32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

PROTOTYPE WHIRL TOWER FOR TESTING INSOLATED ROTOR SYSTEMS IN HOVER

Malgorzata Wojtas[1], Konrad Raczko[1], Łukasz Czajkowski[1]

[1] Łukasiewicz Research Network – Institute of Aviation, Al. Krakowska 110/114, Warsaw 02-256, Poland

Abstract

The paper provides anchored positions, mainly - whirl tower research stands. Several solutions to this type of stands were presented and discussed according to available literature, producent websites and few years of ours experiences. Since valuable information regarding dynamic balance, noise, aeroelastic stability, vibration, and performance as well as structural integrity of rotors at hover condition can be assessed in Whirl Tower tests, these test systems are considered vital in rotor design. The article provides information about new test stand fully designed and manufactured in Łukasiewicz Research Network – Institute of Aviation. Furthermore, the types of tests that can be carried out on this type of test stand, and safety of research were discussed. The work shows the main assumptions of the project, design steps, calculations, construction manufacturing and Whirl Tower systems test. The Whirl Tower was checked for resonance frequencies, which allowed to verify with the calculations a safe range of measurements. Additionally, the tests of rotors, previously tested (with known parameters), were carried out to verify measurement and data acquisition system and to calibrate the stand.

Keywords: rotors, test stand, design, resonance

1. General Introduction

In recent years, the development of rotorcrafts has been observed. This applies to helicopters, gyroplanes as well as multirotor vehicles. The strong emphasis is put on the development of the vertical take-off and landing vehicle, both manned and unmanned.

Manned vehicle market is focused, among others, on private customers, enthusiasts, and businessmen, largely as hobby and entertainment. This applies mainly to light and ultra-light rotorcrafts. EASA, meeting the needs and promoting aviation among a wider group of aviation enthusiasts, opened new categories relating to ultra-light class aircraft - UL 115 subcategory [18]. UL -115 category applies to flying devices with propulsion and maximum mass of 115 kg. Moreover, it is exempt from certification by the relevant aviation authorities and obtaining a permit to fly is limited to training in the field of aviation law, use of the airspace, air traffic regulations, right-of-way, and other regulations, in the scope of flights.

Another direction of rotorcraft development is unmanned vertical take-off and landing platforms. Expected trends in the development of unmanned VTOL platforms are single or multi-rotor drones with high payload, above 200 kg with increased flight range. Such unmanned platforms can be used for cargo, air taxis, firefighting, spraying crops and more.

Nowadays interest is also directed towards to VTOL platforms for space applications. As shown by the recent success of NASA with the drone Ingenuity, which opens the way to completely new rotorcrafts designs.

Recipients of both manned and unmanned aerial vehicles are oriented to new solutions, improvements that increase flight comfort, economy, distance, increase capacity without affecting the flight range, flight speed etc. Great emphasis is placed on the development of new main rotors with new airfoils and new technology of manufacturing using different composite materials as well as smart materials and technologies [12].

The primary structural elements in rotorcraft, which is undoubtedly the main rotor as well as rotor hub, are subjected to numerous tests before being permitted to flight-test. These include, among others, strength tests required by aviation regulations. However, the tests required by the aviation regulations will not provide answers about rotor properties. Therefore, to evaluate structural and aeromechanical performance of the main rotor, tests simulating hover conditions are carried out. Since precious information regarding dynamic balance, noise, aeroelastic stability, vibration, and performance as well as structural integrity of rotors at hover condition can be assessed in Whirl Tower tests, these test systems are considered vital in rotor design [5, 6].

Meeting the market requirements and ensuring the safety of research, at the Institute of Aviation are being developed tests with the use of so-called Whirl Towers stands and other kind anchored stands for testing rotors and propellers.

In the beginning the article discusses the use of Whirl Tower type tests stands. It presents examples of measuring stands for testing rotors and propellers, presents the measurement possibilities, defines the advantages and disadvantages of this type of stands and confronts it with the general safety of research.

The further part of the article contains a study of the design and manufacturing of the prototype Whirl Tower stand, where the main assumption was the universality. The aim of the project was to extend the scope of measurement possibilities of the stand with utilizes a 315 kW (400 HP) electric motor as a drive, reducing the risk of test stand resonance, ensuring the possibility of easy sensors installation and adaptation of the measuring system to the atmospheric conditions. In additional providing the ability to easily move the Whirl Tower stand. This paper provides the main assumptions of the project, design steps, calculations, construction manufacturing and whirl tower system test. The whirl tower was checked for resonance frequencies, which allowed to verify with the calculations a safe range of measurements. Additionally, the tests of rotors, previously tested (with known parameters), were carried out to verify measurement and data acquisition system and to calibrate the stand [13]

1.1 Research safety

Helicopters rotors as one of the main assemblies, require different tests e.g., evaluate performance before operation. Correct and safe measurement of such quantities as: thrust, power consumption, forces occurring in the control system and on the rotor hub, the value and nature of vibrations resulting from the operation of the rotor, bending and twisting moments occurring on the rotor blades and hub, allows for the correct performance, design or modernization of rotor components and the entire rotor.

The use of anchored stands and whirl towers make it possible to conduct effective ground tests of helicopter rotors, minimizing the risk of failure of results and destruction of the system by using forward alternating simulation modeling of test stages, multilateral control of their course and verification of stage results as well as forecasting probable critical situations, and extreme variants by model extrapolation.

Whirl tower type tests stands, allows to conduct measurements of the operating properties of the main rotors or propellers, in the form of models as well as real rotors, without the need to test the entire helicopter. In the case of using test stands before testing on the target rotorcraft, there are more testing possibilities. This is especially important when testing completely new solutions for main rotors or propellers (both blades and heads). The stands are designed in such a way as to enable the safe achievement of critical conditions for the tested rotor or propeller, or the main rotor - tail rotor system.

