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METHODS OF DUCTED FAN AIRCRAFT PROPULSION UNIT NOISE PREDICTION

METODY PROGNOZOWANIA HAŁASU JEDNOSTKI NAPĘDOWEJ KANAŁOWEGO WENTYLATORA LOTNICZEGO

Abstract

The UL-39 ultra-light aircraft which is being developed by the Department of Aerospace Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, is equipped with an unconventional ducted fan propulsion unit. This paper deals with identifying noise sources of this propulsion unit and easily applicable ways of predicting its noise level. At the end, a few potential noise-suppressing design improvements are presented.

Keywords: *UL-39*, *ducted fan propulsion unit*, *rotor-stator interaction noise*, *rotor-alone noise*, *cold air jet noise*, *flow passage noise*

Streszczenie

UL-39 to ultra lekki samolot, który został skonstruowany w Instytucie Inżynierii Lotnictwa, na Wydziale Mechanicznym Czeskiego Uniwersytetu Technicznego w Pradze. Został on wyposażony w niekonwencjonalny wentylator kanałowy jednostki napędowej. W artykule autor zaprezentował metody identyfikacji źródeł hałasu badanej jednostki napędowej oraz łatwe w zastosowaniu metody przewidywania poziomu generowanego hałasu. Zostały również przedstawione propozycje zmian konstrukcyjnych redukujących hałas.

Słowa kluczowe: *UL-39*, *jednostka napędowa wentylatora kanałowego*, *hałas rotor-stator*, *hałas zimnego strumienia powietrza*, *hałas przepływu*

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List of symbols

- a – speed of sound [$m \cdot s^{-1}$]
- $c_{D,R}$ – rotor blade drag coefficient [1]
- c_R, c_S – rotor and stator blade chord length [mm]
- D – sound attenuation [dB]
- d – flow passage diameter [mm]
- f – frequency [Hz]
- F_y – lift force [N]
- K – nozzle experimental constant [1]
- L_p, L_W – noise pressure level, noise power level [dB]
- Ma – Mach number [1]
- p – pressure, acoustic pressure [Pa]
- R_T – parameter respecting the Reynolds number (Goody) [1]
- r – radial coordinate [mm]
- S – flow passage area [m^2]
- $S(\omega)$ – stator blade transversal response function [1]
- $T(\omega)$ – stator blade longitudinal response function [1]
- U, U_e – incident flow and rotor blade relative velocities [$m \cdot s^{-1}$]
- v – flow passage velocity, nozzle exit velocity [$m \cdot s^{-1}$]
- W – acoustic power [W]
- z_R – rotor blade number [1]
- α_∞ – angle of attack [°]
- δ – boundary layer thickness [mm]
- ν – kinematic viscosity [$m \cdot s^{-1}$]
- ρ – density [$kg \cdot m^{-3}$]
- τ – shear stress [$N \cdot mm^{-2}$]
- Φ – acoustic pressure spectral density [$Pa \cdot s$]
- Ω – rotor angular frequency [s^{-1}]
- ω – reduced angular frequency [s^{-1}]

Subscripts:

- i – incident acoustic pressure
- t – transferred acoustic pressure
- p, s – blade pressure side, suction side
- R, S – rotor, stator
- w – relative flow velocity
- 0 – wake
- ∞ – undisturbed flow

1. Introduction

The ducted fan propulsion unit of the UL-39 aircraft (see Fig. 1) which consists of an axial fan of stator-arrangement driven by a piston engine, is encountering difficulties with noise during its experimental operation. Beside the noise generated by the piston engine, tone noise generated by the fan is present in the perceived acoustic spectrum. Therefore, during its future operation, the UL-39 aircraft may not fulfil the requirements concerning noise given by legislature. With these issues in mind, a new fan will be designed which will take into account the necessity of reducing noise while being capable to improve the aircraft flight performance at the same time.

