COMTERID

Investigation of Design Aspects and Design Options for Wind Turbines Operating in Complex Terrain Environments

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ABSTRACT

COMTERID project, the successor and the follow-up of MOUNTURB, which was undertaken within the JOULE-III program by a number of National European R&D institutes, Universities, Private Companies (CRES, NTUA, RISO, CIEMAT, ECN, TG) and WT manufacturers (VESTAS, ECOTECHNIA, NORDIC WIND POWER) was initiated in order to fulfill the following main objectives:

- To integrate the available information gathered in previous projects for the complex terrain environment. This information couples Wind and WT operation characteristics.

- To identify from the above information the particularities in machine behavior, which are due to the complex terrain environment.

- To investigate the reliability of the existing numerical tools in capturing the essential features of the complex terrain WT operation and to establish the limits of their application.

- To use combined experimental and numerical work in order to identify the sensitivity of the machine operation characteristics to the system design parameters for representative complex terrain wind conditions.

Complex terrain sites are a major and critical market for wind energy development and knowledge regarding the wind structure and the WT response to it is still lacking. The work undertaken and completed in this project identifies and quantifies the complex terrain wind structure conditions which are found to be different from the flat terrain standards and through the development of a parameter identification methodology it identifies, evaluates and quantifies the machine's performance sensitivity to the Wind-WT parameters. New data, for wind & machine loading, critical for standards development was also produced within the framework of COMTERID project.

The technical content of the project was based on the following actions:

- The complex terrain wind macro- and micro- characteristics, i.e. the full wind fetch (3D wind profile under which a WT operates) and its turbulent characteristics (rotor 3D wind structure) were established through existing data compilation, a new large scale wind experiment, and wind structure numerical modelling.

- The complex terrain wind macro- and micro- characteristics, were correlated to the full WT response (mean loading, fatigue & power performance) through existing data from Stall and Pitch WTs, new measurements on Stall, Pitch, Variable Speed, Soft Yaw and large sized WTs (up to 1000kW) and numerical modelling. Design tool validation was a critical part of the work.

- The major parameters of the system Wind-WT were identified, studied and understood in detail and the sensitivity of the system output (power, loads) to the system design parameters (design envelope of the machine) was studied and quantified for representative wind conditions at a complex terrain environment. This was accomplished with the development of a parameter identification methodology and evaluation of the machine's performance sensitivity to the Wind-WT parameters.

- Synthesis of the findings and investigation whether machines designed for flat terrain are suitable for complex terrain as well, and whether the complex terrain features can be faced by just trimming existing design concepts or if new design criteria concerning the individual machine components must be devised, was the final stage of the research. The investigation was based on direct design option comparisons of tested WT and numerical modelling of new concepts in terms of mean and fatigue loading.

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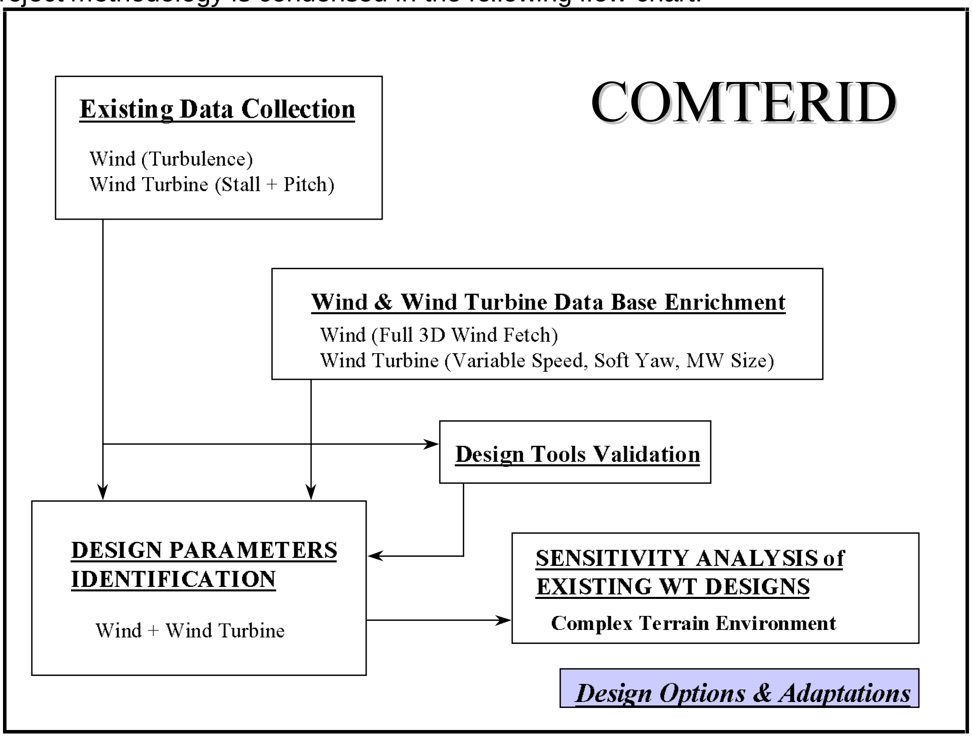
OBJECTIVES OF THE PROJECT

