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VortexCell2050

Specific Targeted Research Project
“Fundamentals of actively controlled flows with trapped vortices”

Publishable executive summary

VortexCell2050 aimed at delivering a new technological platform combining two cutting-edge technologies, the trapped-vortex and the active flow control. Trapping vortices is a technology for preventing vortex shedding and reducing drag in flows past bluff bodies. Active flow control is a form of control which requires energy input. The project outcomes will serve the designers of the next-generation thick-wing aircraft, and will also be applied in other areas where reduction in drag in a flow past a bluff body is desirable. VortexCell2050 developed a tool for vortex cell design, collected a substantial amount of data on three-dimensional and actively controlled flows in vortex cells, and demonstrated the advantage of a thick airfoil with a properly designed vortex cell with active control over a thick airfoil without a vortex cell, thus opening a possibility of trying this technology in specific applications. VortexCell2050 also highlighted several promising avenues for further improvement of the vortex cell performance. The results of VortexCell2050 ensure European Aeronautical Sector a leadership in a small but critical area, the importance of which will grow in the future with an increase in aircraft size. This summary outlines the project context, major activities, and outcomes.

Partners

University of Southampton, UK
Centro Italiano Ricerche Aerospaziali ScpA, Italy
Technical University of Munich, Germany
Battery Company RIGEL, Russian Federation
Technische Universiteit Eindhoven, Netherlands
Institute of Mechanics of the Moscow State University, Russian Federation
Politecnico di Torino, Italy
Piaggio Aero Industries, Italy
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Project motivation, idea, and objectives

Wings of the modern aircraft are thin and streamlined thus ensuring maximum aerodynamic efficiency. From structural viewpoint a thick wing would be more efficient in carrying the load. The tendency of increasing aircraft size shifts the design balance towards giving more weight to structural considerations. As a result, improving aerodynamics of thick wings is essential for further progress in aviation. Thick-wing, or blended wing-body, aircraft are identified as prospective for development over the next 50 years in the NASA and FAA commission report ``Securing the Future of U.S. Air Transportation: A System in Peril,' released in September 2003.

Trapping vortices is a technology for preventing vortex shedding and reducing drag in flows past bluff bodies. Large vortices forming in high-speed flows past bluff bodies tend to be shed downstream, with new vortices forming in their stead (Fig. 1).

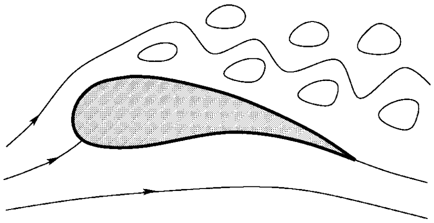

Figure 1

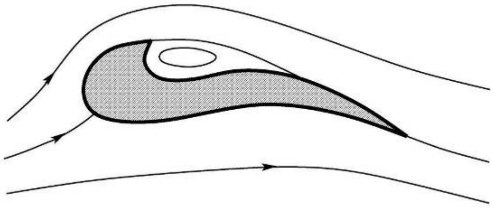

Figure 2

This leads to an increase in drag and unsteady loads on the body, and produces an unsteady wake. If the vortex is kept near the body at all times it is called trapped. Vortices can be trapped in vortex cells, as in Fig. 2. A trapped vortex could be just a steady separation eddy above an aerofoil at high angle of attack, but the use of a vortex cell helps. Practical implementation of the trapped-vortex idea is difficult, since the trapped vortex needs to be almost steady in the sense that it should remain in the close vicinity of the body. Stabilising a trapped vortex was a major challenge for the project.

