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Justification of Methods for Determining Mass and Aerodynamic (Hydrodynamic) Unbalances of a Propeller

This paper theoretically substantiates new methods for determining the mass and aerodynamic (hydrodynamic) unbalance of a propeller, applicable to both air and water propellers with fixed pitch. It is proposed to determine the dynamic unbalance twice: first under normal operating conditions, and then under modified conditions in which only the aerodynamic (hydrodynamic) component changes. The proposed methods are based on: varying the density of air, gas, or liquid; applying reverse propeller rotation; and utilizing the ground effect. The aerodynamic (hydrodynamic) unbalance is quantified as a mass-equivalent unbalance, measured with a balancing instrument under defined operating conditions.
propeller, balancing, unmanned vehicle, manned vehicle, balancing device, ground effect

Problem statement. Propellers are widely used in various types of machinery. The primary source of vibration in such equipment is the mass and aerodynamic (hydrodynamic) unbalance of the propellers. As a result, balancing propellers represents a common and persistent engineering challenge. In single-unit or small-scale production, traditional balancing methods are employed. Aerodynamic (hydrodynamic) balancing is achieved by correcting the geometric profile of the blades, while mass unbalance is corrected using a balancing rig or instrument.

With the advent of small unmanned and manned aircraft, the production of propellers has become large-scale. Under such conditions, traditional balancing methods are no longer feasible due to their labor-intensive nature. For manufactured propellers, a more specific challenge arises — separating the mass and aerodynamic (hydrodynamic) components from the overall dynamic unbalance. This is essential for the development of advanced balancing techniques, for evaluating the manufacturing and balancing quality, and for identifying and rejecting defective units.

Analysis of recent research and publications. Propellers are widely used in manned and unmanned aircraft, surface and underwater vehicles, hovercraft, axial fans, wind turbines, and other applications. A primary source of vibration during the operation of both air [1] and water propellers [2] is mass unbalance and aerodynamic or hydrodynamic unbalance.

Aerodynamic (hydrodynamic) unbalance is similar in effect to mass unbalance. It also consists of static and moment components and generates disturbing forces at the frequency of propeller rotation. As a result, it can be corrected by adjusting the mass distribution [1, 2]. Effective balancing machines and devices have been developed for this purpose [3]. Experimental data demonstrate that the accuracy of simultaneous balancing of both types of unbalance is primarily limited by the precision of the balancing equipment.

But aerodynamic (hydrodynamic) unbalance, unlike mass unbalance, depends on the density of air, gas (liquid), and propeller operating conditions. Therefore, if the propeller is balanced only by adjusting the masses at a certain mode, the balancing accuracy will be violated with changes in the propeller operating conditions.

A promising approach to address these challenges is real-time balancing of both mass and aerodynamic unbalances using passive auto-balancers [4–6]. The operation of these devices is based on the fact that under certain conditions, the corrective weights (balls, rollers, pendulums) in the auto-balancers themselves come to the position in which they balance the rotor.

In [4], it was established numerically for a specific system that at the resonant speeds of rotation of the bladed-disk/shaft, auto-balancers effectively eliminate its mass and aerodynamic unbalance. In [5], it was theoretically established that it is impossible to dynamically balance the impeller of an axial fan (short rotor) with two auto-balancers. But if it is installed in a heavy housing with the possibility of rotation, and the housing is elastically and viscously fixed, then auto-balance will occur at the super-resonant speeds. In [6], these results are confirmed experimentally for the axial fan VO 06-300-4 (Ukraine) with two ball auto-balancers.

The application of passive auto-balancers is effective primarily for rotors mounted on elastically supported shafts operating at supercritical (super-resonant) rotational speeds. This configuration is typically met only by axial fans. Consequently, for the majority of propellers alternative balancing techniques are required.

There is also a simultaneous balancing of two unbalances by aerodynamic means. The fact that aerodynamic unbalance has a significant moment component is used, and the static component can be neglected. In turn, the moment component arises due to the installation of blades with different installation angles. The method is used in the case of variable-pitch propellers - wind turbines, helicopter rotors, aircraft propellers, etc. Let's consider this on the example of wind turbine propellers. Taking wind turbines as an example, the method involves real-time monitoring of vibrational behavior at the tower [7] and nacelle [8], as well as acoustic signatures from individual blades [9]. Then, according to a certain algorithm, the blades are rotated (their pitch is changed), respectively, to minimize vibrations and equalize noise from individual blades. In this case, aerodynamic forces change and at their expense, two types of unbalances are simultaneously balanced. The effectiveness of such methods is increased by using deep machine learning (using neural networks) [10], or conventional machine learning [11]. Aerodynamic (hydrodynamic) balancing has lower accuracy compared to mass correction balancing, since the balancing is not dynamic (not in two correction planes). The method is not applicable for propellers with fixed-pitch.

