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Philippe Beaumier

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Rotorcraft Experimental Databases: Future Needs in the Fields of Aeromechanics and Aeroacoustics

Philippe BEAUMIER

philippe.beaumier@onera.fr

ONERA

Palaiseau, France

ABSTRACT

Considering the exponential increase of computational capabilities, the idea that numerical studies may sooner or later cancel the need for further use of research wind-tunnels sometimes spreads in the rotorcraft community. The objective of this paper is to propose areas where wind-tunnel testing will be required in the next decades in order to improve the technologies and the tools used to develop new rotorcraft. The reasons why experimental validation in wind-tunnel is required are analyzed in the paper. A discussion of the needs in the following fields is given: main rotor, multi-rotor interactions, complete rotorcraft, and new concepts of VTOL aircraft. It is believed that the complementarity between experiment and numerical analysis should be developed in the future, using data assimilation techniques.

INTRODUCTION

The development of aviation has been made possible thanks to the combined use of experimental and numerical analysis. In the rotorcraft community, it is still widely admitted that both approaches are required and complement each other: the numerical approach helps understanding the physics and designing an experiment, but requires validation brought by experimental results in order to validate some of the assumptions they rely on.

All research centers and helicopter manufacturers have extensively used wind-tunnel tests to design new helicopter components or to better understand the physics involved in the fields of aerodynamics, dynamics and acoustics. For example, ONERA (Office National d'Etudes et de Recherches Aérospatiales, the French aerospace research center) has been very active in the last decades to evaluate and design new concepts of helicopter main rotors [1], [2], [3], either to improve their aerodynamic performance or to decrease their acoustic footprint. Through the joint ONERA-DLR Rotorcraft research program [4], both French and German research centers emphasize the strategic need of experimental facilities, through the three following important statements extracted from our mid-term program:

- *A pre-requisite for validated codes and for progress in modeling is the access of ONERA and DLR to test facilities ranging from lab tests to wind tunnel tests in large scale tunnels like DNW LLF and SIMA to highly instrumented flight test aircraft. But this type of validation is now very expensive and not affordable for research studies any more.*

- *For flight mechanics studies, flight simulators are very useful tools.*
- *In addition both Research Centers operate UAS (RESSAC or ARTIS) to develop and demonstrate autonomous flight systems or functionalities. This part of activity is constantly growing year by year.*

Numerical analysis has evolved from analytical, physics-based formula featuring a few degrees of freedom up to the resolution of complex nonlinear partial differential equations (Reynolds-Averaged Navier-Stokes equations) solved in the discrete domain and featuring nowadays billion of unknowns. This astonishing increased use of numerical analysis has been made possible thanks to the rapid increase of computational resources that have followed the well-known Moore's law for more than 30 years (increase of transistor density doubling each 2 years). Even if extrapolating this law for the incoming decade might be hazardous, it is a fact that today high-performance computers allow computing and analyzing the aero-mechanical behavior of a complete aircraft, so that the idea that numerical studies may sooner or later cancel the need for further use of experimental facilities sometimes spreads in the rotorcraft community. More and more time is indeed devoted to analyze numerically new designs before directly testing them in flight, sometimes without the intermediate step of 'physical' testing.

The very first use of wind-tunnels for rotorcraft applications was probably for 2D airfoil testing aiming at the characterization of static and dynamic behavior. Each research center or manufacturer has developed and tested several generations of airfoils. It would be too long and beyond the scope of this article to review all the experimental done worldwide, but airfoil testing remains an essential process to generate 2D look-up tables that are used in comprehensive analysis based on Blade Element

Methods (BEM). A review of the experimental work done at ONERA on airfoil testing can be found in [5].