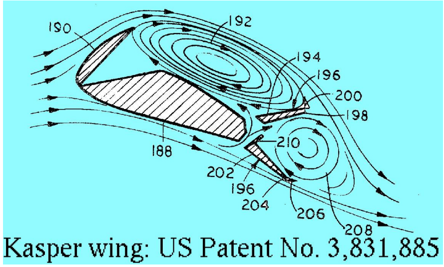

Figure 3

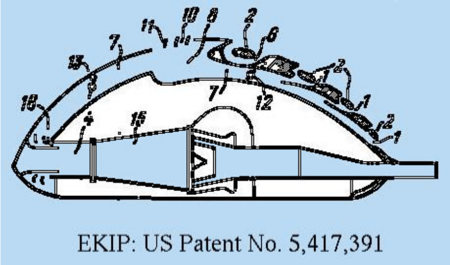

Figure 4

Prior to the final experiment of VortexCell2050 there had been only two reportedly successful implementations of the idea of trapped vortex, namely, the Kasper wing[1] (Fig 3) and the EKIP (Ecology and Progress) aircraft (Fig 4). In the end of 60-ies/early

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[1] The story of the Kasper wing is complicated, controversial, and involves much wider issues than trapped vortices. We provide here only the minimum information. More can be found on the Web using a search engine. Similar comment could be made about EKIP.

70-ies the first successful use of a trapped vortex in a flight experiment was claimed by W.A.Kasper. In 1980-1996 Lev Schukin designed an aircraft 'EKIP', in which trapped vortices prevented large-scale separation. Several models were built, including the radio-controlled aircraft of a wing span 1.2 m. However, attempts made in 1977 by E.W.Kruppa to reproduce Kasper's results in a wind tunnel, while inconclusive, did not confirm Kasper's claims. As far as EKIP is concerned, no quantitative data on its performance were published in peer-reviewed journals. EKIP development was stopped during the period of economic difficulties in Russia, and it has not been resumed yet. It should be noted, however, that certain features of the available sketches of EKIP aircraft are in remarkable agreement with qualitative conclusions obtained and published independently, and that there is a plausible explanation, also published, of the reason for the discrepancy between wind-tunnel tests and flight experiments on the Kasper wing. Therefore, both the Kasper wing and EKIP deserve at least the benefit of a doubt, even more so because of the positive results obtained in VortexCell2050 project.

VortexCell2050 aimed at combining the trapped-vortex technology with active flow control. The specific major objectives of the project were

- To develop a software tool for designing a thick airfoil with a trapped vortex assuming that the flow is stable, apart from small-scale turbulence.
- To develop a methodology and software tools for designing a system of stabilisation of such a flow.
- To design and estimate the performance of an airfoil with a trapped vortex and a stabilisation system for the High-Altitude Long Endurance unmanned aircraft.

Project activities

The project work, aimed at advancing the vortex-cell technology, can be grouped in two large parts.

First part, a highly ambitious but also quite risky line of research was aimed at testing, at the end of the project, a wing with a vortex cell serving as a prototype for a practical application, namely, a High-Altitude Long-Endurance (HALE) aircraft. This required performing series of fundamental experimental studies of the properties of flows with trapped vortices, in order to provide the necessary data for the design tools, which, too, needed to be developed, and also required experiments simply aimed at gaining experience in working with vortex cells with active control. The high degree of risk in this line of research was due to its sequential nature, such that the each following step in the plan could be done only after the previous step has been successfully finished, while, as it is common in scientific research, success could not be guaranteed for any of the steps. Indeed, the final HALE airfoil tested has a system of control not utilising a feedback algorithm, contrary to the initial plan.

Second part of the work had two goals: to mitigate, where possible, the risk in the first part, and to use the chance of exploring, within a favourable context of a common goal, various alternative avenues of research on trapped vortices. Approximately one year into the project the Consortium of partners was joined by a team from Moscow State University. The team brought in additional funding won in a separate call for proposals, and many years of experience in research on trapped vortices. Their program of research, of a very wide scope, became an element of the second part of work.

The two parts of the research were closely interconnected. For example, calculations using Reynolds-averaged Navier-Stokes equations, pursued in the second part, were also extensively used in the first part for various design purposes. Another example is the way in which Large Eddy Simulations, done in the second part, shed light on the experimental results in the vortex cell facility. This list can be continued.