The best result in balancing fixed-pitch propellers is achieved during the manufacturing stage. These are traditional balancing methods. According to them, the propeller is consistently balanced both aerodynamically (hydrodynamically) and by adjusting the masses.

Aerodynamic (hydrodynamic) unbalance of a propeller is characterized by geometric inaccuracy in the manufacture of the propeller [1, 2]. Therefore, aerodynamic or hydrodynamic balancing of propellers is ensured by increasing the accuracy of their manufacture.

To verify the accuracy of propeller manufacturing, the propeller is rotated around its shaft, and the blade geometry is measured at designated control points [12]. Based on the measurement results, the shape of the propeller is corrected. After the shape is corrected, the propeller is balanced by adjusting the masses.

An alternative method for verifying manufacturing accuracy involves measuring the pressure generated by individual blades during rotation. Several pressure sensors are installed behind the propeller, arranged in a row along the blade [13]. The propeller is then rotated.

As each blade passes over the sensors, a signal proportional to its lift force is recorded. If the propeller is aerodynamically unbalanced, the blades will produce varying lift forces, which will be reflected in the sensor outputs. After measuring the lift forces, corrections are made to the shapes of individual blades. The accuracy of the measurements is increased by placing a lattice screen with pressure sensors behind the propeller [1]. The sensors are arranged in rows along the blades. But this complicates the design.

The most precise method for verifying propeller accuracy involves creating a digital information model of the propeller. The information model contains the results of measuring the geometric parameters of the propeller at many control points. The model itself is too bulky, and it takes a lot of time to obtain it. Measurement processes are facilitated through the use of 3D scanners [14], specialized coordinate measuring machines, and photogrammetry (stereophotogrammetry) techniques [15]. To further improve model accuracy, the number of control points and the precision of measurements must be increased, which complicates both the process and the model itself. Nevertheless, the information model enables the development of highly effective geometric correction measures.

The described methods are extremely labor-intensive and therefore are used in single or small-scale production of propellers.

Let us consider small fixed-pitch propellers. These are typically produced in medium or large batches, or even mass-produced. Modifying their geometric shape is generally impractical. For such propellers, a more specific issue arises: the separate identification of mass and aerodynamic (hydrodynamic) unbalance. This is essential for developing advanced methods for balancing propellers of various types, assessing balancing quality, measuring residual unbalance, and rejecting defective propellers during mass production.

It is worth noting that digital models of propellers enable the creation of detailed 3D representations [14, 15]. These models can be processed using computer-aided design (CAD) systems to separately identify mass and aerodynamic (hydrodynamic) unbalance. However, this approach is labor-intensive and not feasible for mass production.

Let us now examine methods based on the analogy between mass and aerodynamic (hydrodynamic) unbalance. In these approaches, aerodynamic (hydrodynamic) unbalance is evaluated through its equivalent mass unbalance.

In [16], the main vector and moment of aerodynamic forces acting on the rotating impeller of an axial fan are determined. Aerodynamic unbalance is found in the following cases: mounting the impeller on the rotor shaft with eccentricity and skew; installing one blade at a different angle of attack; violating the uniformity of the distribution of blades around the circumference. It is established that the impellers of axial fans can be balanced only by adjusting the masses. In this case, the impeller will be balanced over the entire range of rotation speeds, provided that the specific gravity of the air (gas) does not change.

In [17], the aerodynamic unbalance created by a single blade was theoretically investigated and corrective masses were found for its balancing.

According to the results of works [16, 17], it is possible to calculate the mass equivalent of the aerodynamic (hydrodynamic) unbalance of the propeller if additional information is available about the inaccuracy of the propeller manufacturing.

There is also an obvious practical method applicable in production conditions. It consists in measuring the propeller mass unbalance twice: in propeller operation conditions or on a stand that emits propeller operation; in (high) vacuum. In operation conditions or on a stand, the total unbalance is determined, and in (high) vacuum, the mass unbalance is determined. This is sufficient to determine the mass unbalance and the mass equivalent of the aerodynamic unbalance. The implementation of the method is described, for example, in [14] for a gas turbine engine rotor. But this is a laborious and expensive process, because it requires pumping air from the chamber where the mass unbalance is measured, and a person cannot work in such a chamber.

