GPa	$E_x = E_1 = 81.2$ $E_y = E_z = E_2 = E_3 = 7$
Shear modulus, GPa	$G_{xy} = G_{xz} = 2.69$ $G_{yz} = G_{zy} = E_y/2(1 + \nu_{yz}) = 3.9$
Poisson ratio	$\nu_{xy} = \nu_{xz} = 0.3$ $\nu_{yz} = \nu_{zy} = 0.4$
Density, kg/m^3	ρ = 1426.96

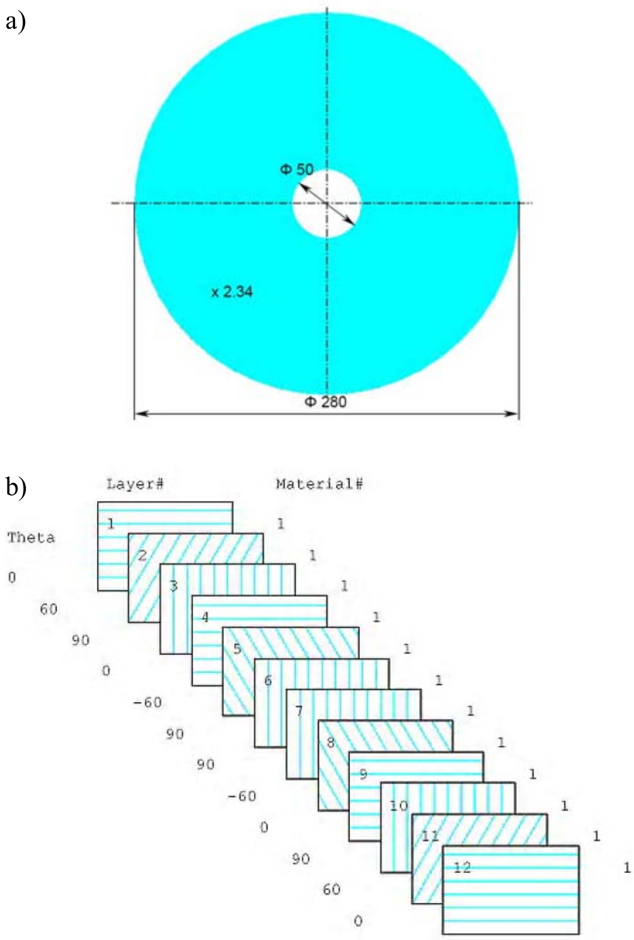


Fig. 3. Dimensions of the investigated composite disk and its stacking sequence

Rys. 3. Wymiary badanego wirnika tarczowego i układ warstw

Three different models of disks were considered. Models differ in the number and size of the attached piezoelectric patches. Locations and sizes of patches applied directly on the surface of the composite disk are shown in Figure 4.

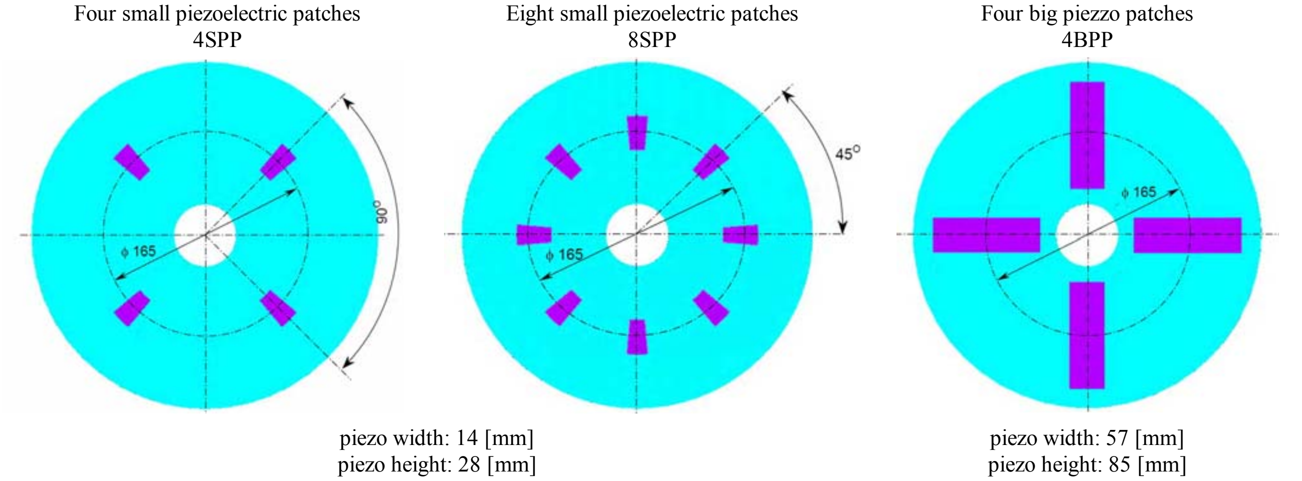


Fig. 4. Location and dimensions of the applied piezoelectric patches

Rys. 4. Położenie i wymiary zastosowanych elementów piezoelektrycznych

TABLE 2. **Properties of a piezoelectric ceramic material PZT5A3 after transformation [13]**
TABELA 2. **Własności materiału piezoelektrycznego PZT5A3 po transformacji [13]**

