User Project: ‘Marine turbulence-induced response of Offshore WT aerofoils’

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MARINET2

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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1 Introduction & Background

1.1 Introduction

Despite laminar flow being an off-design condition, wind turbines (WT) are designed neglecting turbulence at their inflow. The ground for this assumption is that atmospheric turbulence eddies are much larger than the aerofoil chord and therefore they can be accounted as a slow laminar fluctuation. However, turbulence affects significantly the design of a wind farm, e.g. regarding the spacing between WTs. Although plenty of research has been published upon optimal wind farm design, very few works have concentrated on the basic aerodynamic mechanism which triggers the detrimental (or beneficial) effect of turbulence in the inflow.

The project "AerosWay" spurs from preliminary tests at the University of Birmingham. The aim of the research is to understand the effect of large integral length scale turbulence on the aerodynamic behaviour of a WT aerofoil. These previous tests have confirmed that a turbulent flow affects the aerodynamic performance of aerofoils even when the integral length scale is much larger than the chord length. The research has set an important precedent on the development of a robust methodology for varying turbulence characteristics at the inflow of physical simulation, and calls for further setups to be implemented to replicate a wider range of atmospheric conditions, such as those found in the marine environment and relevant to offshore wind energy.

The configuration of the CRIACIV boundary layer wind tunnel is ideal to extend the scope of the work to reproduce a highly turbulent flow in controlled conditions with the possibility of testing high-quality models of various sizes against their aerodynamic response to a set of turbulence to replicate conditions found in the marine environment.

Prior to the wind tunnel tests, numerical tests were carried out at the HPC facility in Birmingham to choose a set of inlet configurations to accurately reproduce a marine environment, namely atmospheric turbulence analogous to the von Karman formulation having turbulence intensities varying from ~5% to ~20%, with a range of integral length scales of ~10-50 m, which translates into a ratio between the length scale and the characteristic size of a wind turbine aerofoil, the chord, of L/c~5-30. Clearly these values are extremely challenging in wind tunnel testing, and the aim of this project is to overcome said limitations and establish a methodology able to test for larger length scales.

Prior discussion to the submission of this proposal has been held with CRIACIV facility managers. Prof. Claudio Borri and Prof. Enzo Marino have been contacted in multiple occasions to establish common ground on research interests about marine research and the scope of the experiment. In particular experience with turbulent inflow generation in Birmingham is combined with experience in aero-elastic wind tunnel model in CRIACIV, using the aerofoil model developed in Birmingham for previous static tests, with the experimental instrumentation available in Florence. Contacts have also been held with researchers at CRIACIV which will be involved in the experimental activity, namely the manager of CRIACIV wind tunnel, dr Tommaso Massai, upon feasibility of the test, and the scientific manager Dr Claudio Mannini.

The CRIACIV wind engineering lab was available for extensive testing campaign from July 2019, when all experimental investigations have finally taken place.

The project "AerosWay" is aimed at showing the effect of typical offshore turbulence statistics on the aerodynamics of a wind turbine aerofoil in free oscillations.

The short term objectives of the project are conceived to provide a test-case to be used as reference for future numerical and experimental studies on the investigation of the interaction between a turbulent inflow with given statistics with the separated boundary layer around a WT aerofoil. This project in particular aims at understanding whether this interaction is strengthened or weakened by the size of turbulent coherent structures in the inflow.

In the long term, this project gives a thorough insight on the robustness of a methodology to produce turbulence characteristics at the inlet of wind tunnel testing for a variety of turbulent wind environments. The issue is to be able to increase the scale of the tested device to measure more statistics than it would be normally possible with a more traditional turbulent boundary layer. The crucial issue is recognised in the generation of relevant turbulence and the ability to provide large length scales and an energy cascade representative of the large eddies found in the atmosphere.

This ambitious goal will possibly contribute with qualitative results towards new investments to improve the understanding of the understanding of the effect of turbulence on the aerodynamics and the consequent optimisation of the efficiency and reliability of WT converters.