This method is more simply implemented for water propellers. On a balancing machine, the unbalance of the masses of a water propeller rotating in the air is determined. In this case, the aerodynamic component of the unbalance is neglected. On a stand that simulates the operation of a water propeller in a liquid, the total unbalance from masses and hydrodynamics is determined.

The mass equivalent of the aerodynamic (hydrodynamic) unbalance of a propeller characterizes this unbalance only under the propeller operating conditions under which it was measured. However, there are such modes of propeller operation that significantly change both the aerodynamic or hydrodynamic forces and the corresponding mass equivalent of the unbalance.

First, this is the reverse rotation of the propeller, which is used quite often [17–20]. Thus, reverse reduces the braking system and accelerates the landing of manned [17] and small unmanned aircraft [18], accelerates landing, picketing, improves the maneuverability of unmanned aerial vehicles [19], improves the maneuverability of ships, swimming vehicles [20]. Reverse rotation of the propeller changes the directions of aerodynamic or hydrodynamic forces and the corresponding mass unbalances to opposite ones.

Secondly, there is the ground (screen) effect [21–23]. This effect becomes noticeable when small [21] or large [22] aircraft operate in ground proximity or near obstacles, as well as during the operation of axial fans in the vicinity of surrounding structures [23]. The ground effect significantly increases the aerodynamic or hydrodynamic forces acting on the propeller and the corresponding mass equivalents.

The considered modes do not change the mass unbalance. They show a significant difference between the mass unbalance and the aerodynamic (hydrodynamic) unbalance of the propeller. The mass equivalent of the aerodynamic (hydrodynamic) unbalance is not as stable as the mass unbalance. This explains why relatively few works use the mass equivalent to estimate the aerodynamic (hydrodynamic) unbalance. On the other hand, the use of balancing machines or devices allows experimentally and with high accuracy to determine separately the mass and aerodynamic (hydrodynamic) unbalance under specific propeller operating conditions.

A review of sources [1–16] shows that practical methods for separately determining the mass and aerodynamic or hydrodynamic unbalance of a propeller are not sufficiently developed. Moreover, we mean methods that correspond to the aerodynamic (hydrodynamic) unbalance with a mass equivalent. Let us agree to substantiate such methods in the future.

Also, the applicability of reverse propeller rotation [17–20] or the ground effect [21–23] for this has not been investigated.

Statement of the task. The purpose of the research is to propose and theoretically substantiate new practical methods for determining mass and aerodynamic (hydrodynamic) unbalances of propeller. This will make it possible to develop methods for balancing propellers, determine residual unbalances, and reject propellers during manufacturing or repair at the factory.

Research objectives:

– theoretically substantiate new practical methods for determining mass and aerodynamic (hydrodynamic) unbalances of propeller, which are based on: replacing the density of air, gas or liquid; using reverse rotation; using the ground effect;

– theoretically evaluate and compare the effectiveness, accuracy and complexity of implementing the developed methods.

Presentation of the main material

1. Research Methodology

1.1. Basic assumptions. To study propeller unbalance, knowledge from rotor balancing theory, aerohydrodynamics, kinetic theory of gases and liquids [25], vacuum physics [26], physicochemical properties of substances [27], and theoretical mechanics is applied.

The analysis assumes that the blades are exposed to laminar flow, and the aerodynamic forces acting on the propeller can be reduced to a resultant force vector and a resultant moment. In the case of an air propeller, it is further assumed that aerodynamic forces are not significantly affected by Mach and Reynolds numbers. For water propellers, cavitation is considered negligible under operating conditions.

It is also postulated that both mass and aerodynamic (hydrodynamic) unbalance (i.e., their mass equivalent) can be determined by measuring the dynamic unbalance under two different conditions: standard operating conditions and modified operating conditions.

The modified operating conditions should affect only the aerodynamic or hydrodynamic unbalance. These changes are treated as the introduction of a test (trial) aerodynamic or hydrodynamic unbalance. To improve the accuracy of determining the aerodynamic or hydrodynamic unbalance, the change in unbalance should be no less than 30% [3].

The following modifications to propeller operating conditions are considered:

– changing the density of air, gas, or liquid;

– reversing the direction of propeller rotation;

– placing a screen in front of or behind the propeller.

The effectiveness of these methods for identifying the components of total unbalance will be evaluated based on the following criteria:

– whether the method enables a change in aerodynamic or hydrodynamic unbalance of at least 30%;

– whether additional factors arise that reduce the accuracy of component identification;

– how complex the method is to implement in practice.

Additional assumptions will be introduced as needed in the course of solving the stated problems.