A lot of attention has been paid on rotor testing, since the main rotor is the most important aerodynamic part of the helicopter. Rotor blade optimization started in the 70' mainly by trying to improve the blade tip design with the primary goal to improve aerodynamic performance. Far from being exhaustive, one can quote the pioneering work done in France by ONERA leading to the design of swept (parabolic) blade tips which equip most of Airbus Helicopters main rotor blades, or the well-known advanced BERP blades proposed in UK with its BERP IV advanced design [6] which equip the AW101 main rotor blades (Figure 1). A detailed review of studies done on helicopter blade tips can be found in [7].



Figure 1. BERP blade tip design

Surprisingly, after a lot of enthusiasm on blade tip designs, few attempts of global passive optimization of the whole blade span have been undertaken, with the noticeable exception of the ERATO blade which will be detailed below. In fact, at the end of the 90', the scientific community has put its efforts in the promising technologies of active blades. Active trailing-edge flaps were studied worldwide leading to nice proof-of-concepts in wind-tunnels by several organizations (see [8], [9] for ONERA works) and scale-1 tests [10],[11]. In the meantime, many efforts were done to develop Higher Harmonic Control (HHC) of the rotor blades (followed by Individual Blade Control, IBC), with the international efforts undertaken through the HART and HART-II teams (Figure 2), which have led to unique experimental data issued from wind-tunnel testing in the DNW-LLF. These data have been essential for the understanding of BVI noise [12],[13]. Other active blade concepts were studied, such as active tabs for noise and vibration reduction by JAXA [14].



Figure 2. HART-II wind-tunnel tests in the DNW-LLF low speed wind-tunnel

Most of these wind-tunnel experiments not only gave access to information on aerodynamic performance through global loads measurement, but also provided important information on airloads, structural loads, elastic deformations and acoustic radiation.

Experimental efforts were also made to measure fuselage drag coefficients with the ultimate goal to reduce shaft power in high speed forward flight conditions. The most efficient ways to reduce fuselage drag were achieved through active flow control technologies, as demonstrated by NASA in the US [15] or by ONERA in France ([16], Figure 3). Here again, wind-tunnel testing was essential to understand how flow separation could be delayed thanks to active flow control, even if such a technology has not yet been applied on production helicopters.



Figure 3. Active flow control on the ASF2 isolated fuselage in the ONERA L1 wind-tunnel

In addition to isolated components of the rotorcraft (fuselage, rotor), complete configurations were also tested in wind-tunnels, in particular to study aerodynamic interactions. Experiments studying rotor-fuselage interactions were undertaken by NASA [17] and ONERA [18]. More recently, European research establishments have joined their efforts in the GoAhead project ([19], Figure 4) which studied many interactional phenomena occurring on a complete helicopter. Moreover, the development of tiltrotors has led to a large number of experimental activities, such as the TRAM tests in the US [20] or more recently the NICETRIP tests of the ERICA tilt-rotor concept in Europe ([21], Figure 5). These

experimental activities have provided exceptional data for codes validation, at a quite high cost however.



Figure 4. The GoAhead fully instrumented model in the DNW-LLF low speed wind-tunnel



Figure 5. The European Nicetrip tilt-rotor model in the ONERA S1MA high speed wind-tunnel

Despite the high number of experimental activities mentioned above, it is believed that important challenges remain for the next decades that need to be addressed through wind-tunnel testing. In order to present these needs, the present paper is organized as follows: in a first part, the main objectives targeted through wind-tunnel testing are recalled, taking the example of the ERATO – BlueEdge™ – H160 story. The second part of the paper is an attempt to present the author’s view with respect to the future needs of testing, in the fields of Rotorcraft Aeromechanics and Aeroacoustics. Finally a short description of the necessary evolutions of testing is given. The ultimate goal of the paper is to propose new fields of experimental research, try to prioritize them and to define how the complementarity between experiment and numerical analysis should be further developed in the future.

WIND-TUNNEL TESTING, WHAT FOR?

The ERATO – BlueEdge™ – H160 story

One of the interests in using wind-tunnel testing of reduced-scale models is to validate concepts much ahead of scale-1 flight tests for proof-of-concept or proof-of-design. A nice example is given by the ERATO – BlueEdge™ – H160 story, illustrated in Figure 6. The

details of this long story are reported in [22],[23], only the main steps are recalled below.