1.2 Development So Far

The project plan originally comprised of five weeks or trans-national access, of which only four have been granted. For this reason the project plan had to be amended, excluding the aeroelastic testing of the two model aerofoils in possession of the University of Birmingham, which was originally planned.

To guarantee the success of the experimental investigation, the project goals have been divided into primary project goals, and secondary ones.

In the next subsections, the experimental investigation progress and the plan for this access are briefly addressed and detailed.

1.2.1 Experimental investigation Progress

The Primary project goals include:

1) preliminary evaluations of the available models and testing facilities;
2) the building of a flexible experimental setup to vary turbulence at the wind tunnel inflow with the possibility of the independent variation of turbulence intensity and integral length scale;
3) the characterisation of the flow field to obtain turbulence analogous to atmospheric and marine winds;
4) the setup of two model aerofoils to retrieve static polars under a varying turbulent inflow;
5) the static measurements for the fixed aerofoil at different angles of attack for 2 aerofoil models.

The primary project goals have all been fulfilled within the duration of the Trans-National Access. Results are discussed in the relevant next sections. Static measurements for the fixed aerofoil will require further tests, which will be performed in due course using the experimental setup implemented in the other primary project goals.

Secondary goals included the extensive comparison of present results with previous results from literature or alternative simulation methods such as CFD. Due to the restricted time available, this report only includes reference to the primary project goals.

The progress of the experimental investigation also includes analysis of the data and the publication of results, which will take place in due course and are not treated in the present report. The relevant in-depth analysis of data will focus on the formulation of a methodology to correlate aerofoil response sensitiveness and turbulence characteristics of the inflow in the marine environment. It was also part of the "AerosWay" project submitted proposal, the drafting of a relevant journal paper and preliminary planning for future research. This will take place in due course once more results are collected from the research, and the Project "aerosWay will be punctually cited together with the Eu Commission and MArinet2.

2 Outline of Work Carried Out

2.1 Setup

The experimental setup at the CRIACIV wind tunnel lab involved in the project "AerosWay" includes three elements:

1) Set of ad-hoc designed passive grids for generation of inlet turbulence analogous to the marine environment;
2) 3D printed 0.125 m chord model fitted with pressure taps for smaller L/c ratios, adapted in the horizontal aerodynamic forces setup at CRIACIV;
3) 3D printed 0.025 m chord model for larger L/c ratios and adaptation of horizontal aerodynamic forces setup;

1.1.1 Passive Grids

Passive grids have received renewed attention in a number of recent studies, as a reliable and simple way of generating a turbulent inflow in wind tunnel testing. In fact, the high isotropy and uniformity of the flow downstream of a passive grid, replicates conditions found in the atmosphere. In the recent past, also at CRIACIV a number of grids has been built to generate turbulence. With the Project "aerosWay" the past experience from the "Aeolus4Future" Marie Curie ITN is borrowed and developed further to obtain a higher quality flow field. The present setup borrows experience matured in wind tunnels at the University of Birmingham, the University of Liege, and the University of Florence, reaching a new standard of quality for the technology.

The setup includes a set of 4 passive grids designed to have similar aerodynamic characteristics. In particular the Drag coefficient of the grid is ~4 for all grids. This research pushes the boundaries of grid turbulence beyond the classical papers in the field about the design of grid turbulence used to generate a turbulent inflow.