1.2 Whirl tower test stands – overview

The use of anchored tests stands, and Whirl Towers is not a new solution. There are many tests stands in the world designed and manufactured by institutes and private companies enable the testing of main rotors and propellers in deferent conditions and configuration. Some of these solutions are discussed in this chapter.

A few companies, for years, specialize in this type of test stands. In addition to the design and manufacturing, they also offer data acquisition, measuring systems, rotor balancing systems and more.

American company - Swangate International - is actively involved in the helicopter rotor programs, as well as whirl tower test stands, and systems dedicated to their management. They developed and implemented the WT-BladeMaster system, which includes the towers with the accessories (shown in Figure 1), these are stands with the most modern, highly advanced technical blade tracking systems, ensuring high quality of dynamic helicopter testing [9].

Figure 1 – The example of Swangate International Whirl Tower systems [13].

The WT-BladeMaster System is a very efficient and flexible tool used in the production and repair of main helicopter rotors. The main task of the WT-B system is very precise tracking and balancing of the helicopter rotor disc, which is intended to assist in design and production improvements of rotor blades and hubs.

Another company involved in manufacturing research stands systems – whirl towers is German company ZF Luftfahrttechnik GmbH [16]. An example of universal test stand in the form of a tower for testing the main rotors of helicopters is presented in figure 2.

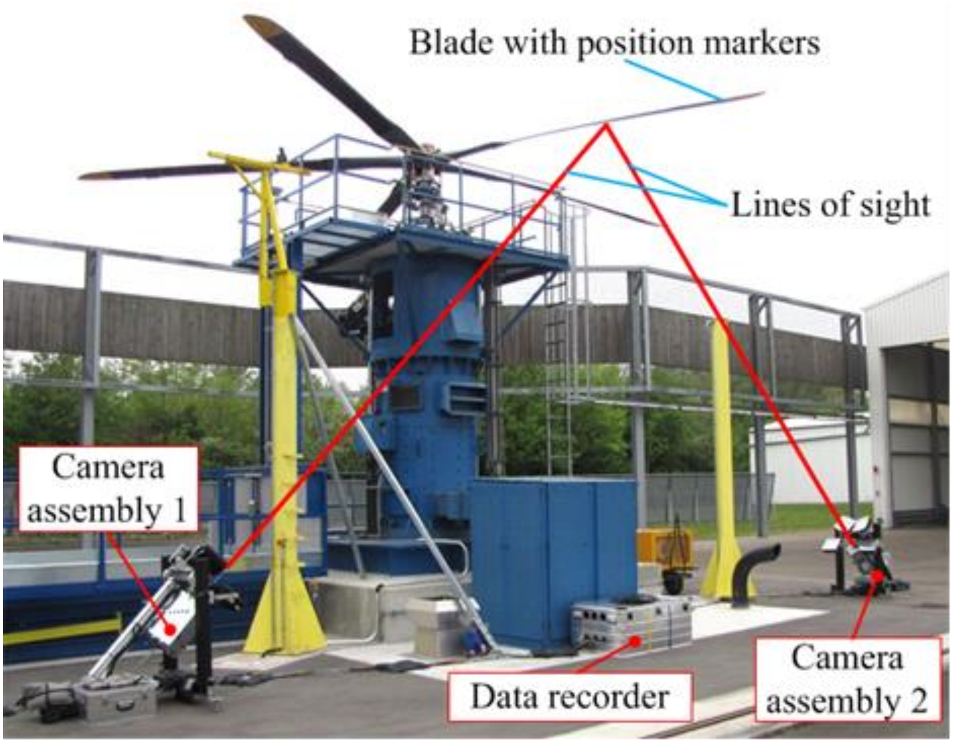


Figure 2 – The example of Luftfahrttechnik GmbH Whirl Tower systems [17]

The test stands of the discussed company allow to test the rotors and obtain the following parameters:

- In the case of series production of rotors, the measuring range includes thrust of each blade, air resistance, forces in the control system, vibrations.

- In the case of rotor development tests, the scope of measurements also allows the examination of total rotor thrust, rotor torque, rotor bending moment, blade forces and the nature of vibrations.

Below, there are several solutions of whirl tower stations, designed and manufactured in projects concerning new helicopter design.

One of the solution - whirl tower test system, shown in figure 3, is discussed in the literature [5, 6]. This solution for rotorcrafts was designed and manufactured in Turkish Aerospace Industries. The main properties of this test stand are rotor blades mounted at 6 m high column, the maximum motor power in the system is 560 kW with maximum torque – 7780 Nm, rotor revolution speed is 744 RPM and maximum diameter of tested rotor is 8 m.

Figure 3 – The TAI whirl tower system [5].

Similar solution can be found in Korea Aerospace Research Institute [4]. KARI WTTF is a multipurpose whirl tower. It can be used for development test and production test (dynamic balancing test). The tower is equipped with universal hub systems, as shown on figure below. The stand has been prepared for the requirements of helicopters from 8000kg MTOW class.

Figure 4 – KARI Whirl Tower Test Facility (WTTF) [4].

The Institute of Aviation also has some experience in using the solutions of anchored positions, including whirl towers. Simple test stands were built for projects such as the IS-2 helicopter, and later the ILX-27 unmanned helicopter, or modern autorotation rotors for gyroplane applications. The stands were designed and manufactured for testing performance as well as determination loads of rotor system (blade, hub) under normal operating conditions and under boundary conditions.

Test stand design was performed for the project titled ‘New Autorotation Rotor’, as a result new rotor, with new airfoil, dedicated to gyroplanes were designed and tested. Test position (shown in figure 5), was equipped with a rigid, two – bladed, universal teetering rotor, adequately oversized to ensure safety during tests. The maximum power of the stand was 180 HP. The distance between the blades and the ground was around 3 meters.