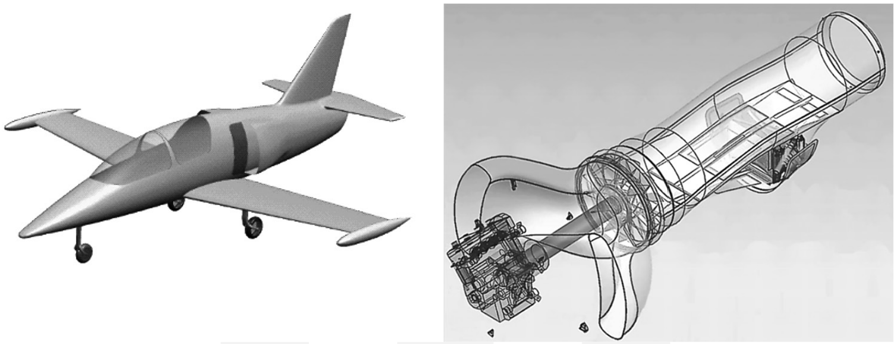

Fig. 1. The UL-39 and its ducted fan propulsion unit

Rys. 1. UL-39 i jednostka napędowa jego wentylatora kanałowego

In this paper, the noise sources of the propulsion unit will be identified and discussed. For each respective source, methods of computational estimation of noise level will be presented. In the final chapter, potential noise-suppressing design improvements will be briefly mentioned.

Beside the noise generated by the piston engine, four basic noise sources can be identified in the UL-39 propulsion unit – the rotor-stator interaction, the rotor alone, turbulent flow inside the flow passages and the cold air jet flowing from the exit nozzle. The cold air jet noise is not included in this paper since the nozzle will primarily be optimized for the best flight performance.

2. Rotor-stator interaction noise prediction

The rotor-stator interaction generates tonal noise with a so-called blade-passing frequency which is caused by wakes behind one blade cascade interfering with another cascade placed downstream. The downstream blades generate instationary lift from which the tonal noise comes. Methods of rotor-stator interaction noise prediction and suppression which can be applied to the UL-39 ducted fan propulsion unit were first used in turbofan engine fan design and development. Therefore, the rotor-stator configuration is only taken into account in the studies referred to. During the future development of the UL-39 propulsion unit, advantages and disadvantages of the respective fan configurations will be thoroughly discussed and the most suitable solution chosen.

The in stationary lift force generated by the stator blade cascade under the influence of incident wakes from rotor blades placed upstream and the resulting noise power level can be computed according to [2].

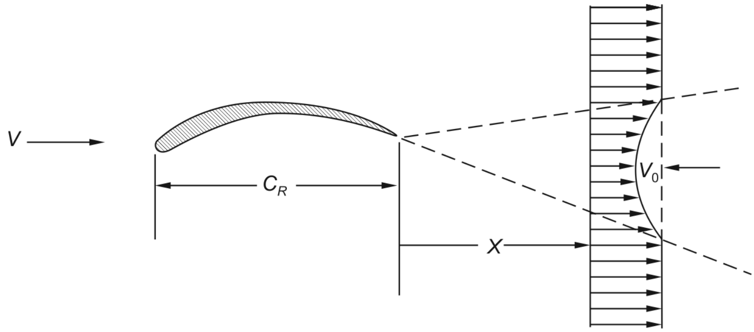

Fig. 2. Model of the rotor wake velocity defect [2]

Rys. 2. Model wadliwego śladu strumieniowego rotora [2]

In this technical memorandum, different equations for computing the wake velocity defect are presented and compared. With different constants, the following relationship is used:

$$\frac{v_0}{v_\circ} \sim \frac{\sqrt{c_{D,R}}}{\sqrt{\frac{x}{c_R}}} \tag{1}$$

The response of the stator blades to the instationary pressure changes caused by the rotor wakes can be expressed using two experimentally determined functions based on the fundamentals of instationary aerodynamics, $S(\omega)$ and $T(\omega)$. These complex functions are related to transversal and longitudinal response of the stator blades, respectively (see Fig. 3). The functions $S(\omega)$ and $T(\omega)$ depend on the so-called reduced angular frequency. The change of lift force is then computed as follows:

$$\Delta F_y \sim S(\omega) - \alpha_\infty T(\omega); \quad \omega = \frac{\pi c_s z_R \Omega}{c_{a,s}} \tag{2}$$