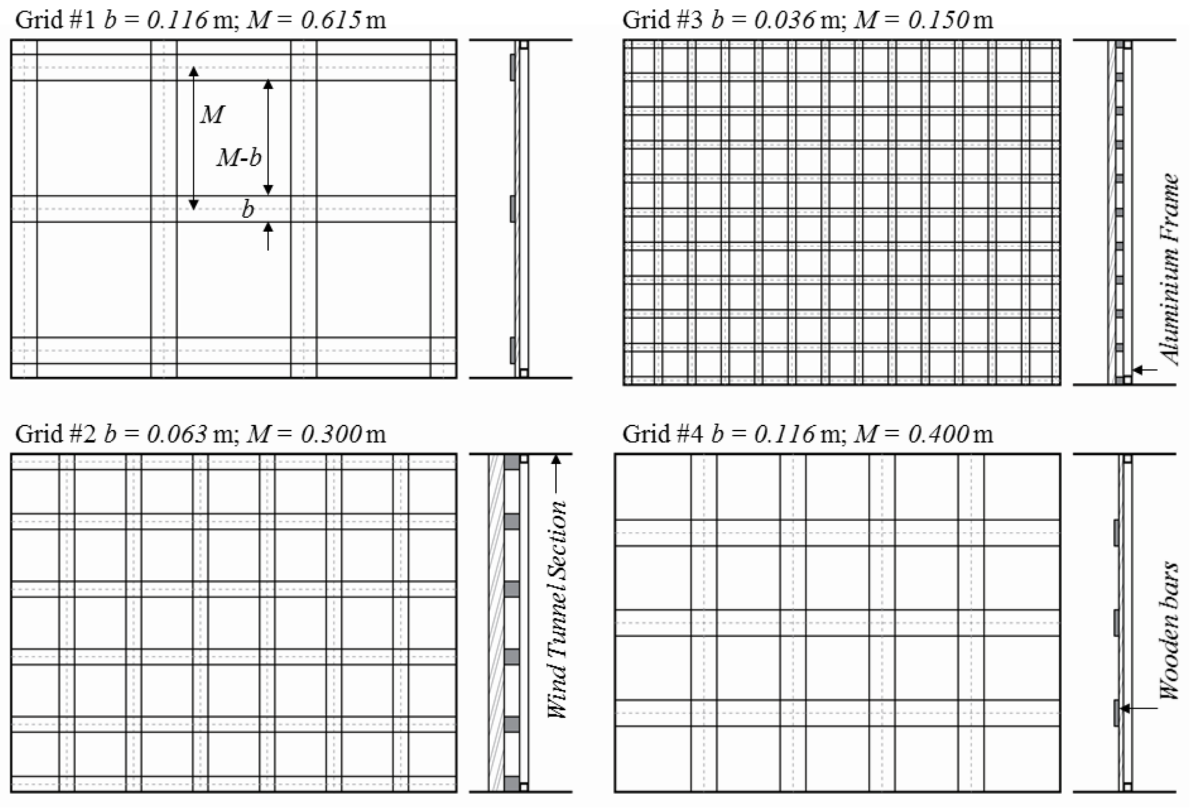

Figure 2.1. Designed passive grids used in the experimental setup

The four grids are shown in Figure 2.1. Three parameters are involved in the design of passive grids, namely mesh and bar size and the distance considered to measure the inflow. Such distance has a minimum value for the flow to be considered uniform, which at CRIACIV was confirmed to be $d_{min}\sim 5M$, where M is the mesh size.

Table 2.1 shows the turbulence characteristics at the inflow. As evident, values up to $I_u\sim 15$ % with large length scales up to $L/c\sim 3$ can be easily achieved. The interesting feature of this setup is the ability to fix a turbulence intensity and obtain several length scales to test the separate effect of the two statistics, which is an absolute novelty in the bluff body aerodynamics community. The setup provides a range of turbulence characteristics spanning $I_u\sim 5\text{-}15$ % and $L_u\sim 2.5\text{-}35\ cm$ which have comparable characteristics in terms of fit to the von Karman spectrum, isotropy, gaussianity and behaviour at the smallest recordable scales.

Results have been measured with two different setups:

1) A rake of single-wire and X-wire anemometers placed at the centre of the test-section;
2) A self-movable setup for the measurement of vertical and horizontal profiles with the same rake of anemometers mounted.

Hot-wire anemometry has been setup to record data al 10 kHz which allows for an advanced description of the energy cascade.

Although not directly relevant to this specific study, the measurement of velocity profile has allowed the detailing of the setup in a way that the flow has a high-degree of uniformity at the bluff body location. This means the effect of a wind shear is excluded, and this is normally the case with grid turbulence if the region of the setup where the grid and the wind tunnel walls interfere is not studied in detail. This setup provides a high quality flow field which is also uniform for $d>5M$.