1.2. Rotor marking, unbalance characteristics. Fig. 1 shows the diagram (and marking) of the rotor, which is required for use in algorithms for calculating complex numbers [3].

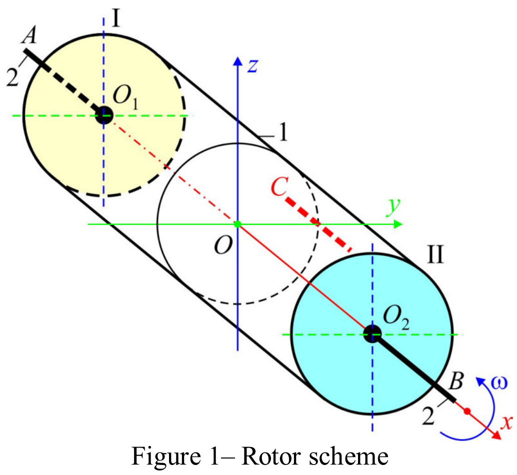

Figure 1– Rotor scheme

Source: developed by the authors

In the Fig. 1: 1 – rotor; 2 – shaft; *A* – left trunnion; *B* – right trunnion; I – first correction plane; II – second correction plane; *C* – zero mark; ω – rotor angular speed.

Let us introduce a rectangular Cartesian coordinate system so that the *x*- axis lies on the axis of rotation of the rotor and is directed in the direction from which the counterclockwise rotation is visible. The *y*- axis is directed perpendicular to the axis of rotation in the direction of the mark, and the *z*- axis so that the coordinate system is right-handed. Two correction planes, I and II, are introduced. The dynamic unbalance of the rotor will be determined within these planes.

Rotor unbalance $\mathbf{U}_j$ in the correction plane *j* shown in fig. 2 [3].

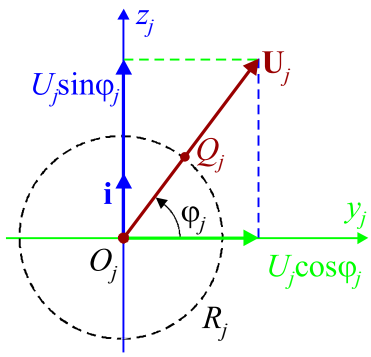

Figure 2– Rotor unbalance in the correction plane *j*

Source: developed by the authors

The direction of the unbalance vector $\mathbf{U}_j$ is determined by the angle φ_j between the y_j axis (parallel to the *y* axis) and the unbalance vector $\mathbf{U}_j$. As is customary in balancing technology, the angle is calculated in the direction of rotor rotation [3].

The unbalance $\mathbf{U}_j$ is formed by a point mass Q_j, installed at a distance R_j from the longitudinal axis of the rotor. The modulus and projections of the unbalance onto the coordinate axes *y*, *z*:

$$U_j = Q_j R_j,\ U_{jy} = U_j \cos\varphi_j,\ U_{jz} = U_j \cos\varphi_j,\ /\,j=1,2\,/. \tag{1}$$

The rotor unbalance vector in the correction plane *j* will be defined by a complex number written in algebraic, trigonometric or exponential form:

$$\mathbf{U}_j = U_{jy} + \mathbf{i}U_{jz} = U_j \cos\varphi_j + \mathbf{i}U_j \sin\varphi_j = U_j e^{\mathbf{i}\varphi_j},\ /\,j=1,2/, \tag{2}$$

where:

$$\mathbf{i} = \sqrt{-1},\ e^{\mathbf{i}\varphi_j} = \cos\varphi_j + \mathbf{i}\sin\varphi_j,\ \ /\,j=1,2\,/. \tag{3}$$

It is assumed that a balancing device, stand, or machine is available that enables the determination of rotor dynamic unbalance in the form (2). The method of determining the unbalance, the type of balancing equipment, the design of the machine or stand, and the type of vibration sensors are not considered critical.

2. Research results

2.1. Methods for determining mass and aerodynamic (hydrodynamic) unbalances of a propeller

2.1.1. Using the dependence of the aerodynamic (hydrodynamic) unbalance of the propeller on the density of air, gas or liquid

ρ_0 be measured during normal propeller operation, and the total dynamic unbalance of the propeller in two correction planes:

$$\mathbf{U}0_j = \mathbf{U}0_j^{(m)} + \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \tag{4}$$

In (4) on the left are measured (known) quantities, and on the right are unknown quantities, with the index "*m*" representing mass unbalance, and the index "*a*" representing aerodynamic (hydrodynamic) unbalance.