The ERATO research project started in the 90’ from the challenge to design, manufacture and test a helicopter main rotor that could reduce the noise by 6 dB compared to state-of-the-art rotors. ONERA and DLR joined their efforts together with Eurocopter, to initiate numerical studies in order to perform parametric studies that aimed at identifying the main parameters that could influence the Blade-Vortex Interaction (BVI) noise radiated in low speed conditions. In addition to a reduction of rotor RPM, it was found that a blade planform with a double sweep shape (forward-backward) was quite attractive provided that aero-elastic behavior of the rotor could be mastered. The newly optimized 4-bladed rotor was then manufactured and instrumented in order to be tested: i) in the ONERA S1MA wind-tunnel to check aerodynamic performance at high advancing speed and evaluate the radiated noise, ii) in the DNW-LLF wind-tunnel to measure the noise radiated in low speed conditions for variety of flight conditions (sweep in descent angles, rotor thrust, advance ratios). These two wind-tunnel tests were done with fully instrumented model scale blades (4.2 m diameter) demonstrated the validity of the double-sweep concept of the ERATO blades to reduce noise up to 7 dB for a wide variety of flight conditions. They also proved that the new rotor consumed less power than the reference rotor for most of the points in the flight envelope, except at high thrust, especially in hover where the ERATO blades exhibited early stall.

Thanks to these positive results, Eurocopter was interested in the ERATO concept and decided to launch a new project called Blade2005 [22] which objective was to upscale the ERATO rotor for a scale-1 demonstration. The blade tip of the ERATO blades was redesigned by ONERA to improve the rotor performance at high thrust conditions and the forward-backward sweep angles of the blades were adapted to be compatible with a real blade structure. The blades were manufactured and installed by Eurocopter on an EC155 helicopter and flight tests were carried out in 2007-2008. In addition to the confirmation of the noise reductions (up to 5 EPNdB), significant increase of mass capability was obtained (increase of hover max efficiency by 7%) and good vibration levels could be measured.

It was later decided by industry (Airbus Helicopters) to use this 5-bladed optimized rotor on the successor of the Dolphin twin-engine medium class helicopter H160 which flight tests were achieved in June 2015, again confirming all the expected benefits in terms of performance, noise and vibrations. Certification of the H160 is underway and expected in 2019.

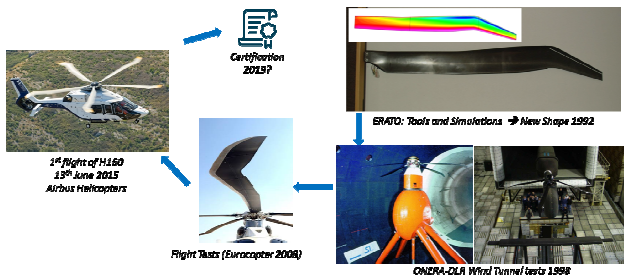


Figure 6. BlueEdge™: the H160 story at a glance

The main lessons learnt from this success story are the following:

- A long story: more than 25 years!
- Wind-Tunnel tests of the main rotor in large facilities (S1MA, DNW-LLF) were essential to validate the design. No doubt that the concept would not have been chosen by industry without these tests.
- Flight tests were essential to identify and solve problems that could not be anticipated in wind-tunnel: vibrations and stability.

Understanding the Physics

The ERATO – BlueEdge™ – H160 story is an outstanding example of the use of wind-tunnel testing to support the design of a new product. For a research establishment, the primary interest of a wind-tunnel test is to understand the physics. Instrumenting main rotor blades with 100-150 unsteady pressure transducers (Kullite) together with strain gauges allow getting unevaluable quantitative information on airloads (sectional loads and moments) and structural loads (bending and torsion moments), in addition to rotor performance. Such data are essential for the validation of numerical codes (whatever they are: low or high fidelity methods). The analysis of the ERATO tests proved to be essential to understand in details the aero-elastic behavior of the ERATO blades and its consequence on the radiated noise. In the end, it can be observed that the BlueEdge™ blades were not tested in a wind-tunnel so that there is no detailed data on the airloads experienced by the scale-1 blades, which made the analysis of the final design of the BlueEdge™ rotor more complicated than expected.