Table 2.1. Passive Grid Generated Turbulence properties

Grid	b [m]	M [m]	β [-]	C_d [-]	x/M [-]	I_u [%]	L_u/b [-]
#1	0.116	0.615	0.66	0.79	5	15.0	1.51
#2	0.063	0.30	0.62	0.97	5	8.35	1.81
#3	0.036	0.15	0.58	1.27	5	9.0	1.84
#4	0.116	0.4	0.5	1.95	5	11.0	1.39

1.1.2 Static polar setup for 0.125 m chord model

A 0.125 m chord wind turbine aerofoil model has been available at the University of Birmingham for tests within the Marie Curie ITN "Aeolus4Future". The 3D printed model is fitted with 40 pressure taps, and combined with the experimental setup studied for the inlet turbulence, allows for L/c ratios of up to ~3, which is a quite important achievement in wind tunnel testing where usually much smaller scales are achieved when simulating an atmospheric wind profile. The model is 1.25 m long, allowing for a healthy aspect ratio of $D/c=10$ to be respected. This allows for high-quality measurement of aerodynamic forces using the setup available at CRIACIV.

The primary goal of the study is to understand the role turbulence length scales play when interacting with a wind turbine. The angle of attack is varied automatically using a setup able to obtain a fine description of the static polar. Time histories of both surface pressure and aerodynamic forces are recorded at 2000 Hz for $T=60$ s. A crucial aim of this study to add to the knowledge is to confirm the disappearance of Reynolds effects in turbulent flows. The highly controlled flow at the CRIACIV wind engineering lab allows for the chord Reynolds to be varied within the range $Re\sim 10'000\text{-}300'000$. This values are fairly close to a possible atmospheric flow field encountered at a location, when considering a small wind turbine blade size, or a large wind turbine with a significant deficit in the mean velocity, i.e. in the wake of other wind turbines offshore. The aim of the static polars is to test the effect of turbulence for the stall mechanism of wind turbine aerofoils. Angles are chosen to obtain a reliable description of the pre-stall, transitional, post-stall and full-stall behaviour. The measurement of surface pressure distributions will also allow for comparison with previous tests to gain an insight into the physical mechanisms occurring and causing stall delay phenomena.

Figure 2.2 – View of the 0.125 chord model aerofoil at the CRIACIV wind engineering Lab.

1.1.3 Static polar setup for 0.025 m chord model

A 0.025 m chord prototype model was also available at the University of Birmingham. However, due to the reduced size of the model it was not possible to conduct tests within the Marie Curie ITN "Aeolus4Future". This 3D printed model allows for L/c ratios of up to ~15, which is a value never achieved before in wind tunnel testing. These scales are representative of a large wind turbines such as those found offshore. The model is conceived in an analogous way as the larger one, with a length of 0.30 cm, allowing for an aspect ratio of $D/c\sim10$. The challenge is to size the experimental setup in a way to respect the sensitivity of the force balance to allow for high-quality measurement.

The primary goal of the "AerosWay" Project is to fine-tune the experimental setup and explore its limitations. The angle of attack is varied in an analogous way as for the larger domain. Time histories of aerodynamic forces are hence recorded at 2000 Hz for $T=60$ s. The limitations for this specific setup is the Reynolds number range, which is limited to $Re\sim2'000\text{-}60'000$., which is representative of service state conditions in offshore wind farms, rather than ultimate limit state ones.

Although this setup might seem similar if not alike to the one for the larger aerofoil, it has required extensive trials to be put into place as the inferior limits of the experimental equipment was used, both in terms of sensitivity and resistance. Therefore it is considered a stand-alone setup with a specific procedure and protocol for the data acquisition, separate from the larger model.

2.2 Tests

All the tests require specific equipment available at CRIACIV. As specified in the Project proposal, the equipment for the various primary goals is listed as follows, alongside with availability and required training.