Let the density of the air, gas, or liquid be changed to a new value, ρ_1. This will result in a change in the overall dynamic unbalance and specifically in its aerodynamic (hydrodynamic) component:

$$\mathbf{U}1_j = \mathbf{U}0_j^{(m)} + \mathbf{U}1_j^{(a)}, \ /j = 1,2/. \tag{5}$$

In (5), it is considered that the mass unbalance will not change when the air density changes.

In [5] it is shown that aerodynamic (hydrodynamic) unbalance is directly proportional to the density of air, gas (liquid). Therefore:

$$\mathbf{U}1_j^{(a)} = k_\rho \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \tag{6}$$

Where

$$k_\rho = \rho 1 / \rho 0. \tag{7}$$

Substituting (6) into (5), we obtain:

$$\mathbf{U}1_j = \mathbf{U}0_j^{(m)} + k_\rho \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \tag{8}$$

Based on equations (4) and (8), the following formulas are obtained for determining the mass and aerodynamic (hydrodynamic) unbalance components under normal propeller operating conditions:

$$\mathbf{U}0_j^{(m)} = \frac{\mathbf{U}0_j k_\rho - \mathbf{U}1_j}{k_\rho - 1}, \ \mathbf{U}0_j^{(a)} = \frac{\mathbf{U}1_j - \mathbf{U}0_j}{k_\rho - 1}, \ /j = 1,2/. \tag{9}$$

Consider the case of an air propeller. Within the framework of the molecular-kinetic theory of an ideal gas [25], the density of the gas is:

$$\rho = m / V = p \cdot M / (R \cdot T), \tag{10}$$

where: p – pressure, T – temperature, M is the molar mass of the gas; R is the universal gas constant.

From (10) the following paths of change in air (gas) density follow:

1) pressure change;
2) temperature change;
3) replacement with another gas with a different molar mass.

2.1.2. Using reverse

Let the total dynamic unbalance of the propeller under normal operating conditions be measured, as expressed in equation (4). Let the total dynamic unbalance also be measured during reverse operation of the propeller. In this case, it can be reasonably assumed that the aerodynamic (hydrodynamic) unbalance changes its direction to the opposite. Therefore, the total dynamic unbalance of the propeller under modified conditions is given by:

$$\mathbf{U}1_j = \mathbf{U}0_j^{(m)} - \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \quad (11)$$

From (4) and (11) we find:

$$\mathbf{U}0_j^{(m)} = (\mathbf{U}0_j + \mathbf{U}1_j)/2, \ \mathbf{U}0_j^{(a)} = (\mathbf{U}0_j - \mathbf{U}1_j)/2, \ /j = 1,2/. \quad (12)$$

Note that this method of determining the components of propeller unbalance is applicable to both air and water propellers.

The substantiated technical solution is protected by a Ukrainian patent for a utility model [28].

2.1.3. Using the ground effect

Let the axial aerodynamic (hydrodynamic) force F_0 and the total dynamic unbalance of the propeller be measured during normal operation, as defined in equation (4).

Now, let a screen be placed either in front of or behind the propeller. Under these modified conditions, let the axial aerodynamic (hydrodynamic) force F_1 and the corresponding total dynamic unbalance of the propeller be measured:

$$\mathbf{U}1_j = \mathbf{U}0_j^{(m)} + \mathbf{U}1_j^{(a)}, \ /j = 1,2/. \quad (13)$$

It is considered here that the mass unbalance will not change when the screen is installed.

We will assume that the aerodynamic or hydrodynamic unbalance has increased in direct proportion to the increase in the axial aerodynamic or hydrodynamic force:

$$\mathbf{U}1_j^{(a)} = k_e \mathbf{U}0_j^{(a)}, \ k_e = F1/F0 > 1, \ /j = 1,2/. \quad (14)$$

Then equation (13) will assume the following form:

$$\mathbf{U}1_j = \mathbf{U}0_j^{(m)} + k_e \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \quad (15)$$

From (4) and (15) we find:

$$\mathbf{U}0_j^{(m)} = \frac{\mathbf{U}0_j k_e - \mathbf{U}1_j}{k_e - 1}, \ \mathbf{U}0_j^{(a)} = \frac{\mathbf{U}1_j - \mathbf{U}0_j}{k_e - 1}, \ /j = 1,2/. \quad (16)$$

Note that this method of determining the components of propeller unbalance is applicable to both air and water propellers.

The substantiated technical solution is protected by a Ukrainian patent for a utility model [29].