The laws of physics are of course universal but some physical phenomena are more pronounced or have more impact on rotorcraft than on other aircraft, so that dedicated experimental research may be required for the following reasons:

- Because of the presence of rotating and fixed parts, forced unsteadiness is inherently present on rotorcraft. This generates unsteady airloads that need to be carefully quantified in wind-tunnels;
- Contrary to transport aircraft which can be designed to be almost free of separation, helicopters always have areas with separated flows, either on the blades (retreating side) or the fuselage. This impacts performance and stability and wind-tunnel tests are

very well suited to study these complex phenomena (static or dynamic stall);

- Because of the low speed capacity of a rotorcraft the vortical structures emitted by the blades or the hub (vortices, shear layers) often impact other parts of the rotorcraft with consequences on performance, vibrations and noise. Wind-tunnel tests are essential to study these phenomena.

Finally, although not specific to rotorcraft, turbulence modeling is still an open issue in high fidelity numerical analysis. It is well known and admitted that resolving directly the Navier-Stokes equations (without the need of turbulence models) on a full transport aircraft would require computational resources that will NOT be available before 2045, according to P. Spalart, the requirement in terms of number of grid points being around 10^{16} ! Thus experimental research will be needed in the future to develop more advanced turbulence modelling.

FUTURE NEEDS

This part is an attempt to describe the author’s vision of the important topics that will require testing in the fields of Aeromechanics and Aeroacoustics for the next decades, concerning: i) the main rotor; ii) multi-rotor interaction and iii) complete rotorcraft. An interesting discussion of these needs was provided by R. Ormiston in [24].

Main Rotor

- Laminar-Turbulent Transition in forward flight

Many experimental databases related to the aeroelastic behavior of the main rotor are now available worldwide and have allowed a detailed validation of numerical methods. The most advanced methods in this field combine a loose coupling between low-order models (comprehensive analysis computing the elastic response of the blade, including trim) and high-fidelity CFD (Computational Fluid Dynamics) codes. The level of accuracy of such methods for computing unsteady airloads and structural loads on the blades for a rotor in forward flight is now outstanding, as demonstrated in particular by US Army and ONERA efforts on the UH-60 and 7A-7AD rotors [25],[26], Figure 7. In hover flight, the partners of the AIAA hover workshop have proven that hover figure of merit can be computed within an accuracy of 1 count, which is an excellent result [27]. However, one of the key points for shaft power evaluation is the accurate prediction of laminar-turbulent transition location. Still today, many CFD results are obtained using a fully turbulent assumption, despite the fact that the presence of laminar areas on the blades has clearly been demonstrated both in hover and forward flight, with significant effect on rotor performance (power reduction by more than 5% compared to fully turbulent assumption, in hover).

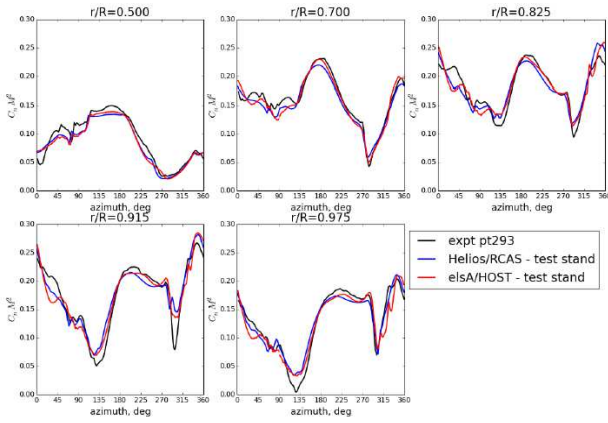


Figure 7. Airloads prediction of the 7A rotor in High Thrust condition [26]

In hover flight, many efforts are being currently done to obtain accurate databases with information on the laminar-turbulent transition location. DLR for example has been applying optical methods [28] on both model-scale and full-scale rotors (Figure 8) that can be used to validate codes.