1) The equipment for the grid generation of inlet turbulence accounts to wooden bars nailed together in various configurations. This material is already available in CRIACIV as per previous experiments with passive grids. Instrumentation includes hot-wire anemometers to measure the three components of the flow field and a traverse system to appropriately position the probe to measure the wind profile downstream of the grids.
2) Aerofoil models are brought at CRIACIV from the University of Birmingham. Models can be easily dismantled and transported and easy to be fitted with instrumentation available at CRIACIV for the measurement of surface pressure and aerodynamic forces. The pressure transducer and dynamic balance are also provided along with the training required by the applicant about the implementation of the set up. Technical assistance is provided by CRIACIV with dedicated available personnel.

Tests yielded in a first instance the velocity field across the wind tunnel test-section. In particular, both the three velocity components at the centre of the test section and the vertical and horizontal velocity profiles for $d=5M$ are measured. Pressure and force time-histories are also retrieved from both large and small aerofoil models.

The novelty of the work includes the analysis of the data, which is focused on fluctuating variables. In fact, bulk statistics (such as mean, variance or skewness) are normally used for this kind of tests and found in literature. However, more insight into the physical phenomenology might be achieved through a more advanced statistical analysis.

2.2.1 Test Plan

Table 2.2 shows the detailed test-plan. Grid properties refer to the characterisation of the flow field, in contraposition to the measurement of aerodynamic forces, which refers to the static tests on the two model aerofoils. Three velocity regimes are studied to understand the role played by the Reynolds number, while adjusting values according to the behaviour of the mean velocity along the wind tunnel fetch length. Three rotor wind speeds are set and appropriately adjusted depending on the Reynolds regime to be set up for the static tests. As for the static tests, data from grid generated turbulence is analysed to identify sets having an analogous turbulence intensity or integral length scale. Such sets are then grouped together to individuate constant turbulence intensity and constant length scale cases. A number of at least 6 cases is found to be possible with the current dataset. The aerofoil models are positioned in the flow field and the angle of attack appropriately varied statically.

Table 2.2 Details of the experimental test-plan with specification of the grid configuration

Test	Aerofoil	Angle of attack	Grid configuration	Velocity Regime
Grid properties	-	-	G1 $M=0.2$ m $d=5-20M$	$U_r = 15$ m/s $U_r = 20$ m/s $U_r = 25$ m/s
	-	-	G2 $M=0.4$ m $d=5-15M$	"
	-	-	G3 $M=0.6$ m $d=5-12M$	"
	-	-	G4 $M=0.8$ m $d=5-8M$	"
Static test (aerodynamic force coefficients)	$c=0.125$ m	Static polar $\alpha=0-30°$	Constant $I_u=5$ % $L_u=8-25$ cm	$U_r = 15$ m/s $U_r = 20$ m/s $U_r = 25$ m/s
		$\alpha=0-30°$	Constant $I_u=10$ % $L_u=8-25$ cm	"
		$\alpha=0-30°$	Constant $I_u=15$ % $L_u=8-25$ cm	"
		$\alpha=0-30°$	Constant $L_u \sim 8$ cm $I_u=5-15$ %	"
		$\alpha=0-30°$	Constant $L_u \sim 15$ cm $I_u=5-15$ %	"
		$\alpha=0-30°$	Constant $L_u \sim 25$ cm $I_u=5-15$ %	"
	$c=0.025$ m	Static polar $\alpha=0-30°$	Constant I_u "	"
		$\alpha=0-30°$	Constant L_u "	"

2.3 Preliminary Results

Preliminary results show the possibility of creating a high quality setup, by pushing the limits of passive grids to fully exploit the capability of wind tunnel testing. Figure 2.3 shows the behaviour of the turbulence intensity for the whole experimental setup. As visible the behaviour of the grids is analogous, although their dimensions vary significantly. This reassures also on the quality of the flow field, which remains analogous for the whole setup. Figure 2.3 also shows that the flow has a high degree of isotropy, which is ideal to test turbulence effects and avoid any unwanted parasite effects from irregularities in the flow field.