2.1.4. Generalized mass equivalent of aerodynamic (hydrodynamic) unbalance

Let the aerodynamic (hydrodynamic) unbalance of the propeller under normal operating conditions be determined using one of the proposed methods. Considering equations (6), (11), and (14), the mass equivalent of the aerodynamic (hydrodynamic) unbalance under modified operating conditions of the propeller is determined by the following formula

$$\mathbf{U}1_j^{(a)} = k_\rho k_e k_\omega \mathbf{U}0_j^{(a)}, \ /j = 1,2/. \quad (17)$$

In (17): k_e considered only when installing the screen, otherwise $k_e = 1$;

$$k_\omega = \mathrm{sign}(\omega 1/\omega 0), \quad (18)$$

where $\omega 0$ is the angular speed of rotation of the propeller under normal conditions, and $\omega 1$ is the angular speed of rotation of the propeller under changed conditions.

This mass equivalent simultaneously considers the change in aerodynamic (hydrodynamic) unbalance from: change in specific gravity of air, gas or liquid; reversal; ground effect. It shows a significant difference between aerodynamic (hydrodynamic) unbalance and mass unbalance. It can be used to model the motion of machines and devices with propellers.

2.2. Assessment of the effectiveness, accuracy and complexity of implementing methods for determining propeller unbalances

2.2.1. Assessing the impact of pressure changes

The method based on pressure variation is applicable only to air propellers. According to equation (10), the density of air (gas) is directly proportional to the pressure. If the air propeller operates in a special chamber with modified pressure, it becomes possible to identify the individual components of the total unbalance of the air propeller. Let the pressure change by k_p times. Then from (10) it follows that the density of air (gas) will also change by k_p times. Then:

$$k_\rho = k_p \tag{19}$$

and formulas (9) will assume the following form:

$$\mathbf{U}0_j^{(m)} = \frac{\mathbf{U}0_j k_P - \mathbf{U}1_j}{k_P - 1},\ \ \mathbf{U}0_j^{(a)} = \frac{\mathbf{U}1_j - \mathbf{U}0_j}{k_P - 1},\ \ /j = 1,2/. \tag{20}$$

The pressure in the chamber can be increased or decreased. In high vacuum $k_p \approx 0$, formulas (20) take the simplest form [14]:

$$\mathbf{U}0_j^{(m)} = \mathbf{U}1_j,\ \ \mathbf{U}0_j^{(a)} = \mathbf{U}0_j - \mathbf{U}1_j,\ \ /j = 1,2/. \tag{21}$$

Indeed, in a vacuum there are no aerodynamic forces or aerodynamic unbalance. Therefore, the total unbalance measured in a vacuum coincides with the mass unbalance. In engineering and applied physics, a vacuum is understood as an environment consisting of gas under a pressure lower than atmospheric [26]. In production conditions, the use of a low vacuum region (Low vacuum p=10^3–1 mbar). In this case, the pressure in the chamber must be at least 30% less than atmospheric. A person can work in such conditions.

The substantiated technical solution is protected by a Ukrainian patent for a utility model [30].

2.2.2. Assessment of the impact of changes in air (gas) temperature. The method using temperature change is applicable only for air propeller. From (10) it follows that the density of air (gas) is inversely proportional to temperature. If the air propeller will operate in a special chamber with a changed temperature, then it will be possible to determine the individual components of the total unbalance of the air propeller. Let the temperature change by k_T times. From (10) it follows that the density of air (gas) will change by $1/k_T$ times, whence:

$$k_\rho = 1/k_T. \tag{22}$$

Then formulas (9) will assume the following form:

$$\mathbf{U}0_j^{(m)} = \frac{\mathbf{U}0_j - \mathbf{U}1_j k_T}{1 - k_T},\ \ \mathbf{U}0_j^{(a)} = \frac{(\mathbf{U}1_j - \mathbf{U}0_j) k_T}{1 - k_T},\ \ /j = 1,2/. \tag{23}$$

Let us consider how the change in air (gas) temperature affects aerodynamic unbalance. Normal conditions correspond to a temperature of 0° C (273.2 K). Let the temperature in the special chamber be changed to +50° C (323.2 K). Note that at such a temperature it will be difficult for a person to work in the chamber. The temperature difference is very significant and is ΔT = 50° C. But $k_{\rho} = 1/k_T = 273.2/323.2 = 0.845$ and the air density will change (decrease) by only (1–0.845)·100=15.5%. Therefore, it is not advisable to use the change in air temperature to determine the unbalances of the air propeller.