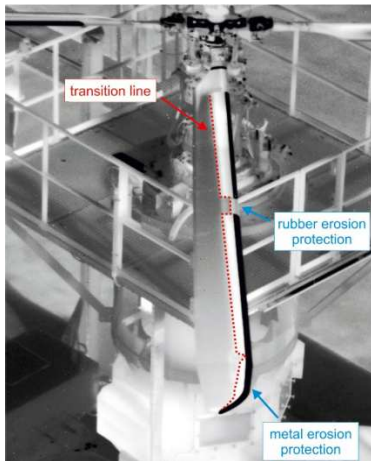


Figure 8. Transition measurement on the BK117-type full-scale helicopter main rotor [28]

In forward flight, few experimental results exist. The problem is of course more complex since the transition line depends on the azimuthal position of the blade. Despite attempts to measure the transition location in forward flight using different techniques (hot films, σ - C_p method from DLR [29], optical method), there is still a strong need of a comprehensive database for aeromechanical performance of a rotor in forward flight with detailed measurement of the transition location. This need is all the more important that several transition methods are already included CFD codes (methods based on criteria or on transport equations) but these methods suffer from a lack of validation for 3D unsteady flows like a rotating blade. An illustration of the discrepancy between the results obtained by these methods is presented in [30]. A scatter of more than 50% chord lengths can be found at

some azimuthal locations between the predictions obtained by different computational methods (Figure 9).

Obtaining such a database should be done in the next 5 years and wind-tunnel tests are mandatory to achieve this goal if we want to better predict the main rotor performance in forward flight.

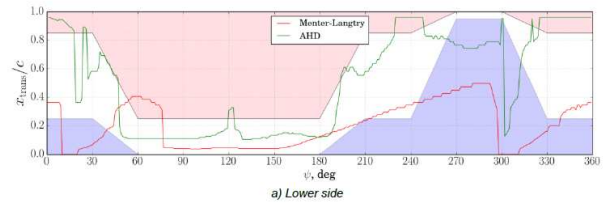


Figure 9. Transition prediction of a section of the 7A rotor in forward flight [30]

- Main rotor at high advance ratio

Conventional helicopters are inherently limited in maximum speed around 160 KTS. Since 10 years, there is a renewed interest in transforming the helicopter to reach higher cruise velocities, and trying to develop configurations less complex than a tiltrotor. In this context, compounds helicopters have emerged. Compounding consists in adding a propulsive device (one or more propellers) that ensures most of the propulsive force in forward flight so that the main rotor can be used essentially for its lifting capability. Figure 10 illustrates two of these concepts. One of the challenges for these concepts is to reduce as much as possible the drag at high speed, and especially the drag of the main rotor and its hub. It has been demonstrated that reducing the RPM (up to 40-50%) can significantly increase the lift-to-drag (L/D) ratio at high speed. By doing this, the non-dimensional parameter μ (advance ratio) is automatically increased, which means that a larger and larger part of the main rotor disk operates in reverse flow conditions.



Figure 10. Two compounds concepts. Left: The Defiant from Sikorsky-Boeing. Right: The RACER from Airbus Helicopters

Today, the impact of flying under these high μ conditions in terms of airloads, vibrations, stability, control remains largely unknown, because of lack of experimental results, with the noticeable exception of the data from the Full-scale UH-60A rotor test in NFAC 40- by 80-Foot Wind Tunnel [31].

Acquiring an experimental database of rotor at high μ conditions could be a challenging objective of European research centers for the next decade.