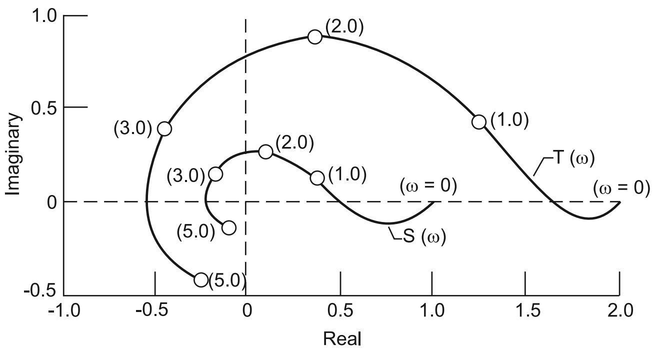

Fig. 3. Transversal and longitudinal blade response functions [2]

Rys. 3. Wzdłużna i poprzeczna funkcja odpowiedzi dla ostrza

Using this computation, no absolute noise level can be determined. However, the current fan and the new one can be compared with each other since the noise power level difference can be calculated.

$$\Delta L_W = 20\log\frac{\Delta F_{y,2}}{\Delta F_{y,1}} \tag{3}$$

It should be noted that the above-mentioned method is not numerically precise since the equations it incorporates were derived considering a flat and isolated air foil (not installed in a cascade). Regardless of that, it can still be used for comparing the currently-used fan to a new one.

A more sophisticated method of rotor-stator interaction noise prediction is presented in [7]. In opposition to the previous method, it is already based on a blade cascade, not an isolated air foil. Moreover, the cascades are assumed to be placed in a cylindrical duct of infinite length. The coordinate system used by this method is shown in Fig. 4. The wakes behind the air foils placed upstream which generate can be modelled using various functions, including hyperbolic functions or Gaussian distribution. Recommendations concerning the wake models are presented in [8].

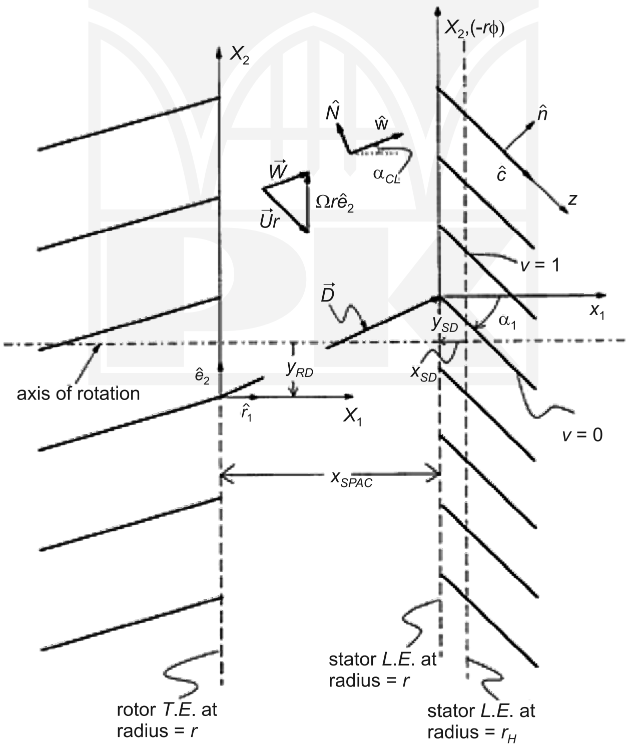

Fig. 4. Model of rotor and stator blade cascades presented in [7]

Rys. 4. Model łopatek kaskadowych wirnika i stojana [7]

Using this method, the acoustic pressure field inside a cylindrical fan duct can be computed as well as noise power level generated by the fan. Since this method involves using sophisticated mathematical operations, such as Green functions or integral equations, it comes as a computer program called *V072* created by the NASA. This program is distributed via the Internet [14] on request.

