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Arturas KILIKEVIČIUS
Vytautas RIMŠA
Mirosław RUCKI

INVESTIGATION OF INFLUENCE OF AIRCRAFT PROPELLER MODAL PARAMETERS ON SMALL AIRPLANE PERFORMANCE

BADANIA WPŁYWU MODALNYCH PARAMETRÓW ŚMIGŁA NA ZACHOWANIE MAŁEGO SAMOLOTU

The aim of the current paper is to investigate a small airplane model propeller of class F2D according to requirements of Fédération Aéronautique Internationale (FAI, or World Air Sports Federation). In some cases, practical tests show that F2D models with flexible propellers produce specific extra noise and increase flight speed in comparison with "rigid" propellers. Therefore, the following hypothesis could be proposed: flexible characteristics of the increased noise are related to the resonant eigenfrequencies of the propeller. The operating range of the F2D class propeller (28,000-35,000 rpm) is close to or equal to the eigenfrequency resonance. The current investigation addresses dynamic/flexible vibrations of elastic propeller during engine run and researches dynamic parameters of the propeller as well as the contribution of these parameters to the model flight characteristics. To resolve this type of a problem, a stand, which allows completing a physical investigation of flexible propeller vibration modes and dynamic characteristics was created.

Keywords: *aircraft propeller, dynamics, vibration, operational modal analysis.*

Celem artykułu jest przedstawienie wyników badań śmigła małego modelu samolotu zaliczanego do klasy F2D (według klasyfikacji Fédération Aéronautique Internationale, FAI). W niektórych przypadkach testy wykazały, że modele F2 z giętkimi śmigłami, w porównaniu do śmigieł sztywnych, wydają dodatkowy hałas i zwiększają prędkość samolotu. Dlatego wysunięto hipotezę, że elastyczne charakterystyki zwiększonego hałasu są powiązane z rezonansem częstotliwości własnych śmigła. Zakres pracy śmigła klasy F2D (28 000-35 000 obr/min) jest zbliżony do jego częstotliwości własnych. Badania dotyczą elastycznych wibracji dynamicznych śmigła giętkiego w czasie rozruchu silnika i są nakierowane na wyznaczanie parametrów dynamicznych i ich wpływu na charakterystyki lotu modelu. Wykonano i opisano stanowisko, na którym przeprowadzono testy modalne drgań giętkiego śmigła. Na tej podstawie uzyskano charakterystyki dynamiczne.

Słowa kluczowe: *śmigło lotnicze, dynamika, wibracje, analiza modalna.*

1. Introduction

The phenomenon of aero-elasticity is a significant field of research in aviation. The studies show the interactions among inertial, elastic and aerodynamic forces that occur when flexible body is exposed by the fluid flow [1, 7, 25]. Aero elasticity draws on the study of fluid mechanics, solid mechanics, structural dynamics and dynamical systems. The conventional classification of aero-elasticity includes two fields: static aero elasticity, which deals with the static or steady response of an elastic body to a fluid flow; and dynamic aero elasticity, which deals with the body's dynamic (typically vibrational) response.

The phenomenon of dynamic aero elastic stability is formed by vortex oscillations and has a significant influence on the propeller working process. The turbulence is caused by the rotating parts of the turbine (propeller or gas turbine or engine rotors). Whirl flutter instability is a specific type of aero elastic layer instability that can occur in turbo propellers [8, 15]. The propeller is intended to change motion of the engine's shaft into the traction power of the aircraft. It conversion takes place due to differential pressure which is created in the front and in the aft of the propeller blades. Therefore, it leads to high vortex oscillation effect especially near the tip of the propeller. That may be an issue especially in case of small aircrafts [20].