The substantiated technical solution is protected by a Ukrainian patent for a utility model [31].

2.2.3. Assessment of the effect of replacing air (gas) or liquid with a gas or liquid of a different density

The method involving the replacement of air (gas) or liquid with a medium of different density is applicable to both air and water propellers. In this case, air (gas) can be substituted with a liquid (e.g., water), and vice versa. If the air propeller operates in a special chamber filled with another gas, it becomes possible to isolate and determine individual components of the total unbalance of the air propeller. Let the density of the other gas be k_M times greater or less. Then:

$$k_{\rho} = k_M, \tag{24}$$

and formulas (9) will assume the following form:

$$\mathbf{U0}_j^{(m)} = \frac{\mathbf{U0}_j k_M - \mathbf{U1}_j}{k_M - 1}, \ \mathbf{U0}_j^{(a)} = \frac{\mathbf{U1}_j - \mathbf{U0}_j}{k_M - 1}, \ /j = 1,2/. \tag{25}$$

Below is Table 1, which compares air density with water densities and some gases under normal conditions [27].

Table 1– Comparison of air density with the densities of water and some gases under normal conditions [27]

No.	Gas (liquid)	Density, kg/m^3	Ratio to air density k_M
1	Helium	0.178	0.138
2	Neon	0.900	0.696
3	Air	1.293	1.000
4	Argon	1.784	1.380
5	Carbonaceous	1.977	1.529
6	Krypton	3.743	2.895
7	Water	1000.000	773.395

Source: compiled by the authors using the source [27]

Table 1 lists the cheapest and most explosive gases. The substantiated technical solution is protected by a Ukrainian patent for a utility model [32].

4.2.4. Evaluating the use of reverse rotation or ground effect

Reverse rotation of the propeller most significantly changes the aerodynamic (hydrodynamic) forces, which increases the accuracy of determining the components of the total unbalance. But the assumption that the aerodynamic (hydrodynamic) unbalance during reverse has changed direction to the opposite will be sufficiently accurate only for a propeller with flat symmetrical blades. Therefore, non-flat and asymmetrical blades are a source of error in determining the components of the total unbalance.

The use of the ground effect at low air or fluid velocities can increase aerodynamic or hydrodynamic forces by up to a factor of two. This enhances the accuracy of identifying the components of total unbalance. However, it is known that the presence of a screen shifts the center of pressure toward the trailing edge of the blade, which in turn reduces the accuracy of determining the individual components of total unbalance.

4.2.5. Comparison of the complexity of the designs of stands for determining propeller unbalances

Fig. 3 shows a variant of the stand for determining the mass and aerodynamic unbalance of the propeller (axial fan impeller) by any of the proposed methods.

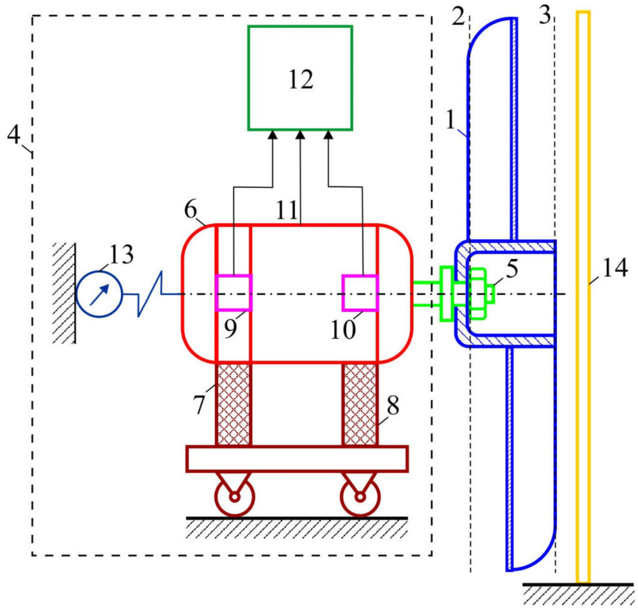

Figure 3 – Possible version of the stand for determining the mass and aerodynamic unbalance of the propeller

Source: developed by the authors

Fig. 3 shows a propeller 1, which has two correction planes 2, 3, in which the propeller unbalance is determined. The propeller is installed on a stand 4. The stand has a shaft 5, on which the propeller is mounted. The shaft rotates in a forward or reverse direction by an electric motor 6. The electric motor is supported by two elastic movable supports 7, 8. Two vibration sensors 9, 10 are installed near the supports. The beginning of a new shaft rotation is recorded by a speed sensor 11. The balancing device 12 receives and processes signals from the vibration and speed sensors, calculates the dynamic unbalance of the propeller in two correction planes. The axial force is measured by a dynamometer 13. A screen 14 is used to create the ground effect.