3. Flow passage noise prediction

Inside the flow passages of the ducted fan, broadband noise is generated by turbulent air flow. This type of noise can be suppressed by applying acoustic liners along the duct walls (which will be described below) or by reflecting the forward-radiating noise back downstream by the stator inlet guide vane (if present).

A method of quantifying the attenuation by the inlet guide vane can be found in [12]. It is based on using the longitudinal and transversal stator blade response functions, $S(\omega)$ and $T(\omega)$, already mentioned above. The calculation is to be made in elementary cylindrical layers of the fan inlet guide vane. The vane is modelled as a cascade of flat air foils. The incident acoustic wave is assumed to be planar. A part of the incident wave (its acoustic pressure is denoted p_i) passes through the blade cascade (p_t) while the other part is reflected. The ratio of acoustic pressures of the transmitted and incident waves is a function:

$$\frac{p_t}{p_i} = f(Ma_w, \alpha, \vartheta) \tag{4}$$

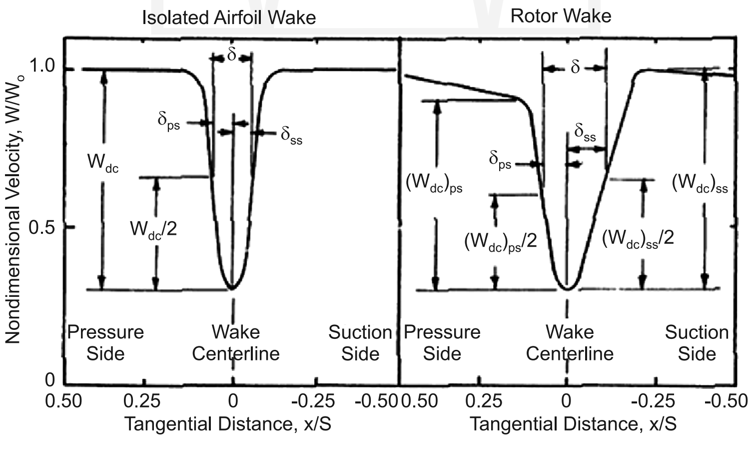

Fig. 5. Examples of wake models presented in [8]

Rys. 5. Przykłady modeli łopatek [8]

In this equation, Ma_w means the relative velocity Mach number, α is the angle between the acoustic wave direction and the blades and θ is the angle between the blades and the axis of rotation (as shown in Fig. 6). The resulting sound attenuation can be calculated as follows:

$$D = \frac{\int_d^D \left(\frac{p_t}{p_i}\right)^2 \left(\frac{\partial F_y}{\partial t}\right)^2 \frac{1}{r}\,\mathrm{d}r}{\int_d^D \left(\frac{\partial F_y}{\partial t}\right)^2 \frac{1}{r}\,\mathrm{d}r} \tag{5}$$

The lift force time derivative can be computed using the functions $S(\omega)$ and $T(\omega)$, Mach numbers of various velocities, the blade drag coefficient and their chord length (described in [12]). The acoustic pressure ratio is determined by calculating a system of partial differential equations. This calculation is described step by step in [6].

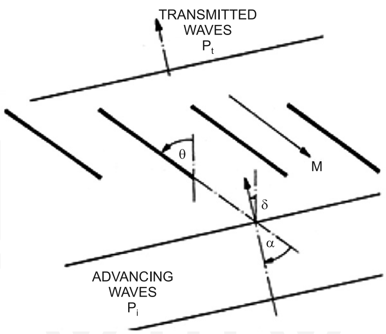

Fig. 6. The method of inlet guide vane attenuation [12]

Rys. 6. Schemat wlotu prowadzącego łopatki [12]

4. Rotor-alone noise prediction

As can be seen from the physical nature of the problem, the noise produced by the rotor itself is caused by a multitude of factors and it is not easy to predict. Not only does the rotor generate noise by its presence (and rotation) in a turbulent mean flow. It can also ingest flow instabilities from upstream or boundary layers separated from the duct walls, both of which contribute to the noise generation by locally increasing the turbulence intensity.