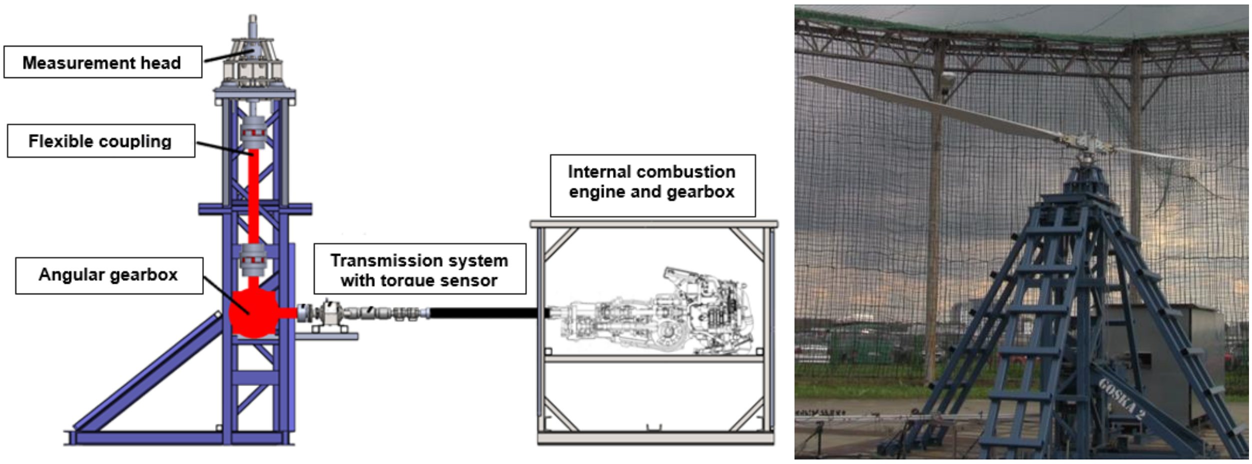


Figure 5 – The whirl tower system for gyroplane and unmanned helicopter main rotor tests [10].

Another solution used in the tests of the gearbox and the coaxial rotor is briefly discussed below [1, 14]. It is a stand that allows conducting tests of the coaxial rotor head and gearbox. The stand was powered by an 11kW electric motor. The distance between the first rotor blades and the ground was 1 meter. The stand was equipped with a measuring system allowing for the measurement of vibrations, torque, rotor thrust, power consumption and rotational speed.

Figure 6 – Coaxial rotor whirl tower test stand [1].

The last solution briefly presented in this work is the research stand from Carleton University in Canada. A Whirl Tower enables the centrifugal testing of a rotary-wing apparatus, i.e., helicopter and wind turbine rotors or propellers, before entering a wind tunnel or flight test campaign [8].

Figure 7 – The Whirl Tower Test Chamber and Test Stand [7]

It is driven by a 60 HP, 575 V 3-phase, 1,800 RPM motor, which is controlled via a variable frequency drive. The whirl tower is in a test chamber with a diameter of 15 ft (4.57 m) as show on figure above.

As can be seen from the briefly presented overview, ground test stands for testing rotors, propellers, main rotor heads or gearboxes are quite commonly used. Depending on the needs, the stands are equipped with different measuring systems. They can be used for operational measurements of rotors/propellers, measurements of rotor parameters in hover, vibration assessment, rotor/propeller balancing, rotor testing in wind tunnels etc.

2. Universal Whirl Tower stand

With the development of new solutions of rotors and propellers, or interest about the possibility, determining the various structures vibration which are within range of helicopter rotors such as the facades of buildings in elevated airports. All this contributed to the development of a new whirl tower type test stand concept that will meet the requirements of the market. Based on the years' experience and the overview briefly outlined in paragraph 1.2, a prototype Whirl Tower type test stand has been developed as part of the project of the Institute of Aviation.
The purpose of the project was to extend the scope of measurement possibilities of the stand, reduce the risk of stand resonance, ensure the possibility of easy sensors installation. It was also critical to ensure the mobility of the test stand and to provide an electric drive to ensure reliable operation of the stand and the possibility rotor blades noise measurement. Another important parameter was the adaptation of the measuring system to the atmospheric conditions which will improve the process of test preparation, thus significantly reducing the time of tests itself.

2.1 Design problems and solutions

2.1.1 Two test stand concepts

The first concepts of the stand were based on the use of an electric motor placed in a horizontal position as shown in the visualization below, on figure 8. This concept assumed the selection of an electric motor with a rotational speed of 1500 - 3000 RPM, minimum power of 250 kW and an angular gearbox with an appropriate transmission ratio to obtain revolutions after the gearbox of approximately 600 to 700 RPM, and a torque of approximately 4000 Nm. The stand in this version would consist of two parts: drive, with the motor properly mounted and secured, and the whirl tower part with the gearbox. The assumption was that these parts will be disassembled when there will be a need to move the stand. This concept, however, had a lot of disadvantages. One of them was one the angular gearbox. The design and manufactured such a gearbox that meets the requirements of the test condition of the test bench was complicated and expensive process. The elimination of the gearbox would allow for performance long-term tests without need for use complicated cooling systems. The next crucial obstacle of this solution is the impact of the drive part on the air flow under the rotor during test. This problem has already been encountered with previous versions whirl towers with combustion engines. In addition, the use of this solution would limit the measuring capabilities to helicopters or gyroplanes rotors which nominal rotational speed do not exceed 500 - 600 RPM.