As it was already known before the start of the project, the performance of the vortex cell crucially depends on its shape. Stabilising the flow in a vortex cell of not optimal shape is difficult. Hence, the shape has to be carefully designed. Since the flow in question is turbulent, for designing the cavity one needs to have a turbulence model. Existing semi-empirical turbulence models are known to perform poorly in case of separated flows, but what is even more important, even if the model is tuned for separated flows, it is tuned to non-stabilised separated flows. To tune the model to stabilised flow, one needs first to get the data on stabilised flow, and for that one needs to get the cell geometry right. This creates a closed loop, a chicken-and-egg situation.

This problem has been resolved by designing a special experimental facility in which stabilisation of the vortex cell flow was ensured by the geometry itself. It was built in the University of Southampton (see Fig. 5).

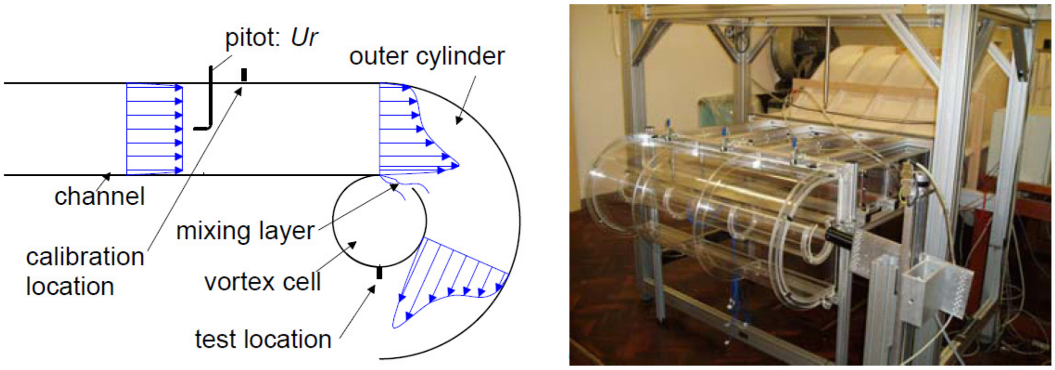

Figure 5

Experimental data were collected to select the turbulence models which work in this situation. The experiments also revealed the presence of large-scale, although relatively weak, three-dimensional unsteady flow pattern inside the vortex cell. Large-Eddy Simulations (LES) of a similar flow conducted by the team of Technical University of Munich confirmed the presence of three-dimensional patterns (Fig. 6), and the Southampton University team concentrated more effort on the study of 3D effects.

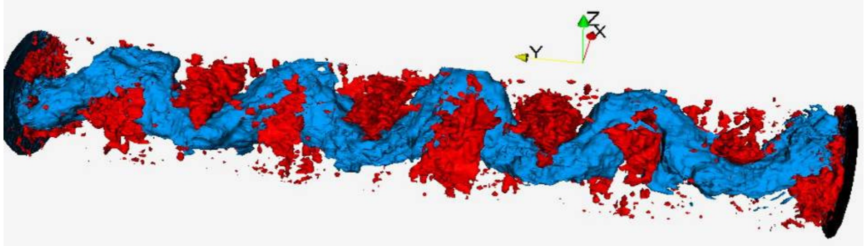

Figure 6. Iso-surface of kinetic energy (blue) and energy of the fluctuations from LES

The task of providing additional data on the effect of pressure gradient for turbulence model selection was taken over by the team from the Moscow State University, which performed the necessary experiments in their facility (Fig.7) with a vortex cell located on the wall of a diffuser of variable angle.