Permitivity F/m	Piezoelectric constant	Stiffness m^2/N	Density kg/m^2
$\varepsilon^S_{11} = 15.32 \times 10^{-9}$ $\varepsilon^S_{33} = 15.05 \times 10^{-9}$	$e_{31} = -5.35$ $e_{33} = 15.78$ $e_{15} = 12.32$	$c^E_{11} = 12.03 \times 10^{-10}$ $c^E_{12} = 7.52 \times 10^{-10}$ $c^E_{13} = 7.51 \times 10^{-10}$ $c^E_{33} = 11.09 \times 10^{-10}$ $c^E_{44} = 2.11 \times 10^{-10}$ $c^E_{66} = 2.26 \times 10^{-10}$	$\rho = 7700$

TABLE 3. **Results of modal analysis of composite disk rotor model without piezoelectric patches (0PP)**
TABELA 3. **Wyniki analizy modalnej modelu wirnika kompozytowego bez piezoelementów (0PP)**

Angular velocity rpm	Eigenfrequency, Hz									
	1	2	3	4	5	6	7	8	9	10
0	66.135	66.135	91.426	137.23	137.23	319.1	319.1	562.27	562.27	733.18
1000	68.34	68.34	92.162	139.89	139.89	321.22	321.22	564.16	564.16	734.02
2000	74.565	74.565	94.334	147.6	147.6	327.5	327.5	569.81	569.81	736.54
3000	83.917	83.917	97.831	159.62	159.62	337.69	337.69	579.09	579.09	740.71
4000	95.478	95.478	102.5	175.07	175.07	351.46	351.46	591.83	591.83	746.53
5000	108.17	108.54	108.54	193.11	193.11	368.4	368.4	607.81	607.81	753.94
6000	114.65	122.62	122.62	213.09	213.09	388.08	388.08	626.78	626.78	762.91

The piezoelectric material was modelled with the use of Solid 5 finite element [13]. It was assumed that the type of a piezoelectric material was Navy II piezoelectric ceramic PZT5A3. Table 2 shows properties of the piezoelectric material [15].

RESULTS

The first stage of research was aimed at the application a numerical modal analysis of a reference model of the composite disk without piezoelectric patches (0PP). Values of eigenfrequencies obtained for different rotational speeds are shown in Table 3.

At the next stage, a modal analysis of the composite disk model containing piezoelectric patches was conducted. Similarly, the experiment was repeated for different rotational speeds. Values of the first ten eigenfrequencies of each model of the composite disk with piezoelectric patches were obtained.

Figure 5 shows exemplary results of the modal analysis of the disks without piezoelectric patches and with 4 big piezoelectric patches. They show the change of the first ten eigenfrequency values against the rotational speed. The plots concerning the disk without piezoelectric patches show that the values for following eigenfre-