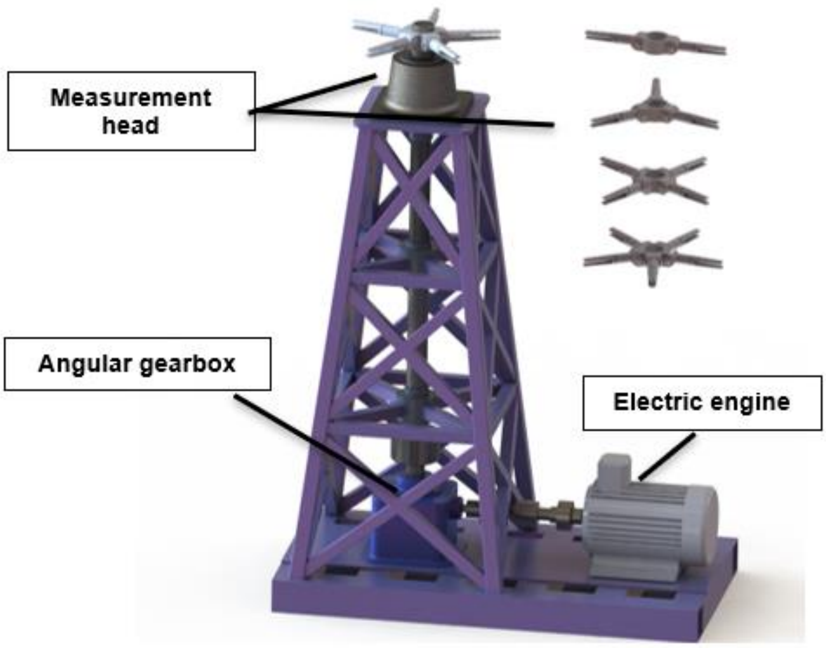


Figure 8 – Concept of the whirl tower system with horizontally mounted electric motor.

After performing the analysis of available solutions for electric motors and getting acquainted with the comments and suggestions of experts in this field, a new concept of the stand was developed with electric engine in vertical position, with nominal rotational speed of 750 RPM, maximum power 315 kW and maximum moment of 4000 Nm. Thus, elimination of the main problems of the previous solutions and the provision of the possibility of extending the measurements to higher rotational speeds was achieved. The visualization of test stand second concept is shown on the figure 9.

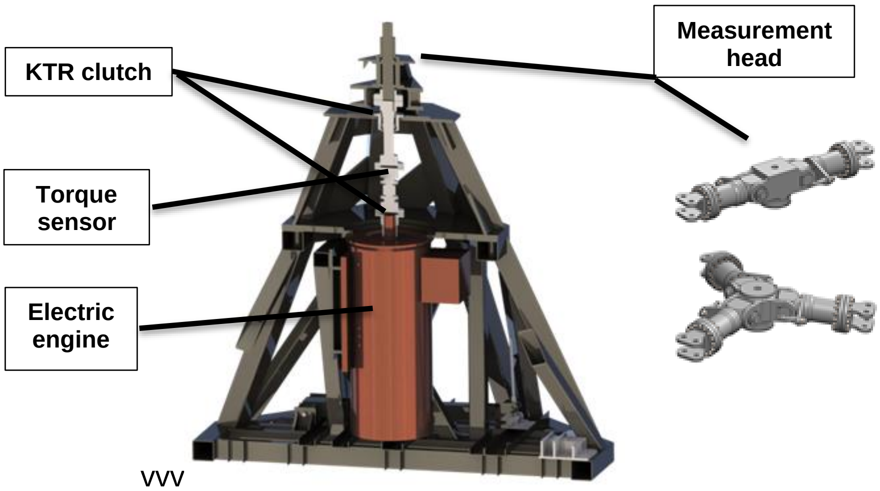


Figure 9 – Concept of the whirl tower system with vertically mounted electric motor.

2.1.2 *Test stand mobility*

One of the requirements that makes the design quite difficult was test stand mobility. The stand is in so-called ‘Rotunda’. ‘Rotunda’ is a place specially designated for testing rotating objectsmainly helicopters, gyroplanes, but also rotors, propellers, or fans as well as small drones.

With the relatively large mass of the stand (about 13 tons), it was necessary to develop a system that would allow you to easily move the bench using the tools and trucks available at the Institute. For this purpose, the ‘retractable chassis was designed. It consists of two wheels made of steel with a diameter of 300 mm and a track width of 80 mm. The chassis is retracted and released with a lever as shown in visualization below (figure 10), in a - case the cassis is hidden, in b-case it is released. The stand can be moved using a forklift truck with a minimum lifting capacity of 3.5 tons. The pitchfork of truck is placed in a designated place on the stand frame. The stand chassis is lowered, and the forklift truck lifts the stand to a height of about 200 mm and push or pulls them.

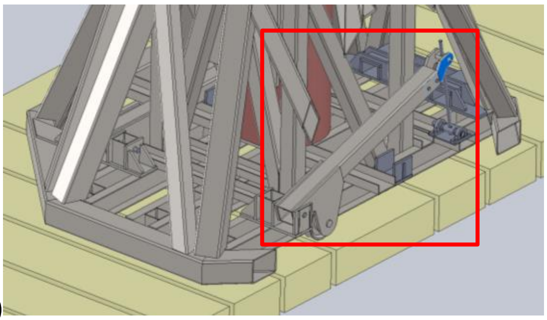
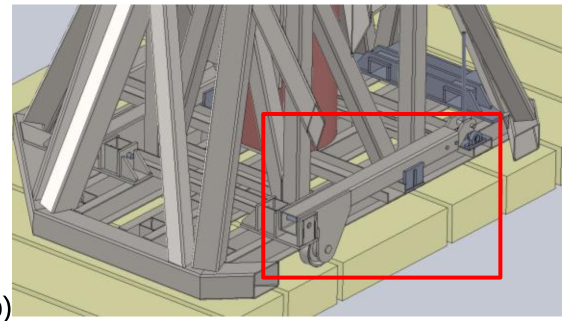
a)  b) 

Figure 10 – Retractable chassis – visualization.