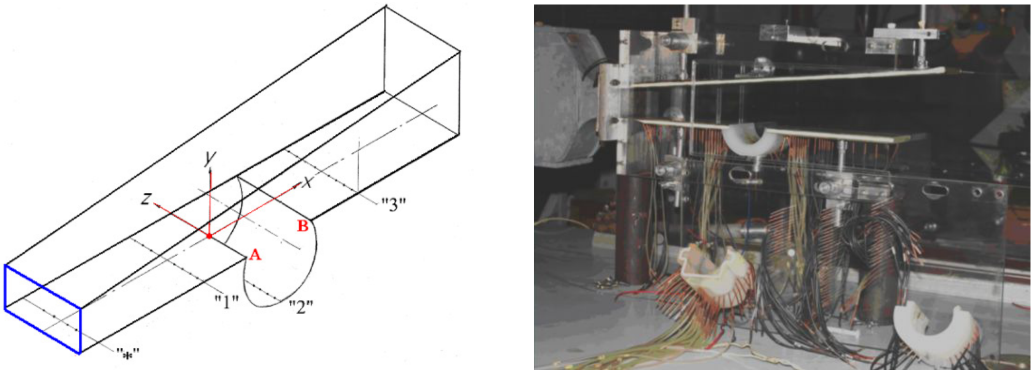

Figure 7

The data obtained from these experiments were used to validate turbulence modelling in the approach for efficient calculation of flows with vortex cells, developed by the team of the University of Southampton. The approach was based on the idea of replacing laminar viscosity in the high-Reynolds-number asymptotic theory of such flow with turbulent viscosity. This model also utilised the code calculating the so-called inviscid Batchelor-model flow, developed by the teams of Politecnico di Torino and University of Bordeaux 1. The computational efficiency of the developed approach allowed using it within the genetic optimisation code, developed first at Politecnico di Torino and then in Glasgow University, for optimising the geometry of the HALE airfoil.

Experimental investigation of actively controlled flow in a vortex cell is a serious challenge. For example, for PIV study one needs to overcome the difficulty of the line of sight being obstructed by the complicated geometry of the vortex cell and by the elements of the control system. The largest volume of the experiments on flows with vortex cell was conducted in a specially designed test-bed facility Centro Italiano Ricerche Aerospaziali ScpA (CIRA). The distinguished feature of the test-bed is the interchangeable section with a vortex-cell, as shown in Fig. 8. The first-ever and so-far unique PIV analysis of the flow with a vortex cell with stabilising suction was conducted in this facility.

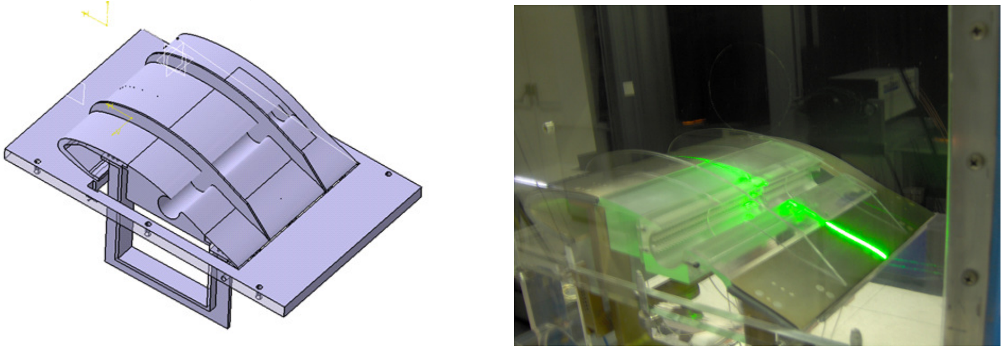

Figure 8. Test-bed sketch and a photograph showing laser illumination for PIV

A study of a possible interference of the vortex cell flow with acoustic resonance instabilities in a wind tunnel or wing vibration in flight was performed by the team of Technische Universiteit Eindhoven. The scheme of their experimental facility and the airfoil with a vortex cell used in the experiments are shown in Fig.9. Loudspeakers were used to simulate external perturbations. The effect on the vortex cell flow was found to be insignificant, but it has to be noted that the vortex cell flow was not stabilised in this experiments.