A prediction method concerning the acoustic pressure spectral density on the surface of the rotor blades is described in [13]. The spectral density can be determined from the following integral:

$$\Phi_{p,R} = \frac{z_R c_R}{4\pi f^2} \int_0^R U^2(r)[\Phi_{p,p}(r,f) + \Phi_{p,s}(r,f)]\,\mathrm{d}r \tag{6}$$

The functions denoted $\Phi_{p,p}$ and $\Phi_{p,s}$ (acoustic pressure spectral densities on the pressure and suction side of the blades, respectively) can be determined both experimentally and computationally. The experimental evaluation of these functions is also described in [13] and involves using a miniature microphone placed inside a rotor blade close to its trailing edge (on both the pressure side and the suction side, consecutively).

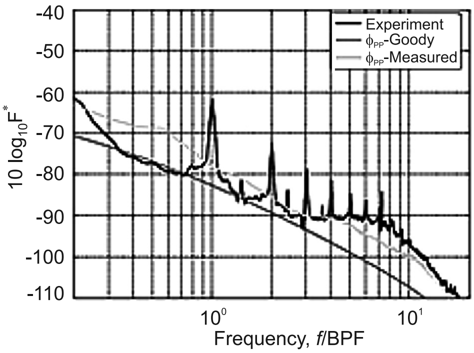

Fig. 7. Comparison of spectral acoustic densities determined by Goody model and experiment [13]
Rys. 7. Porównanie gęstości akustycznej spektralnej określonej przez model Goody'ego oraz wyznaczonej doświadczalnie

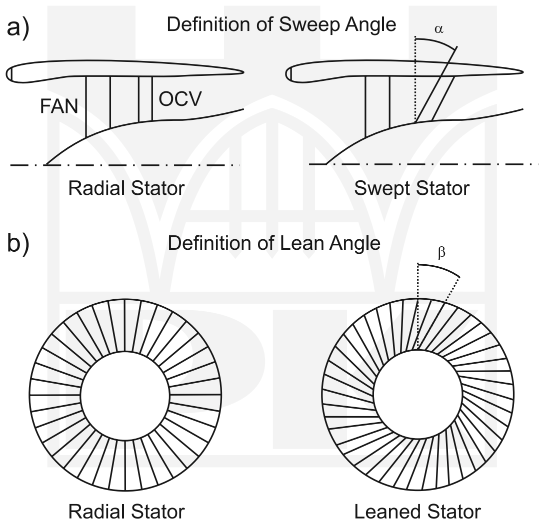

Fig. 8. The swept and leaned stator concept [4]
Rys. 8. Koncepcja omiatania i pochylania sią statora [4]

The computational determination of these functions is relatively easy and incorporates a model of a dependence of the spectral acoustic density on reduced frequency − the Goody model. The Goody model is defined by the relationship:

$$\frac{\Phi_p(\omega)U_e}{\tau^2\delta} = \frac{3\omega^2}{(\omega^{0.75}+0.5)^{3.7}+(1.1R_T^{-0.57}\omega)^7} \tag{7}$$

in which $\omega = 2\pi f\delta/U_e$ stands for the reduced frequency, δ denotes the boundary layer thickness (can be determined from the wake model shown in Fig. 5), U_e is the relative velocity of the incident flow, τ is the blade surface shear stress which can be calculated with the use of various boundary layer models, and R_T is a parameter respecting the Reynolds criterion. It can be calculated from the relation: $R_T = 0.11 \cdot (U_e\vartheta/\nu)^{0.75}$, in which, according to [13]: $\vartheta = \delta/11.6$. These relationships are valid for both the pressure side and the suction side of the blades. In [13], this model is compared to the experiment and it is stated that, for most cases, the results of both methods coincide to a satisfying extent (one of the results of this comparison is shown in Fig. 7).

It is clear that the Goody model can be very helpful during preliminary fan design stages for comparing the currently-used fan to a new one in terms of rotor noise as well as determining the key design parameters which may help decrease this type of noise.