2.2 Resonance validation

2.2.1 *Modal analysis*

The critical step was to perform a modal analysis of the designed test stand. Modal analysis was performed using the finite element method FEM in the Nastran-Patran environment. The purpose of the analysis was to determine the natural frequencies of the designed structure. In general, as the frequency limit of the vibration mode, the maximum vibration frequency of the tested rotors was assumed, i.e., maximum rotor speed, about 500 rpm (8.33 Hz) multiplied by number of rotor blades (≤ 3) what gives us 25 Hz.

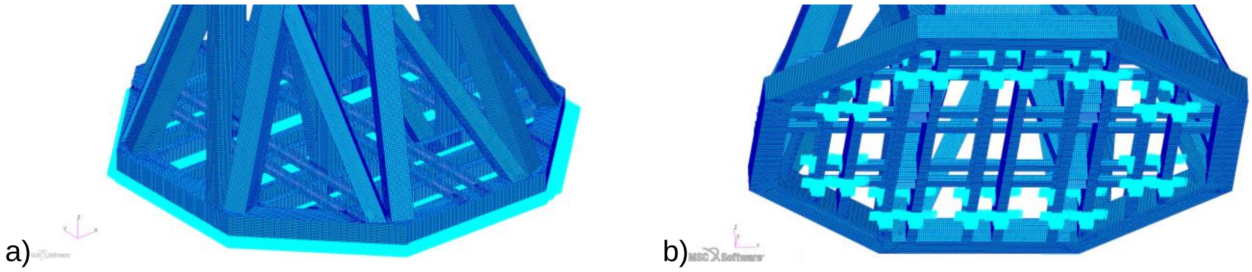


Figure 11 – Tower model with boundary conditions: a) Case 1 – fastening the whole base; b) Case 2 – fastening in 10 points.

The analyzes were carried out for various conditions of fixing the stand to the ground, for example a stand fixed to the ground with its entire base and a stand fixed in selected points distributed evenly along the radius and of the circle (shown in figure 11). The table no.1 presents test stand natural frequency results for two cases of fixing test stand to the mounting plate.

Table 1 – Summary of the results of the frequency calculation, for two cases.

n	Case 1	Case 2	Frequency mode description
	Frequency f [Hz]	Frequency f [Hz]	
1	43.9	26.7	flexural in XZ plane
2	45.3	35.1	flexural in YZ plane
3	62.3	58.8	flexural the XZ and YZ plane with local displacement of the vertical engine plate in the X direction
4	69,8	66.9	flexural the XZ and YZ plane with local displacement of the horizontal engine plate in the Y direction
5	75.4	73.4	flexural the XZ and YZ plane with local displacement of the horizontal engine plate in the Z direction
6	90.3	81.6	flexural –torsional In the YZ plane

2.2.2 Resonance tests

Modal analysis allowed for the validation of the Whirl Tower test stand design before its manufacturing. Furthermore, modal analysis help designers verified distribution of the mounting bolts which fixing test stand to the mounting plate. However, to carry out safe tests, it is necessary to accurately determine the resonance frequencies of the ready test stand. To make such verification, one should perform resonance tests. Tests are aimed at determining the vibration properties of the stand, frequencies of basic vibration modes and their damping coefficients. Determining these properties will allow to carry out test of different rotors. The collected data will allow to estimate the possibility of occurrence of dangerous resonances during various tests.

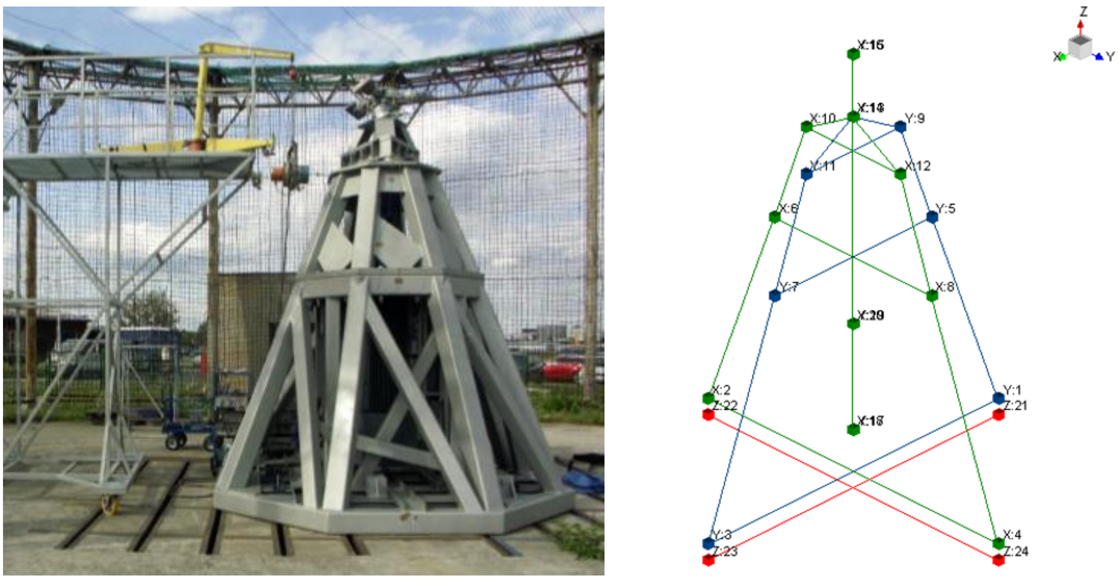


Figure 12 – Rotor test stand during resonance tests and layout of the measuring sensors.