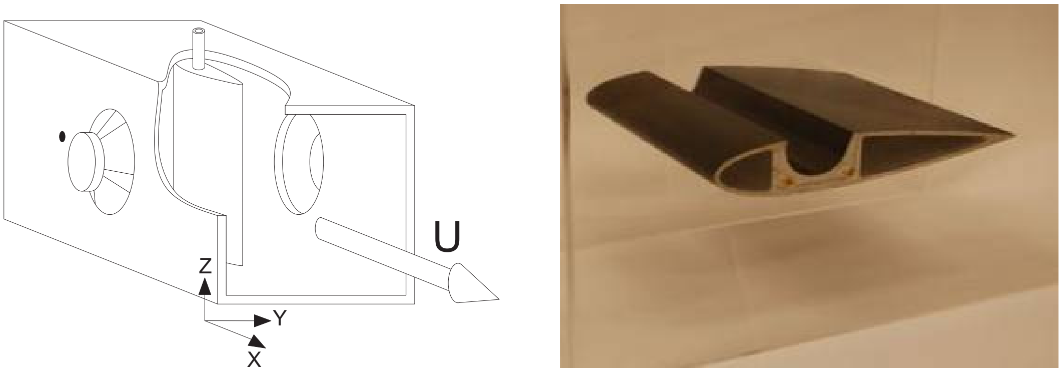

Figure 9

Feedback and open-loop control was studied by the team of the University of Southampton using a discrete vortex code. Then a control system, shown in Fig.10, was designed and built in Southampton and tested in CIRA in the test-bed facility.

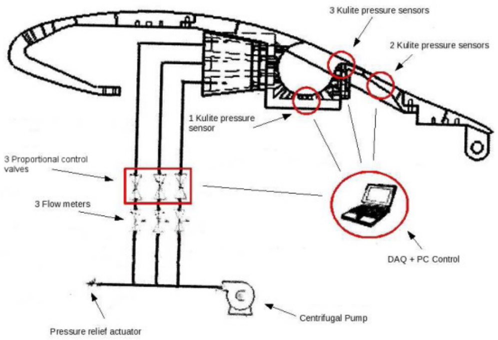

Figure 10

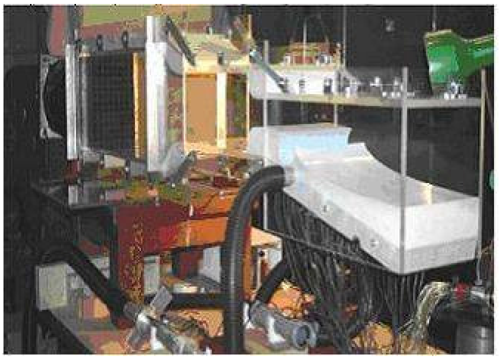

Figure 11

Unfortunately, electronic valve malfunctioning rendered the results inconclusive. An attempt on feedback control was also made by the team of the Moscow State University in their second facility shown in Fig.11, but in this case the system was unable to prevent the separation from the upper and side walls, not equipped with vortex cells.

Experiments in these facilities often required input from and provided material for comparisons for numerical calculation based on the Reynolds-Averaged Navier-

Stokes equations. A significant volume of such calculations was performed by the teams of Battery Company RIGEL, Piaggio Aero Industries, and CIRA.

On the basis of the accumulated results and experience it was decided that the HALE airfoil will have a constant-suction-flow rate control system with suction inside the vortex cell. For an ordinary aircraft the lift-to-drag ratio, being directly linked to the aircraft range, is the main characteristic of the wing quality. For HALE aircraft, however, the maximum flight time is more important than range. The flight time can be increased by having more fuel on board and/or by increasing the lift coefficient while decreasing the flight speed at the same time. This might justify using a thick wing in HALE. Accordingly, a NACA 0024, which is a relatively thick airfoil, was selected as the baseline. A vortex cell was designed using the shape optimisation code developed at the earlier stage of the project. The model has a chord length of 500mm and a span of 1200mm. Tests were performed in the Politecnico di Torino. Airfoil with a vortex cell stabilised with suction, and, for comparisons, the same airfoil without the vortex cell but with distributed suction though the surface were tested. Figure 12 shows the sketch of the airfoil with a vortex cell and a photograph of the rear view of the airfoil in the wind tunnel, with the a rake of total pressure probes for wake measurement. Note that the vortex cell occupies only the central 1/3 of the wing, in order to eliminate the end effects. (Some experiments with a vortex cell spanning the entire wing were performed by the Moscow State University team.) In analysing the performance of the airfoil, an account was taken of the energy required to run the suction system. The equivalent additional drag corresponding to this energy was estimated and added to the measured drag. Experiments showed that there exist a range of the angle of attack within which the wing with a vortex cell can perform better than the baseline wing without suction and better than the baseline wing with distributed suction. However, a hysteresis loop was found to exist in the flow past the wing with a vortex cell, and the wing gives better performance only on one branch of the hysteresis loop. This means that for utilising the advantage a system of hysteresis control will also be required.