The vortex oscillation effect is the interaction of solid body motion and aerodynamic forces (FSI), which are very common for such elements as the gas turbine engine rotor or propeller. Rotating mass increases the number of degrees of freedom and creates extra forces and moments [5, 24]. In some cases, vortex oscillations result in highly large and unstable aerodynamic forces and moments thus affecting the propeller or the aircraft as such and can lead to the distortion of the construction. Moreover, the vibrations in the airplane usually have a negative effect, so many researches are aimed to reduction their impact on the construction [11-14, 22]. This paper is focused on the resonance phenomena in F2D model class, where resonance may affect durability performance of the construction. On the other hand, it helps to increase propeller trust, which is the key factor [16, 23]. Investigation of propeller blade deflection and frequencies analysis demonstrated, that higher model speed was achievable.

However, in some cases experimental tests show that F2D models with flexible propellers have specific extra noise and increase the speed of flight in comparison with "rigid" propellers. The test demonstrated up to 2.2% higher speed, which decreased 1 km distance flight time from 23.0 s down to 22.5 s. This is a remarkable improvement of the F2D model flight speed within restrictions set by FAI (Fédération Aéronautique Internationale, or World Air Sports Federation) regulations.

This article discusses the specifications of F2D class aircraft propellers and their dynamic characteristics. The article introduces an experimental propeller test stand that allows to determine the dynamic characteristics of a flexible propeller. Experimental studies have shown that when using flexible propellers with first and second resonant frequencies within the working range of the aircraft, better flight parameters are achieved.

2. Modal Analysis issue

Operational modal analysis (OMA) is a sort of 'inverse' problem where one is interested in gaining knowledge about the instrumented structure based on measured response [26]. The method is economical and feasible, so it is becoming a common practice in full-scale vibration testing worldwide [2]. There are two main types of OMA algorithms, one operating in time domain and other in frequency domain [6]. In the first group can be found approaches based on the dynamic state equations and stochastic subspace identification (SSI), which provides fairly accurate estimates of the low frequency modes under normal operating conditions but may be further improved [3, 4]. The second group is represented with various methods of the system responses decomposition in the frequency domain, such as Basic Frequency Domain (BFD), Frequency Domain Decomposition (FFD), or Enhanced Frequency Domain Decomposition (EFFD) [9, 17, 19]. The key requirements that the system under analysis must meet are the following: the structure is unchanging in time; low inhibition; well-separated specific frequencies; structure-induced excitation is stationary broadband noise.

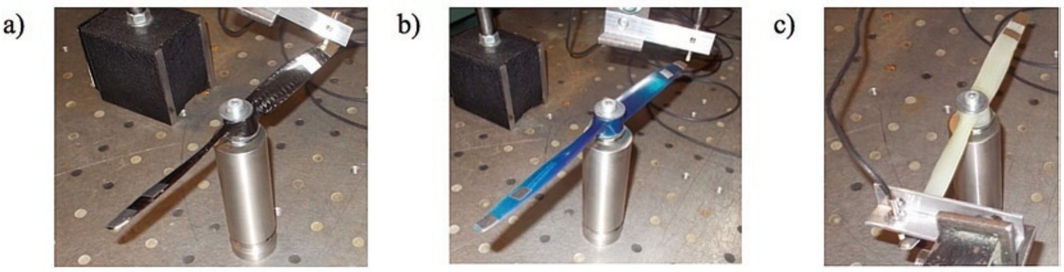


Fig. 1. The propellers under tests: a) F2C class carbon sample; b) F2D class "C1" fiber glass; c) F2D class "ZM" fiber glass

Grosel and co-authors [10] provided the following relation between excitation $x(t)$ and response $y(t)$:

$$\left[G_{yy}(j\omega)\right] = \left[H(j\omega)\right]^* \left[G_{yy}(j\omega)\right]\left[H(j\omega)\right]^T \quad (1)$$

where the brackets [] represented a matrix, [G] - the power spectral density matrix with index xx representing the input and the index yy denoting the output, [H] - represents the matrix of the frequency response function, T – transposition, and the asterisk * means the complex conjugate.