The tests were carried out on a fully equipped test stand. Test stand was properly attached to the mounting plate. Masses were installed on the measuring head to simulate the main rotor blades. Tests were performed simulating rotors weighing approximately 6 kg, rotor span from 6 to 8 m, dedicated to for rotorcraft with a maximum thrust up to 1000 kg. The stand ready for resonance tests is shown in the photos above (Figure 12, left). Vibration sensors are mounted on the tower frame, measuring head and electric engine. A simplified diagram of sensors layout is shown in Figure 13 on the right.

The tests were carried out by exciting the object using two methods: with a modal hammer, with a tip enabling the induction of vibrations up to 200 Hz and an electromagnetic exciter with monoharmonic force up to 200 N.

Table no. 2 shows the test results, the natural frequencies of the test stand and the damping coefficients.

Table 2 – Results of Whirl Tower vibration measurements

n	Frequency mode description	Frequency f, Hz	Damping factor, %
1	Tower bending / swaying in the X direction	10.90	2,18
2	Tower bending / swaying in the Y direction	18.00	5.62
3	Vibrations of the motor and measurement head in the Y direction	34.70	2.52
4	Vibrations of the motor and measurement head in the X direction	38.55	1.60
5	Vibrations of the motor and measurement head in the Z direction	44.46	2.07
6	Bending in the Y direction (tower frame)	47.36	2.14
7	Bending in the X direction (tower frame)	55.99	0.52
8	Twisting (tower frame)	62.34	1.60
9	Bending in the X and Y directions (tower frame)	85.40	0.79

2.3 Data acquisition system and measurement possibilities

The stand is equipped with real time acquisition system based on National Instrument hardware and software. The basic measured parameters: torque, power consumed, rotational speed, thrust and vibrations and force in the control system. The stand additionally has an independent system of high-speed cameras, allowing for blades dynamic tracking and balancing. From the application level, it is also possible to control the collective pitch of the rotor. The test stand and system have been designed it that way so it can be modified and adapted to more sophisticated tests without a lot of work and costs. For example, it possible to add additional sensors, such as: acceleration sensors, distance force or angle sensors. It is possible to change the measuring heads, as well as to adjust the original helicopter hubs. In some test cases additional masses can be mounted to detuning the rotor system, etc.

Thanks to a change in the stand and measurement system, it is possible to carry out tests, among others:

- determination of rotor (blades and heads) loads showing under normal and boundary conditions.
- aeroelastic phenomena such as: blade flutter or phenomenon of “weaving”, “interlacing” characteristic of teetering rotors,
- propagation of damage after damage caused during rotating the rotor.
- tests simulating the “jumping start” of gyroplanes.
- using a modified head with a system for “jump start”.

Using additional equipment, it is possible to perform aerodynamic a measurement such as:

- pulsation of the pressure of the rotor stream on the ground.
- trace of the rotor stream.

- aerodynamic optimization (blade geometry, profile distribution), and
- rotor noise tests (as shown in figure 13). More case studies and bench tests can be found in the literature [2, 3].

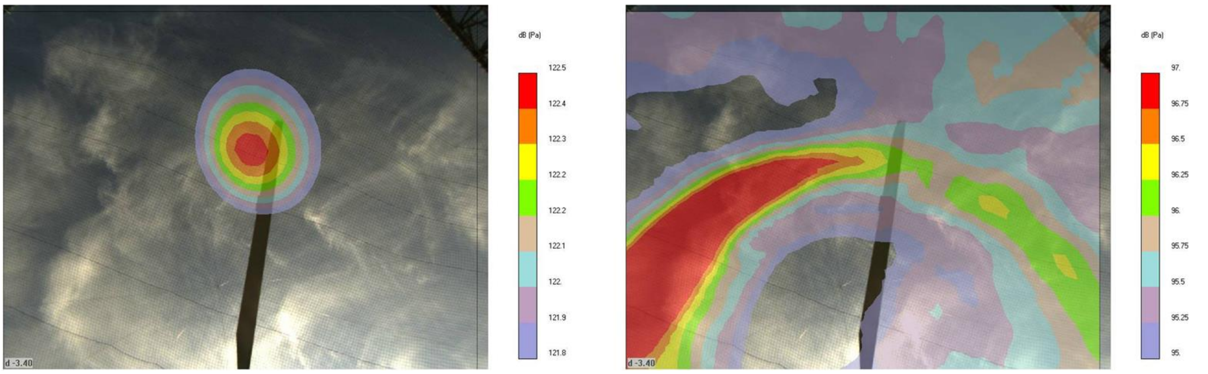


Figure 13 – Noise of rotor blade tip: image with synchronized rotation of the rotor (left); image with nonsynchronized rotation of the rotor (right).

3. Test Stand calibration

After conducting the resonance tests and checking the data acquisition system, calibration tests of the stand were prepared. The rotor has been tested at the stand, the characteristics of which are very well known. The rotor has already been tested and many analyzes, and calculations have been made.
The test stand was checked in several stages. Initially, the electric drive was checked and calibrated. Then rate of increase of the rotational speed on the control cabinet was set. The next step was to check the drive control systems, the collective pitch control system, and the data acquisition system. The systems are checked at low rotational speeds, approx. 300 RPM, with blade stimulating masses mounted in the measuring head. After the initial check of the system, it was run to a speed of 750 RPM, this test lasted a several minutes and was repeated a few times. After analyzing the vibrations recorded on the measuring head, nothing disturbing was found. The recorded vibrations were in line with the predictions from the resonance tests. The next step was to conduct tests with the main rotor. Further, the research object and test results in the form of pole characteristics of the lift rotor are discussed.