- Dynamic stall

Dynamic stall has been extensively studied since the very beginning of rotorcraft development. It is probably the most complex aerodynamic phenomenon that can be encountered because it involves flow separation, unsteadiness, viscous effects ... and can have an impact of the aeroelastic stability of the rotor (stall flutter).

Researchers have been spending decades experimenting 2D airfoils under static and dynamic conditions. 2D databases are now available all over the world and will probably be no more needed in the future, given the fact that the two-dimensional nature of dynamic stall is more than questionable.

More recently, experimental efforts have been undertaken to obtain databases for 3D oscillating wings [32],[33], Figure 11.



Figure 11. Dynamic stall OA209 oscillating wing models [32]

A next step could be a Mach-scaled rotor in forward flight. However, the author believes that this may not be the highest priority for future tests for the following reasons:

- good quality experimental databases of rotors under dynamic stall already exist, even if the details of the flowfield under dynamic stall conditions were not measured,
- recent numerical analysis have shown a fairly good prediction of the airloads and structural loads of a rotor under dynamic stall conditions [34].

Revisiting dynamic stall experiments for 3D oscillating and unsteady flow conditions will certainly be required in the future, maybe beyond the next decade.

- Active rotors

As already presented in the first part of this paper, active technologies have been the focus of many studies for the

past 15 years. It seems that the enthusiasm of the scientific community for these technologies has been reduced during the last 5 years, probably because of the complexity of the actuation systems.

The next step of active rotors development could be based on active twist technology which is quite attractive to improve performance and reduce noise and vibrations. An international effort under the STAR (Smart Twisting Active Rotor) consortium might be launched in the next five years in order to test in a wind-tunnel such an instrumented model-scale rotor.

Multi-rotor Interactions

The aerodynamic interactions between the main rotor and the fixed components of the helicopter have been extensively tested, either on conventional helicopters or on tilt-rotors.

The observation of the transformation of helicopters clearly shows two trends: i) compounds to reach higher velocities, ii) multi-rotor configurations to address the new market of urban mobility thanks to more electric propulsion systems. In both cases, the number of rotors is increased from 2 (main rotor, tail rotor) for a conventional helicopter to 3 or 4 for a compound and up to 18 in the example of the VOLOCOPTER (Figure 12).



Figure 12. The VOLOCOPTER e-VTOL

The multiplication of rotors increases the probably of rotor-rotor interactions especially, but not only, in low speed conditions. When the wake of a rotor (shear layers, tip vortices) impacts another rotor, there are obviously consequences on performance, vibration and noise. Today, we can observe that no databases exist to increase our understanding of these phenomena. This is why ONERA has initiated a research program on this topic, based on the experimental configuration illustrated in Figure 13. Even if the size of the rotors will not be large enough for a detailed instrumentation of the blades, it is believed that valuable information will be obtained when testing this kind of configuration in a wind-tunnel. Such studies and results should be made available within the next 5-years, in order to better understand the physical phenomena of rotor-rotor interactions and ultimately better design the emerging e-VTOL configurations.

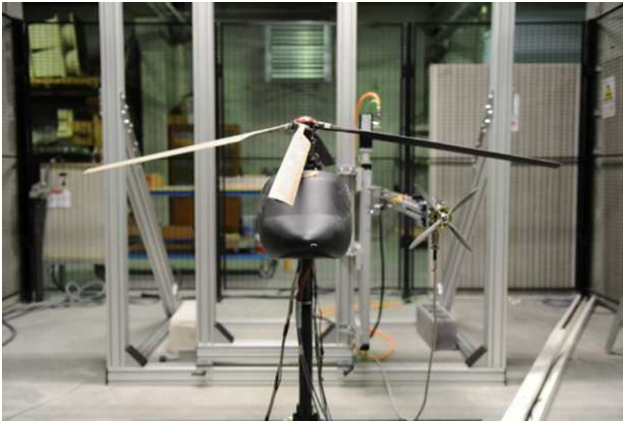


Figure 13. Multi-rotor interaction test rig in the ONERA Lille facility

Complete Rotorcraft

- Dynamics

Predicting the dynamic behavior of a full helicopter is certainly a challenge for the next decades. Today, this remains a major issue, illustrated by the fact that the final design of a helicopter is never frozen before the first flight test because of vibrations (or even worse: instabilities) that are only discovered during flight tests. The mechanical complexity of a helicopter structure is at the origin of nonlinear dynamic behavior that is extremely difficult to predict. Even the prediction of the dynamic behavior of a fuselage structure without rotating parts is not that easy.