They further proposed the splitting of the response matrix using the Singular Value Decomposition as follows:

$$\left[G_{yy}(j\omega_i)\right] = [\Phi_i][\mathrm{S}_i][\Phi_i]^H \quad (2)$$

where S_i – diagonal of the Singular Value Decomposition, Φ_i – unitary matrix containing vectors that are proportional to their own value vectors. The diagonal elements of the S_i matrix contain information about their frequencies.

Dynamic behavior of the structure in a given frequency range can be modeled as a set of individual modular vibrations. It is assumed that the structure acts as a linear, time-changing system. Each resonant frequency can be described by the following parameters: self-frequency or resonant frequency, (modal) shape, and damping factor. These parameters are called modal parameters. Using modal parameters for structural modeling, vibration problems caused by these resonances (mods) can be assessed and analyzed. In addition, the model can be used to provide possible solutions to individual issues. Modal parameters can be derived from Frequency Response Functions (FRF) measurements consisting of one or more reference positions and multiple measurement positions required to describe the model behavior.

3. Experimental equipment for assessment of dynamic parameters

In the current investigation, the examined objects were the air model propellers. For the test three different propellers were used: (1) F2C class team race propeller made from carbon rigid sample, (2) F2D class propeller called "C1", made from fiber glass, one of the most popular propellers (length 155mm; pitch 80) which is used in various weather conditions, and (3) F2D class propeller called "ZM", made from fiber glass, which is known from the practical perspective as a resonant propeller (length 155 mm, pitch 80 mm). The propellers are shown in Fig. 1.

The "Brüel & Kjær" and "Lion Precision" measuring instruments were used to measure vibration parameters. In Fig. 2, the main subunits of the devices are shown: 1) Excitation Vibrator 4810 with

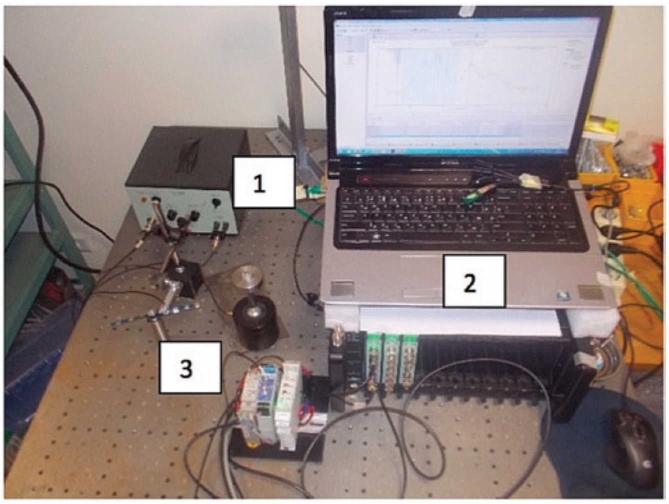


Fig. 2. Apparatus for the vibration tests of propellers

amplifier, 2) Portable measurement processing, storage and control equipment No. 3660D with PC, and 3) Displacement sensors “Lion Precision” U3B and U20B with amplifier. Data flow is presented in the chart in Fig 3.

The measurements of the propellers’ vibration were performed when the propeller was rigidly fixed to the rod in the same way as it is shown in the model. The rod was fixed to the vibration frequency generator. Vibration test was done by the use “sweep sine” method in the range of frequency from 100 up to 2000 Hz.