3.1 Test Object

The object of the research is a three-blade rotor in a semi-rigid suspension. The rotor blades were made in the prepreg technology. The design of the blades was carried out at the Institute of Aviation, the blades were designed for use in unmanned platforms with high capacity. The rotor diameter is 7110 mm; blade chord variable along the span, blade tip bent. The family of aerodynamic profiles used in this solution has been specially designed. More information on these solutions can be found in the literature [11]. The tested object is presented below, figure 14.

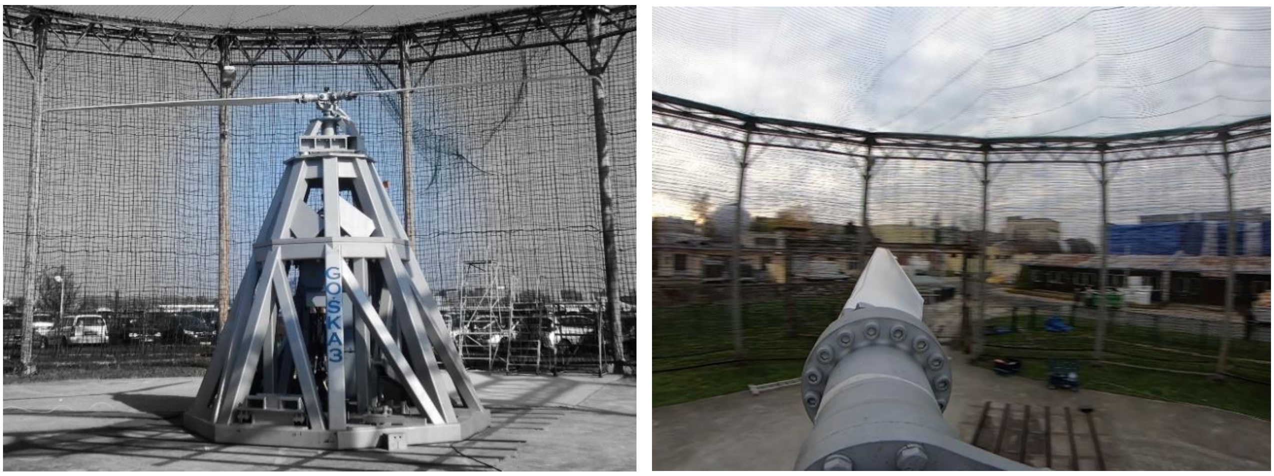


Figure 14 – The rotor test stand with rotor, and rotor blade view during testing from go-pro camera.

3.2 Results

The rotor's polar characteristics were taken into account when calibrating the rotor. Graph below (figure 15) presents a summary of the characteristics obtained from the experiment carried out on two different measuring stands, and theoretical analyzes. As can be seen, the characteristics obtained during the experiment at higher collective angles with the same power consumption, the thrust is reduced by about 2 - 4 %, for tests on a stand with a combustion engine (old test stand). These differences may result from different drives and measurement accuracy when analyzing the data from the old stand. On the other hand, with higher rotor blades collective pitch, the characteristics of the experiment (new stand) correspond very well with the theoretical values.

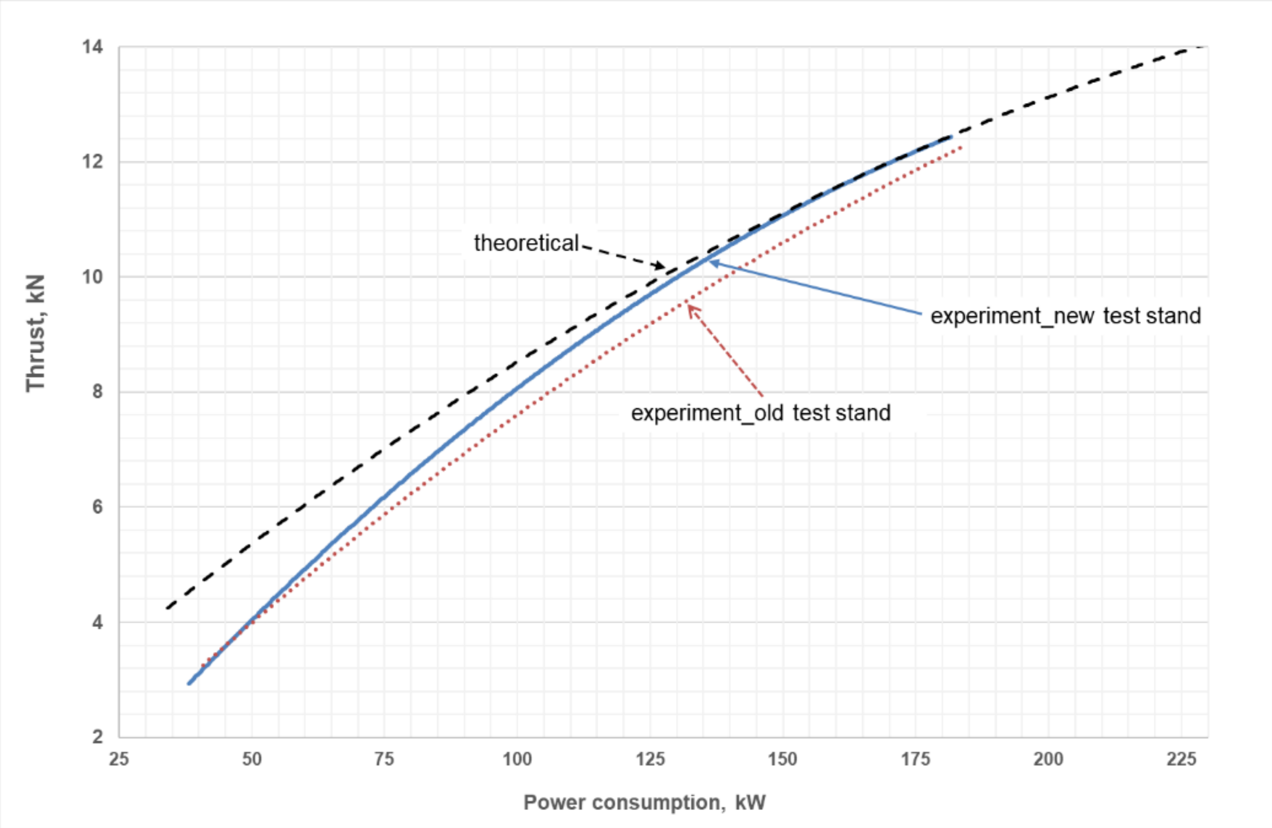


Figure 15 – Rotor pole characteristic.