Concerning the vibrations generated by the main rotors, it seems that the level of accuracy of numerical methods has improved sufficiently to predict correctly unsteady loads in the rotating system. But work remains to develop accurate methods to predict how these loads are transferred from the rotating to the fixed parts of the helicopter through the mast, pitch links, dampers...

A wind-tunnel experiment dedicated to the understanding of the aforementioned mechanical problems would be of great help if we want to make progress in the prediction of the dynamic behavior of the rotorcraft.

- Drag reduction, engine integration

Performance of the complete helicopter can certainly still be improved. In the context of the development of compounds (especially with co-axial contra-rotating main rotors), a lot of efforts have been made to optimize the shape of the main rotor hub particularly in the context of the X2 – Raider™ development [35]: thanks to dedicated wind-tunnel experiments with detailed instrumentation, significant progress has already been made in this field.

On the contrary, engine integration has been the focus of very few experimental studies. Here the objective of an experimental investigation could be not only to validate a specific design for a more efficient integration of the

engine, but also and mainly to provide a detailed database that should be used in order to understand the differences in engine performance between the engine on the ground and the engine in-flight installed on the helicopter. It is however unsure whether a wind-tunnel experiment would make sense for the latter objective, but probably some methodological aspects could be addressed.

New Configurations (e-VTOLS)

Wind-tunnel testing may offer nice opportunities for the development of e-VTOLS in the context of Urban Air Mobility (UAM). Despite the very large number of configurations (Figure 14), a lot of phenomena that are common to all configurations and that were not of high interest in the past could be investigated. One of them is the noise generated by such configurations. Noise will indeed be a key aspect in the development of this new market since e-VTOLS will operate in urban or peri-urban environments. Here, the very first field of interest should be the understanding and modeling of the noise sources, even if other aspects such as noise propagation in a perturbed environment or noise perception is of interest too.

Acoustic sources at the origin of the noise radiated by a conventional helicopter are nowadays well understood, characterized and modelled. It can be observed that tone noise of the main rotor, the tail rotor or the engine dominates for most flight conditions. The situation is quite different for e-VTOLS for the following reasons:

- due to the relatively small scales of e-VTOLS, it is likely that broadband noise will have a more pronounced contribution because e-VTOLS operate at lower Reynolds numbers than helicopter main rotors; the relative contribution of tone noise and broadband of e-VTOLS, in addition to the characterization of electric engine noise should be considered by the scientific community;

- the multiplicity of rotors or propellers is such that interactions between them will for sure occur in specific flight conditions, with an impact on acoustic emissions; not only the aerodynamic interactions should be considered, but also acoustic wave interactions may appear; on these topics, little is presently known;

- many of these e-VTOLS configurations have ducted propellers instead of “open rotors” like in conventional helicopters, which is certainly a good point for safety and noise reduction; however, the length of the ducts is generally not that large compared to the diameter of the propellers so that the efficiency of the duct to attenuate all relevant acoustic waves can be questioned and should be studied.

Wind-tunnel tests should rapidly be used to characterize all these open issues in the field of acoustics of e-VTOLS.