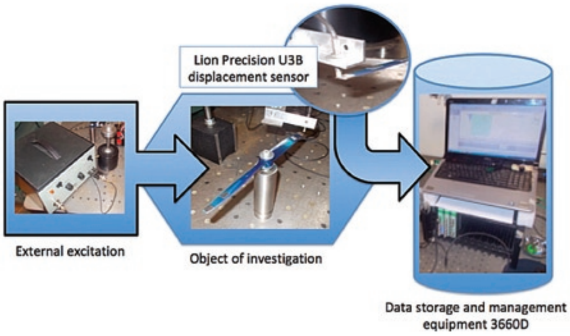


Fig. 3. Measurement data flow chart

4. Results and discussion

Fig. 4 shows the graphs of power spectra of the three investigated propellers obtained using Frequency Domain Decomposition (FDD) technique, which allow for estimating natural frequencies and mode shapes of the structural system [18]. The areas of modal domain are marked with green colors with estimated modes shown in red squares. The natural frequencies of investigated propellers are presented in Table 1. In the Table 2, the shapes obtained from Operational Modal Analysis (OMA) and Blade Element Momentum (BEM) are shown. Classical momentum theory can be applied to the ideal propeller, but blade element theory is used for more detailed analysis of its exploitation characteristics [21].

The presented results demonstrated that F2C class carbon propeller had its resonating frequencies close to each other in the span of ca. 150 Hz between 905 and 1050 Hz. The largest, almost six times wider span between the modes was found in the “ZM” propeller, which was ca. 850 Hz between 400 and 1250 Hz. However, only in case of F2D class “C1” propeller made out of fiber glass, its resonant frequency was covered by the operating conditions. Namely, F2D class aircraft models had operating range 28,000-35,000 rpm, corresponding with 467-583.3 Hz. Most probably, its improved exploitation characteristics can be attributed to that fact.

Both OMA and BEM models indicate larger deformations of the propeller blade on its tips. This phenomenon can provide explana-

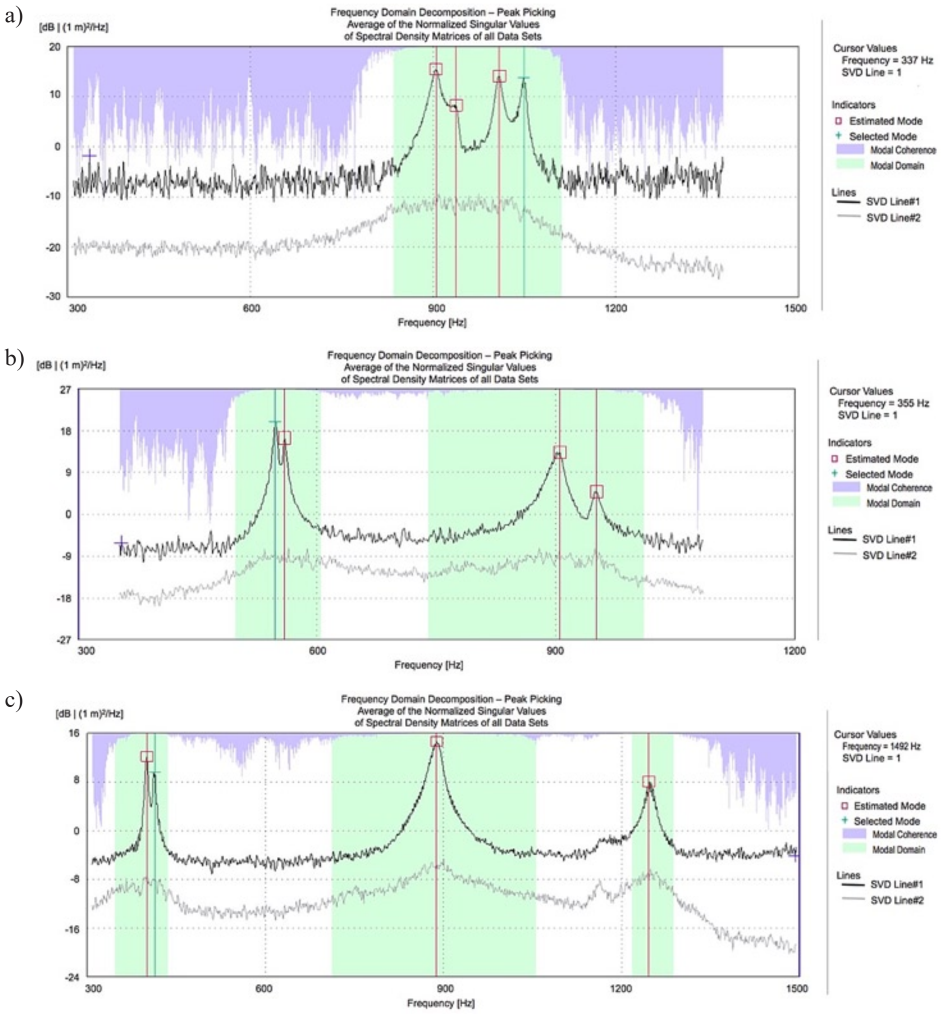
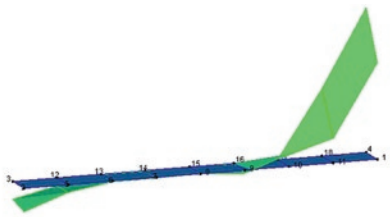
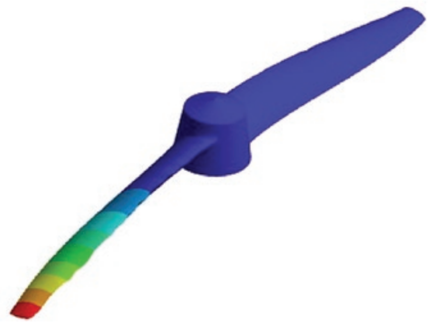