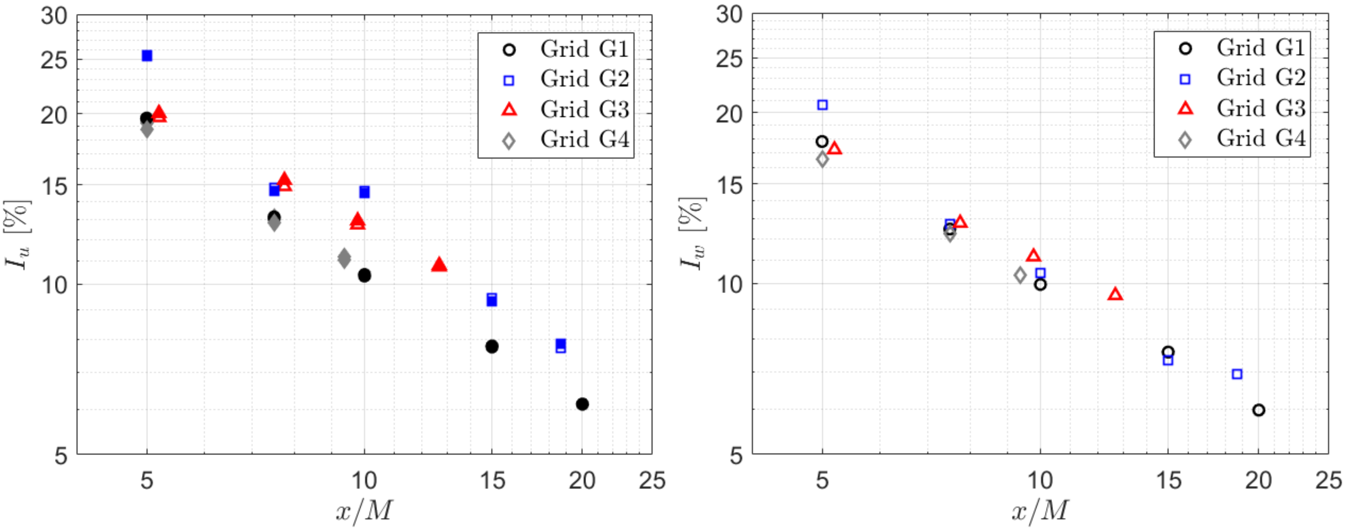

Figure 2.3. Turbulence intensity decay for the experimental setup.

Figure 2.4 shows the integral length scale decay, which is in line with results found in literature and similar conclusions can be drawn as in Figure 2.3 on the quality of the flow field and its isotropy.