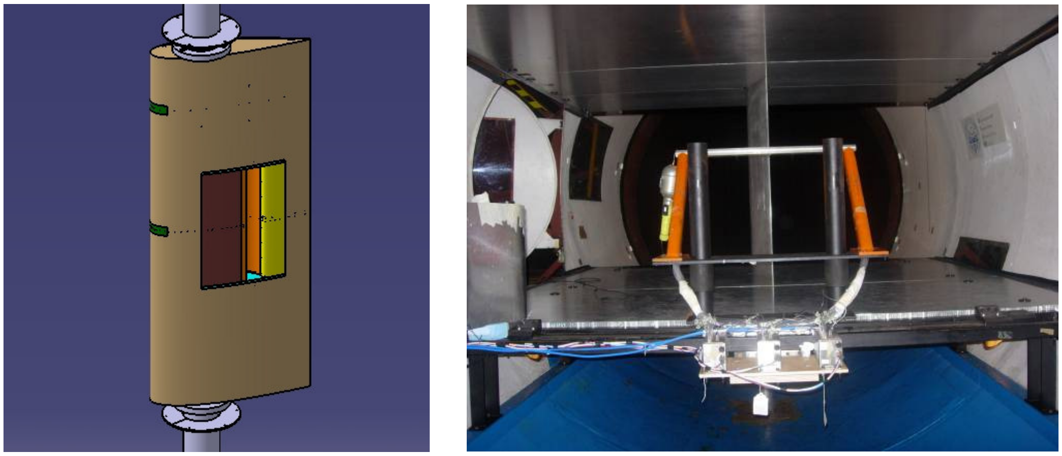

Figure 12

Project outcomes

Overall, the project has been completed successfully. The results obtained generally meet the objectives specified at the start of the project, and provide the solution to the problem initially addressed, namely:

- A software tool for designing a flow past a thick airfoil with a trapped vortex assuming that this flow is stable, apart from small-scale turbulence, was developed.
- A methodology and software tools for designing a system of stabilisation of such a flow were developed.
- An airfoil with a trapped vortex and a stabilisation system for the High-Altitude Long Endurance aircraft was designed, built, tested and its performance was estimated.

The software tool developed in the project optimises the vortex cell shape for the case of zero mean flow rate of the stabilisation system, as it was initially preconceived, while the developed control scheme requires a non-zero mean flow rate. Therefore, further developments should either generalise the optimisation tool to non-zero mean flow rate or achieve control with zero mean flow rate.

The developed scheme of active control should be classified as an open-loop scheme, rather than the initially envisaged closed-loop scheme. However, the numerical results obtained but not tested in experiment suggest that there are significantly more efficient control schemes. Further work should be concentrated on unsteady and feedback control schemes.

The performance of thick airfoil with a vortex cell and control system designed and tested was observed to be better than the performance of the thick airfoil with control system but without the vortex cell, but only in a certain range of the angle of attack, and, more importantly, only when the flow past an airfoil with a vortex cell was in the more favourable branch of the hysteresis loop of the flow regime. While methods of attaining the favourable branch were identified numerically, further experimental research should take care that the corresponding provisions are made in the design.

The results obtained in the project provide a significant step forward as compared to the state of the art. In particular, the development of the software tool for optimising the shape of the vortex cell, the significant body of data on three-dimensional effects collected, and the significant body of data obtained on the actively controlled flows past airfoils should be distinguished.

The results of the project were reported at about 40 conferences and in about 20 journal articles. All the project deliverables have been submitted and the milestones reached.

The partners developed close links over the duration of the project, with many parts of the research done in genuine collaboration. As a group, the partners now have a world-leading position in the area of actively controlled flow with trapped vortices. This is the main outcome of the VortexCell2050 project.