The objectives of the project were the following:

- To integrate the available information gathered in previous projects for the complex terrain environment. This information couples Wind and WT operation characteristics, and together with the new measurements to be undertaken within COMTERID (Greece, Spain, Sweden) and the comparisons with similar measurements in flat terrain (Spain, Denmark, USA, Sweden) should provide the WT Industry with *the first full picture of the complex terrain environment*.
- To identify from the above information the particularities in machine behaviour, which are due to the complex terrain environment. Different machine sizes, 110kW to 1000kW, and design concepts, *fixed and soft yaw*, and control strategies, *stall, pitch and variable speed* will be investigated.
- To investigate the reliability of the existing numerical tools in capturing the *essential features of the complex terrain WT operation* and to establish the limits of their application. These tools concern both the wind characteristics (macro and micro) and the machine performance (power and loads). The capabilities and limitations of these tools will be assessed through systematic comparisons with experiments.
- To use combined experimental and numerical work in order to *identify the sensitivity of the machine operation characteristics* to the system design parameters *for representative complex terrain wind conditions*. This information will be used in an attempt to assess existing design options and *propose alternative design scenarios or design adaptations for complex terrain WTs*.

The overall project methodology is condensed in the following flow-chart:



TECHNICAL DESCRIPTION

The project was divided into the following working areas:

WA1: Complex Terrain Wind Properties and Prediction Capabilities

All the information concerning the wind-field structure as it effects WTs in a complex terrain environment gathered and analysed within this phase. Existing data, ongoing and new experimental data gathered in a data base, which was used to validate wind field and turbulence prediction codes. Emphasis was put in correlating the local ground topography with the mean velocity field characteristics, including longitudinal and transversal shear and deformation, evolution of the turbulence kinetic energy, power spectra and coherence of the turbulence structure, in an attempt to extend and generalise the work initiated with MOUNTURB.

WA1.1 Wind Field and Wind Structure Measurements
Typical complex terrain sites where mast arrays were installed for wind measurements were selected. Measured wind characteristics were analysed in terms of wind speed components and directions, wind shear, turbulence intensity and spectra. The new experimental work in Evia island (Marmari) was contained in this task.

WA1.2 Wind Field Modelling
Advanced models (see below in available numerical tools) were used to predict the detailed velocity field and the kinetic energy of turbulence for the pre-selected sites, in a range of privileged wind speed directions, in order to compare them with the detailed wind structure characteristics.

WA1.3 Wind Structure Modelling
Modelling tools were used to predict the turbulence spectral density and coherence characteristics taking into account site effects so as to produce complex terrain representative time series for the wind components structure.

WA1.4 Wind Modelling Limitations and Assessment
Numerical results were compared with the experimental data. The reliability limits of wind characteristics prediction, as they effect WT operation, were established for a number of sites and conditions.

WA1.5 Complex Terrain Wind Data Base
A synthesis of the experimental data and numerical results was performed at a final stage, aiming to interrelate the wind-field structure with the local ground topography.