Vibration sensors can be accelerometers, vibration velocity or vibration displacement sensors. It does not matter in principle which balancing device, by which algorithm and by which method the dynamic unbalance of the propeller is determined. But the best way to determine dynamic unbalance may be the method of three test starts [3].

When using methods for determining propeller unbalances based on changes in air and gas density, reverse propeller rotation, mobility of elastic supports, dynamometer and screen are not used. These elements can be removed from the design of the stand. But to implement the methods, a chamber is required for changing pressure, temperature or replacing air or gas. This complicates the implementation of the methods.

When using the method based on reverse propeller rotation to determine unbalances, elastic support mobility, a dynamometer, and a screen are not required. These components can be excluded from the stand's design. This makes it the simplest method to implement.

The most complex stand design is associated with the method that utilizes the ground effect. However, the implementation of this method does not require an additional vacuum chamber.

Conclusions

1. To determine the mass and aerodynamic (hydrodynamic) unbalances of a propeller, it is sufficient to measure the dynamic unbalance of the propeller twice using a balancing device. The first measurement is performed under normal operating conditions, and the second under modified conditions that significantly affect the aerodynamic (hydrodynamic) unbalance while leaving the mass unbalance unchanged. In this way, the mass equivalent of the aerodynamic (hydrodynamic) unbalance can be determined.

To improve the accuracy of identifying the components of the total unbalance, it is recommended to alter the propeller’s operating conditions in such a way that the aerodynamic or hydrodynamic unbalance changes by at least 30%.

The following modifications to the operating conditions are considered effective:

– altering the density of air, gas, or liquid;

– reversing the direction of propeller rotation;

– installing a screen either in front of or behind the propeller.

In turn, changes in the density of the working medium can be achieved by:

– replacing air, gas, or liquid with another gas or liquid, including substitution of air or gas with a liquid, and vice versa;

– changes in air or gas temperature for air propellers;

– changes for air or gas pressure propellers.

2. Among these methods, the highest potential accuracy is offered by those based on replacing the fluid medium with one of a different density. However, for air propellers, the method based on temperature variation is difficult to implement due to the need to achieve a temperature change of more than 70°C.

Reverse rotation of the propeller changes the direction of aerodynamic or hydrodynamic unbalance vectors to the opposite, though with a certain degree of error. This error is smaller for flat, symmetrical blades, but the method may still introduce inaccuracies.

The method involving the installation of a screen in front of or behind the propeller not only alters the magnitude of the aerodynamic (hydrodynamic) unbalance but also slightly changes its direction. This, too, may introduce errors into the determination of unbalance components.

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Обґрунтування методів визначення масової та аеродинамічної (гідродинамічної) незрівноваженості гвинта

Теоретично обґрунтовано нові методи окремого визначення масової і аеродинамічної (гідродинамічної) незрівноваженості повітряного чи гребного гвинта з фіксованим кроком. Для цього запропоновано визначати динамічну незрівноваженість двічі: за нормальних умов роботи гвинта; за змінених умов, за яких змінюється лише аеродинамічна (гідродинамічна) складова незрівноваженості гвинта.

Запропоновані методи базуються на: зміні густини повітря, газу або рідини; застосуванні реверсивного обертання гвинта; використанні екранного ефекту. Зокрема, зміни густини можна досягти шляхом заміни робочого тіла на тіло з іншою густиною або шляхом зміни його температури чи тиску. Теоретична основа базується на таких властивостях аеродинамічної (гідродинамічної) незрівноваженості: вона прямо пропорційний густині середовища; її напрямок змінюється на протилежний при зворотному обертанні гвинта; її величина збільшується, коли перед або за гвинтом встановлено екран (екранний ефект). Аеродинамічна (гідродинамічна) незрівноваженість кількісно визначається як еквівалентна масова незрівноваженість, виміряна балансувальним приладом за певних умов роботи гвинта. Запропонований закон зміни цієї незрівноваженості, що залежить від умови роботи гвинта.

Ефективність цих методів оцінюється на основі їхньої практичної доцільності та потенційного впливу на точність розділення складових незрівноваженостей. Ці результати можуть бути корисними для розробки вдосконалених методів балансування, оцінки залишкової незрівноваженості та контролю якості під час виробництва та ремонту гвинтів.

гвинт, балансування, безпілотний апарат, пілотований апарат, балансувальний пристрій, екранний ефект

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