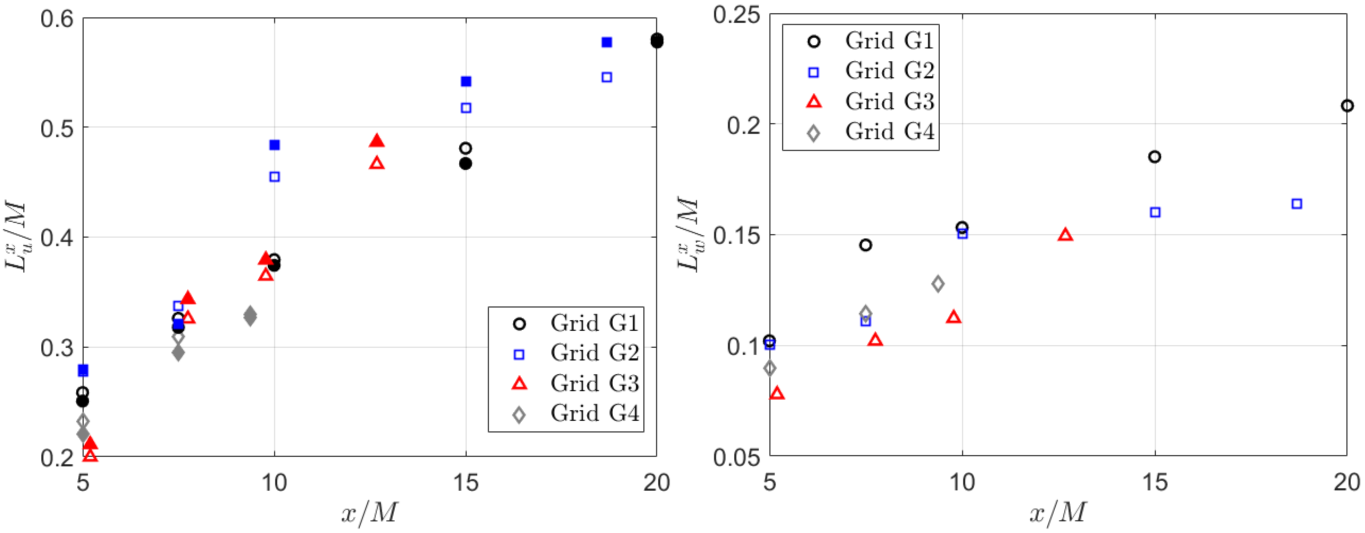

Figure 2.4. Integral Length Scale decay for the experimental setup.

2.4 Conclusions

The Project "AerosWay" is aimed at developing experimental setup developed at the CRIACIV Wind Engineering Lab to test the effect of atmospheric turbulence on bluff bodies. Results show the high-quality of the flow field obtained and how it allows for the investigation of the separate effect of the turbulence intensity and length scale on the behaviour of wind turbine aerofoils in stalled conditions, which is typical for wind turbines placed in marine environments.

3 Main Learning Outcomes

3.1 Progress Made

The experimental setup implemented within the "AerosWay" Project is now readily available and tested for further investigations. The plan for this access was ambitious in stating the scope of this project to develop a novel experimental setup in such a short amount of time to extend previous experience done among the University of Birmingham and the University of Liege. The aim of the Project has been achieved in having a reliable setup which might shed a renewed light on the problem of the malfunctioning of wind turbines or the power output of wind farms in the presence of enhanced turbulence in the atmosphere, a condition which might be present at times in marine environments, experiencing slowly decaying wakes and neutral atmospheric stability.

The work has also highlighted the intrinsic difficulty in varying the flow field accurately without a time-expensive fitting of the passive grids, which need to be moved and screwed to the wind tunnel walls. This also greatly affects the flow field and even a small irregularity in the positioning of the grid might lead to non-uniformity in the resulting flow field.

3.1.1 Progress Made: For This User-Group or Technology

The CRIACIV wind engineering lab has now a trustworthy setup to vary the turbulent flow field accurately. This setup can be adapted for a multitude of uses to test the effect of wanted flow characteristics on a bluff body to be placed in the atmospheric boundary layer, but with such a size and scope to not allow for tests with traditional boundary layer wind tunnels.

The User-Group used the opportunity of the "AerosWay" Project to conducting further experiments on research initiated in the University of Birmingham. The progress allows more results to be collected and confirm the importance of more research for the topic within the scope of bluff body aerodynamics.

3.1.2 Progress Made: For Marine Renewable Energy Industry

This setup could be fine-tuned to replicate the turbulence intensity and wake characteristics downstream of an offshore wind turbine to develop a methodology to assess and predict wind farm losses due to the interaction of wind turbines with a turbulent flow field. This also applies to onshore wind turbines. The outcome of this research would also be a first step for the development of a better design strategy to take into account turbulence effects and adjust the wind turbine performance and power output.

3.2 Key Lessons Learned

- Grid turbulence more flexible and generous that thought in terms of isotropy and uniformity of flow field;
- Grid turbulence useful from distance $>5M$ (not $10M$ as stated in literature);
- Turbulence intensity of $\sim 20\,\%$ and Length scale of $\sim 30\,\mathrm{cm}$ can be achieved;
- Characteristics varied separately maintain their uniformity and energy spectrum shape;
- Velocities of up to $20\,\mathrm{m/s}$ can be achieved safely without unwanted vibrations or problems;
- Ideal size of models ~10cm to allow for elevated number of pressure taps;
- Ideal size of models ~2cm for sensitivity of normal force balances for aerodynamic forces measurements.

4 Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- "On the construction of passive grid for inlet turbulence generation in wind tunnel testing"
- "The effect of large integral length scale of turbulence on the stall mechanism of wind turbine aerofoils"
- "Reynolds Effect and turbulent inlet"