Fig. 4. The power spectral density functions of the investigated propellers obtained from FDD technique: a) F2C class carbon sample; b) F2D class “C1” fiber glass; c) F2D class “ZM” fiber glass

Table 1. The natural frequencies of investigated propellers

Mode	Frequency [Hz]		
	F2C class carbon propeller	F2D class glass propeller (C1)	F2D class glass propeller (ZM)
Mode 1	905	548	402
Mode 2	938	560	413
Mode 3	1009	905	889
Mode 4	1049	951	1253

Table 2. Deformations of the blades in modes 1 and 2 obtained from OMA and BEM models

OMA shapes		BEM shapes
Mode 1		
Mode 2		

tion why the differences between two analyzed modes 1 and 2 are so small, namely, between 2.2% and 3.6% for any type of the tested propellers.

5. Conclusion

The current analysis of the dynamic characteristics of propellers used in F2D class aircraft models engaged both experimental measurements and operational modal analysis. Their operating range was between 28,000 and 35,000 rpm. Three different propellers of different shape and structural materials were investigated in terms of modal frequency parameters. The investigation revealed the frequencies of the propellers, which were: 1.: 905, 938, 1009 and 1049 Hz for F2C class carbon racing, 548, 560, 905 and 951 Hz for F2D class (C1) fiber glass propeller, and 402, 413, 889 and 1253 Hz for F2D class (ZM) fiber glass propeller, respectively.

The first two resonant frequencies (548 and 560 Hz) of the C1 propeller have been found in the frequency range corresponding with the F2D aircraft models operating conditions, i.e. 467-583.3 Hz corresponding to the propeller rotational speed 28,000-35,000 rpm. To that fact may be attributed its higher speed.

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Arturas KILIKEVIČIUS
Institute of Mechanical Science,
Vilniaus Gedimino Technical University,
J. Basanaviciaus g. 28, Vilnius LT-03224, Lithuania

Vytautas RIMŠA
Department of Aviation Technologies,
Vilniaus Gedimino Technical University,
Linkmenų g. 28, Vilnius, LT-08217, Lithuania

Mirosław RUCKI
Faculty of Mechanical Engineering,
Kazimierz Pulaski University of Technology and Humanities in Radom
ul. Stasieckiego54, 26-600 Radom, Poland

E-mails: arturas.kilikevicius@vgtu.lt, vytautas.rimsa@vgtu.lt, m.rucki@uthrad.pl