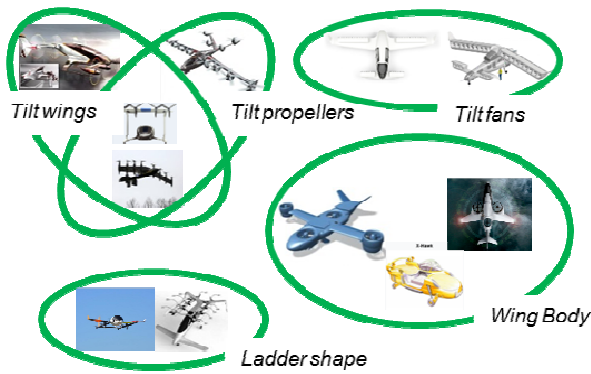


Figure 14. The multiplication of e-VTOL configurations

NECESSARY EVOLUTIONS OF TESTING

The main reasons why wind-tunnel testing is attractive compared to flight tests are:

- Control of boundary conditions, as opposed to flow conditions that can hardly be quantified in flight (due to fluctuations of atmospheric conditions for example),
- Reduced cost for testing a wide range of flight conditions,
- Detailed model instrumentation and related measurement techniques.

The last item of this list is essential to improve the attractiveness of wind-tunnel tests. Some improvement in advanced experimental techniques are still required and briefly detailed in the four directions given below:

- i. Model (elastic) deformation: combination of advanced optical techniques and traditional ones based on strain gauges should bring more confidence in measurements;
- ii. Smarter use of instrumentation: for example, Kullites transducers traditionally used for pressure measurement may also be used for transition assessment [29], thus reducing the complexity of adding hot films or deploying optical systems (IR thermography for example) for laminar-transition assessment;
- iii. 3D & Time Resolved-PIV (Particle Image Velocimetry) in combination to 3D Background-Oriented Schlieren techniques (BOS3D): application to a model rotor for an exhaustive investigation of dynamic stall would be very valuable;
- iv. Additional efforts should be made to apply the Pressure Sensitive Painting (PSP) technique on rotating blades in order to have a global view of unsteady surface pressure; such techniques have already been applied with an accuracy that remains too low for validation purposes.

Another objective of future experimental studies could be to validate numerical predictions to further increase their accuracy, with the ambitious objective to reach the “one drag count accuracy” that has been reached for fixed-wing applications. Maybe more important than the absolute accuracy itself, the author believes that the assessment of the accuracy of results (either experimental or numerical ones) should be systematically done. More attention should thus be paid to Uncertainty Quantification (UQ), for which nice mathematical models exist but unfortunately seldom applied. Application of UQ techniques in wind-tunnel testing could bring valuable new information.

Finally, the link between numerical and experimental results should be further strengthened. It is of common practice to perform pre-tests predictions in order to anticipate the phenomena that will be encountered in the wind-tunnel and to define an appropriate test matrix. Similarly, the comparison of numerical and experimental results contributes to the validation of the models that are used in numerical codes. But, we can go much further thanks to the technique of data assimilation: the main idea here could be for example to limit the instrumentation on the blades and to combine numerical results and experimental ones to provide an image of the flowfield as close as possible to the reality. Such ideas have already been applied at ONERA in research wind-tunnels and could be further developed in pre-industrial wind-tunnels.

CONCLUSIONS

The discussion undertaken in this paper is an attempt to describe future needs in terms of testing for rotorcraft applications.

The author believes that the most urgent needs that require wind-tunnel testing are related to the following topics:

- Laminar-turbulent transition on the main rotor in forward flight,
- Dynamics / vibrations of the fuselage with rotating blades,
- Multi-rotor interactions,
- Main rotor at high advance ratio.

The following other topics could be considered with a lower priority: dynamic stall on the rotor, active twist rotors.

In a near future, it is sure that advanced non-intrusive measurement techniques (Time-Resolved PIV for example) will have to be available even in pre-industrial wind-tunnels because the level of details of the physics we are interested in will be more and more demanding.

Finally, a huge field of improvement lies in the smart combination of experimental data and numerical analysis.

It is the author's opinion that digitalization will not kill wind-tunnel testing in the next decades; in particular, the use of data assimilation techniques could bring a renewed interest in wind-tunnel testing.

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