An overview of the performed experiments and related analyses for the site characterisation work, as well as the constructed wind data bases is presented in the following table:

Participant	Site	Type of terrain
CRES	Marmari, GREECE	Complex
RISO	Sky River, USA	Complex
RISO	Lammefjord, DENMARK	Flat
TG	Nasudden, SWEDEN	Complex
CIEMAT	Tarifa, SPAIN	Complex

An overview of the numerical code developments and performed simulations and related analyses is presented in the following table:

Participant	Analyzed Sites	Numerical Tool
NTUA	Askervein Andros Evia Evia (Marmari region)	3-D steady Navier – Stokes
LTL	Askervein Lavrio Andros	AIOLOS-T
CRES	Askervein Andros Lavrio Marmari Lyse	3-D Boundary Layer Method

WA2: Complex Terrain Machine Response and Prediction Capabilities

All the information concerning the machine operation characteristics with respect to the surrounding wind-field structure in a complex terrain environment were gathered and analysed within this work area of the project. Existing, ongoing and new experimental data were gathered in a data base, which were used to validate machine performance prediction codes. Emphasis was be put in correlating the local velocity field characteristics with the machine loading and power production.

WA2.1 Wind Turbine Load and Power Measurements
The sites where machine loads were measured along with their detailed wind characteristics were selected. Machines of different design concepts (stall and pitch regulated, variable speed, fixed and soft yaw) and sizes (110kW to 1000kW) were used in order to increase the representatibility of the approach. The new WT experimental campaigns (GREECE, SPAIN, SWEDEN) were launched. Measured power and loads (rotor-tower) were analysed using common standard techniques, according to the experience gained and data gathered in MOUNTURB. Control characteristics were also monitored, along with the coupling of the WT to the grid, due to the fact that in most cases grids on complex terrain are not very strong, and create an increased number of start and stop cycles for the WTs.

WA2.2 Wind Turbine Modelling
Advanced models (see below in available numerical tools) were used to predict the detailed machine response including rotor aerodynamics and aeroelastic behaviour (loads, performance), drive train response, controller logic, e.t.c.

WA2.3 Wind Turbine Modelling Limitations and Assessment
Numerical results were compared with the experimental data. The limits of machine characteristics prediction were established.

WA2.4 Wind Turbines in Complex and Flat Terrains
Experimental results from the different WTs in their different sites of operation were compared and the measured differences in flat and complex terrain operation were established.

WA2.5 Wind and the Wind Turbines in Complex Terrains
A synthesis of the experimental data and numerical results was performed, to interrelate the wind-field structure with the machine response.

An overview of the performed experimental work, related analyses and WT data base construction is presented in the following table:

Wind turbine Make and type	Power output	Power control	Operation site	Type of Terrain	Measuring institute
AOA 100	100kW	variable speed stall	Skyros island	Complex	CRES
HMZ 300	300kW	pitch	Evia island	Complex	CRES
ECTN 44/600	600kW	stall	Tarifa, Spain	Complex	CIEMAT
VESTAS V39	600kW	pitch	Lem, Denmark	Flat	RISO
VESTAS V39	600kW	pitch	Sky River, USA	Complex	RISO
NWP1000	1000kW	variable speed	Nasuden, Sweden	Flat	TG
WINCON 110XT	110kW	stall	Ag.Marina, Lavrio	Complex	CRES
VESTAS V27	225kW	pitch	Andros island	Complex	CRES
NTK500/37	500kW	stall	Crete island	Complex	CRES

An overview of the numerical code developments and performed WT simulations and related analyses is presented in the following table:

Participant	Wind field model	Aeroelastic code	Analysed WT
NTUA	INWIND	GAST	NTK 500/37 VESTAS V39 ECOTECNIA 44/600 3MW ‘paper’ WT
TG	SOSSIS	VIDYN	NTK 500/37 Nordic NWP 1000
ECN	SWIFT	PHATAS	NTK 500/37 VESTAS V39
RISO	Mann model	HawC	NTK 500/37 VESTAS V39

WA3: Investigation of Design Aspects and Design Options

Experimental data and numerical tools were employed in order to identify the parameters which dominate machine performance at complex terrain environments. The sensitivity of the machine operation characteristics to the identified design parameters were studied. This information was used in order to assess the existing design options and, possibly, to propose alternative design scenarios. To accomplish the target the use of reliable tools whose prediction capabilities and limitations are well documented were established.
The full treatment of the design problem for all WTs involved was prohibited because of the limited duration of the project. The design task was launched in this context by performing first a parameter identification study and then by evaluating the performance sensitivity of the available machines. The method performed the analysis by fixing, each time, one of the entries (wind, machine). The wind characteristics influence was studied by considering the same machine installed at different sites. This will be done using the obtained experimental data. To investigate the design concept influence, the wind entry will be fixed and numerical testing will be performed for the machines involved in the project for specific site conditions. In both cases this study will indicate which are the crucial parameters and to what extend they influence the machine performance at complex terrain, and these results will form the basis for the required WT adaptations for complex terrain operation, through the sensitivity analysis.