4. Conclusion

Whirl towers type research stands are used by many companies dealing in the design, manufacturing and testing of rotorcrafts. Such test stands have in their possession companies from ‘General Aviation’ sector as well as small private companies and R&D Institutes. The development of small rotorcraft in the new UL-115 category, VTOL drones or development of new rotors equipped with new aerodynamic profiles, produced with the use of the latest technologies, requires dissemination of research techniques that ensure the safe use of these design. Anchored positions discussed in the paper provides safety during tests enabling the testing of rotors and propellers without the need to install them on the flying object (like helicopter, or drone). Allows to test the head-rotor system, blades or propellers in critical conditions, which increases safety during use these elements on the aircraft. Such activities, i.e. determining the natural frequencies of the test stand for certain measurement ranges, have a positive effect on increasing the safety of the tests, and help to predict the possibility of the occurrence of dangerous situations. Another important system for ensuring test safety is a well-calibrated measurement system that processes data in real time as well as tracking and dynamic balancing systems.

Discussed stand has the possibility to test rotors of helicopters, gyroplanes, and rotors / propellers dedicated to drones weighing over 200 kg. The stand has replaceable measuring heads and the possibility of adapting to other rotor hubs. Safe tests can be performed on them in the range of up to

700 RPM for rotors with a span of 6 - 8 m and for smaller ones up to about 1500 RPM. The maximum torque that can be achieved on the bench is 4000 Nm at 315 kW (for max 800 RPM).

Currently, apart from the discussed stand for testing larger objects, work is underway on test stands for testing smaller rotors and propellers with a maximum span of 2 - 3 m. The development of VTOL drones shows that the demand for safe testing of rotating systems (such as propellers, rotors) is growing year by year.

5. Contact Author Email Address

mailto: malgorzata.wojtas@ilot.lukasiewicz.gov.pl

6. Copyright Statement

References

[1] Czajkowski Ł., Mechanical analysis process of a coaxial counter rotor for applications in unmanned ultra-light units, Transactions of the Institute of Aviation, No. 2 (255), pp.44-2=64, 2019.

[2] Cieślak S. , Krzymień W., Drivetrain Noise of the Gyroplane I-28, Transactions of the Institute of Aviation, No. 2 (251), pp. 22-29, 2018.

[3] Cieślak S. , Krzymień W., Initial analysis of helicopter impacton hospital helipads, Transactions of the Institute of Aviation, No. 3 (256), pp.14-23, 2019.

[1] Deog-Kwan, K., et al., "An operational test and dynamic balancing sensitive study of the rotor blade on the whirl tower", 38th European Rotorcraft Forum, 1, pp. 412-421, Amsterdam, 2012

[2] Ergul, B. P., Yasa, O. A., Tursun, G., Determination of structural integrity of teetering rotor system by whirl tower tests, 39th European Rotorcraft Forum, Moscow 2013.

[3] Ezertas, A., Yucekayali, A., Ortakaya, Y., Hover performance assessment of 3 meter radius rotor on whirl tower, 39th European Rotorcraft Forum, Moscow 2013.

[4] Feszty, D., Nietzsche, F., Review of Active Rotor Control Research in Canada, International Journal of Aeronautical and Space Science, Vol. 12 (2), pp. 93-114, 2011.

[5] Kim, D.-K., et al., An operational test and dynamic balancing sensitive study of the rotor blade on the whirl tower, 38th European Rotorcraft Forum, Amsterdam, Vol. 1, pp. 412-421, 2012.

[6] Richter K., Schülein E. et al., Boundary Layer Transition Characteristics of a Full-Scale Helicopter Rotor in Hover, 2nd Annual Forum of the American Helicopter Society, Florida, USA, 2016

[7] Sobieszek, A., Wojtas, M., Composite rotor blades tests essential before mounting on gyroplane, Journal of KONES Powertrain and Transport, Vol. 23, No. 4, pp. 487-494, 2016.

[8] Stalewski W., Design and optimisation of main rotor for ultralight helicopter, Journal of KONES Powertrain and Transport, Vol. 24, No. 4, pp. 287-295, 2017.

[9] Szczepanik, T., Analysis of the state of the gyroplane world market, Transactions of the Institute of Aviation, No. 3 (244), pp. 227-238, 2016.

[10] Wojtas, M. and Czajkowski, Ł., A prototype test stand for testing insolated rotor systems, Journal of KONES Powertrain and Transport, 26(3), pp. 257- 264, 2019

[11]Wojtas M. Czajkowski Ł, Stanisławski J. Szumański K., Numerical analyses of different state of flight of new concept coaxial rotor dedicated to unmanned helicopters, 45th European Rotorcraft Forum, Warsaw 2019.

[12]Wojtas M., Czajkowski Ł., Sobieszek A., The influence of the blades leading edge anti-erosion protection on main rotor performances, Journal of KONES Powertrain and Transport, Vol. 25, No. 2, pp. 409-414, 2018.

[13]https://www.zf.com.

[14]https://colloquia.et.utwente.nl/?lang=nl&id=1765

[15]https://www.fusioncopter.eu/