5. Applicable design improvements of the propulsion unit

5.1. Rotor-stator interaction noise

In [2], the following methods are presented:

1. Increasing the gap between the rotor and stator. By doubling its length, a noise power level suppression of 2 dB can be achieved.
2. Lengthening the stator blades' chords. A longer chord means more wavelengths of the incident acoustic pressure waves acting on the stator blades. The incident and reflected waves can interfere and thus reduce the acoustic pressure.

Optimizing the rotor speed or reducing the rotor blade drag coefficient are other possibilities.

In [4] and [5], another noise suppression method is presented which is called the *swept and leaned stator* (see Fig. 8). The fundamental idea of this concept is increasing the number of incident wakes from the rotor blades acting on each stator blade (by leaning the stator blades) and diversifying the phase angle of these wakes at the same time (by sweeping the blades) which means that if a stator blade is swept, the pressure waves generated by wakes in different places along the radial coordinate hit it at each at a different time. The effect of the swept and leaned stator can be easily simulated using the model presented in [7].

5.2. Flow passage turbulent flow noise

The turbulent flow noise, can be efficiently suppressed by applying acoustic liners. Different types of acoustic liners used in aircraft propulsion are described in [3]. Two types of liners are distinguished – locally and non-locally-acting ones.

Locally-acting liners consist of a perforated sheet, a honeycomb core, and a solid back plate. Their denomination comes from the fact that they don't allow the acoustic waves to radiate in the direction parallel to their surface. Their working principle is that of a Helmholtz resonator.

The locally-acting liners are, as already suggested, designed to absorb acoustic waves in a relatively narrow bandwidth of approx. one octave (which corresponds to the fan tone noise, for example). Non-locally-acting acoustic liners contain porous materials instead of honeycombs. They can absorb acoustic waves within a bandwidth of more than three octaves. When applying acoustic liners to the propulsion unit if the UL-39 aircraft, the following issues are to be taken into account:

1. The complicated nature of interaction between the locally-acting acoustic liners and the surrounding flow field prevents any simple mathematical prediction method from being applicable. However, the liners must be tuned very precisely in order to act at the frequencies needed. The fitted design of these liners would be so complicated as to require extensive research capacities. This already restricts the use of acoustic liners in the UL-39 propulsion unit to non-locally-acting ones.
2. By using acoustic liners, the weight of the aircraft would increase considerably. Moreover, the longitudinal stability conditions of the aircraft would change.

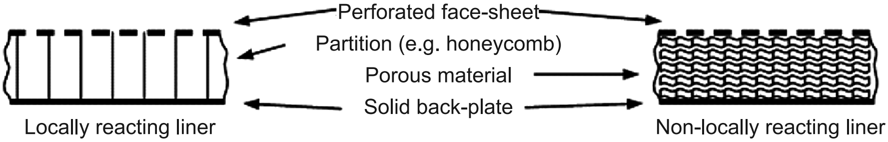

Fig. 9. Two types of acoustic liners as described in [3]

Rys. 9. Dwa przykłady linii akustycznej opisane w [3]

5.3. Rotor-alone noise

One useful method of rotor noise suppression is discussed in [1]. It is based on using so-called tip platform extensions at the tips of the rotor blades. The fundamental idea of this improvement is reducing the generation of tip leakage vortices by preventing the air from flowing from the pressure side to the suction side of the blades to a certain extent. The vortices generated by the tip leakage flow cause instationarities and turbulent momentum transfer in the flow which produces noise and induces aerodynamic losses inside the fan stage. As stated in [1], the use of tip platform extensions at the rotor blades reduces the rotor noise, widens the range of high fan efficiencies and increases its thrust.

6. Conclusions

All of the computational methods presented in this paper are relatively easy to apply and will be, of course, used during the design process. As for the noise-suppressing design improvements, one of the potentially most effective and, at the same time, easiest methods is increasing the length of stator blades and the rotor-stator gap. Sweeping and leaning the stator of the fan will be applied preferably as well. After performing the measurements needed, using rotor tip platform extensions or roughening the inner surface of the exit nozzle is also possible.

The goal of all the computational and design measures introduced in this paper is safely adhering to the limits given by the noise legislature while maintaining sufficient properties in terms of flight dynamics of the aircraft.

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