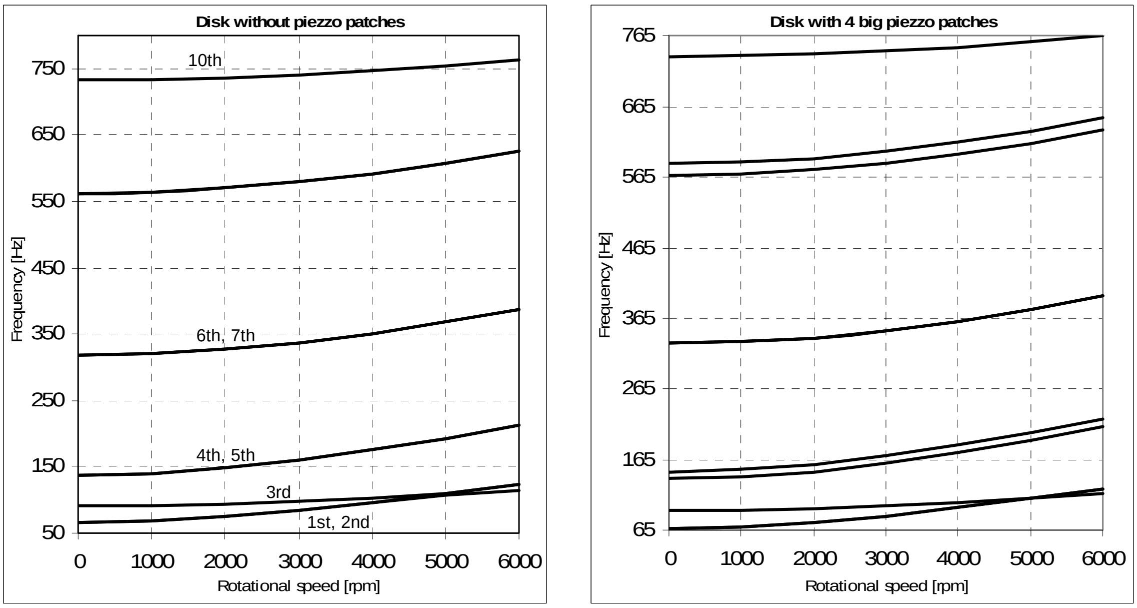


Fig. 5. Eigenfrequency of the disk versus its rotational speed

Rys. 5. Częstotliwości drgań własnych wirnika w funkcji jego prędkości obrotowej

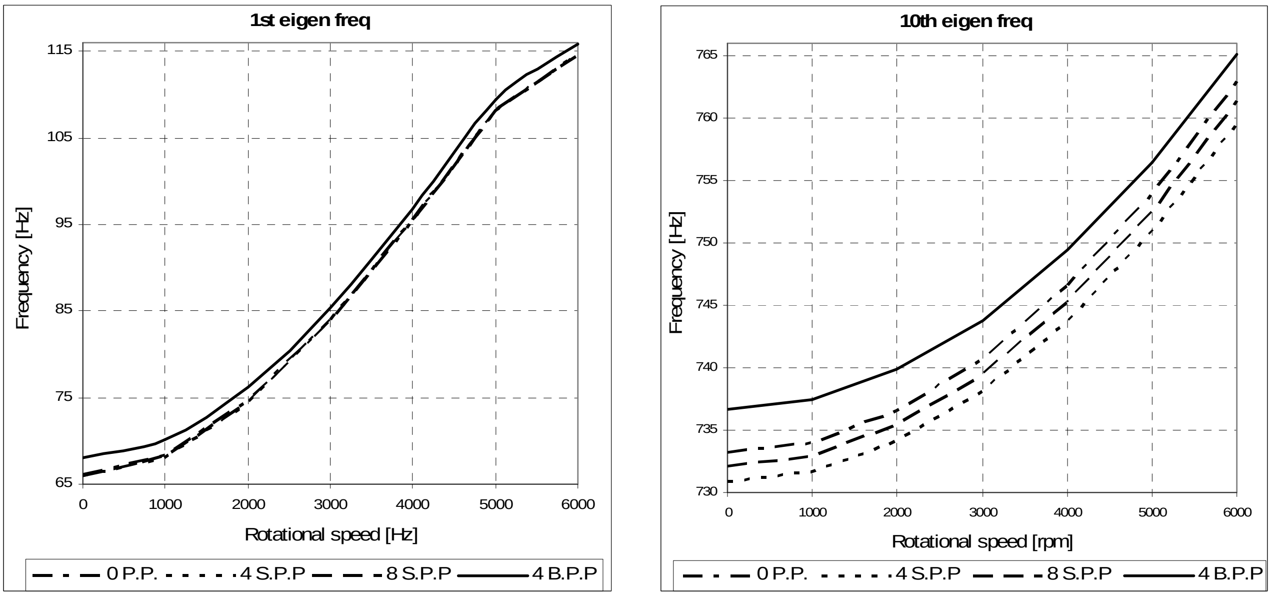


Fig. 6. Influence of embedded sensors on 1st and 10th eigenfrequency versus rotational speed

Rys. 6. Wpływ wbudowanych czujników na 1. i 10. częstotliwość drgań własnych w funkcji prędkości obrotowej

quency pairs: 1st and 2nd, 4th and 5 th, 6th and 7th, 8th and 9th are very similar. The application of piezoelectric patches increases eigenfrequency values with comparison to the case of the disk without a piezoelectric patch (Fig. 5b). The differences in eigenfrequencies between the disk without piezoelectric patches and disks with 4 or 8 small patches were lower than between values for the disk without piezoelectric patches and with 4 big piezoelectric patches. For disk with 4 small patches differences at rotational speed 0 and 600 rpm were respectively 0.17 and 0.04%. For disk with 8 small patches differences at the same speed were 0.37 and 0.09%. For disk with 4 big patches differences were 2.90 and 1.03%.

Differences between eigenfrequency values of the disk without piezoelectric patches and all considered cases with embedded patches decreased when rotational speed increased.

Figure 6 shows plots of changes of the 1st and 10th eigenfrequency versus rotational speed for all investigated numerical models. Plots show that the application of big piezoelectric patches considerably increases eigenfrequency values. The difference is growing with increasing eigenfrequency number.

SUMMARY

On the base of the presented results it can be stated that the modal properties of the composite rotors can be significantly influenced through the embedding of piezoelectric sensors and that this influence depends on the size and the number of the sensors. The shift of eigenfrequencies and the alteration of modal shapes can be reduced using smaller, regularly spaced sensors. In fur-ther investigations, the effectiveness of small sensors applied as the signal source of diagnostic systems for composite rotors has to be proved.

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