WA3.1 Identification of Design Parameters for WTs in Complex Terrain
The design parameters for stall and pitch WT technologies were identified using the results produced in MOUNTURB, and the additional insight and experience gained from WA1 and 2.

WA3.2 Wind Conditions Effect on Machine Performance at Complex Terrain
The parameter identification and sensitivity analyses were performed for fixed machines using experimental data. From the constructed wind data bases, basic models that described the wind structure, as a set of correlated distributions that describe not only the basic wind magnitudes like mean wind speed and turbulence but also the lateral and vertical turbulence component and other magnitudes as well, were developed. The models were used in order to simulate the effect of the wind structure on the fatigue loading of the wind turbines for long time periods. Thus the relative fatigue life consumption of a given wind turbine when located at sites with different wind structure was quantified.

WA3.3 Wind Turbine Design and Complex Terrain
The parameter identification and sensitivity analysis was performed for fixed wind conditions using computational tools. The selected wind turbines were tested for fixed site conditions. CRES' complex terrain test site, where the most detailed wind data were available, provided the "representative wind characteristics" information. The study showed how the machine size influences its performance at complex terrain how the machine concept is influencing the performance, and how specific component characteristics and design options change the WT response. The work in this task, identified the crucial WT design parameters for complex terrain operation and the output of the sensitivity analysis led to the "required" WT adaptations.
The design study was performed by TG, RISO and NTUA and regarded the NTK500/37 WT. The examined design options were related to use of softer/stiffer rotor blades, softer/stiffer towers and the utilisation of variable speed control.
Furthermore, an overview of the design options currently used in relation to complex terrain, was performed by the comparative assessment of non-dimensional mean-load and fatigue magnitudes for several WT of different size and control concept.

WA3.4 Wind Turbine Adaptations for Complex Terrain Operation - Design Options
The wind turbine adaptations for complex terrain operation and the related design options assessment was based on the synthesis of the results of the whole work area.

COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACTUALLY PERFORMED

The performed work followed the planned activities. The detailed description of the performed work is presented in the previous chapter of the present document. The deviations that occurred regarded the place

where specific experiments were performed. The alterations were made under the perspective of the best choices regarding terrain complexity of the sites and WTs with specific control strategy and size.
Comments on each work item in respect to program alterations are given in the following table.

Work item	Comments
WA1.1 Wind Field and Wind Structure Measurements	The new large wind field experiment was decided to be performed in Evia island instead of Ag.Marina. Evia presents higher mean wind speeds and terrain complexity compared to Ag.Marina.
WA1.2 Wind Field Modelling	Work performed as planned
WA1.3 Wind Structure Modelling	Work performed as planned
WA1.4 Wind Modelling Limitations and Assessment	Work performed as planned
WA1.5 Complex Terrain Wind Data Base	Work performed as planned
WA2.1 Wind Turbine Load and Power Measurements	The ongoing experiments were performed as planned. The new experiments by CRES regarded AOA100kW variable speed and the HMZ300kW passive yaw pitch regulated WT. The new experiments by CIEMAT regarded ECOTECNIA 600kW.
WA2.2 Wind Turbine Modelling	Work performed as planned
WA2.3 Wind Turbine Modelling Limitations and Assessment	Work performed as planned
WA2.4 Wind Turbines in Complex and Flat Terrain	Work performed as planned
WA2.5 Wind and the Wind Turbines in Complex Terrain	Work performed as planned
WA3. Investigation of Design Aspects and Design Options	Work performed as planned

RESULTS AND CONCLUSIONS

The approach followed during the execution of the project is outlined below and is directly linked with the four work areas identified in the project technical annex:

- The complex terrain wind macro- and micro- characteristics, i.e. the full wind fetch (3D wind profile under which a WT operates) and its turbulent characteristics (rotor 3D wind structure) are established through existing data, a new large scale wind experiment, and wind modelling.

- The complex terrain wind macro- and micro- characteristics, are correlated to the full WT response (loading & power performance) through existing data from Stall and Pitch WTs, new measurements on Stall, Pitch, Variable Speed, Soft Yaw and large size WTs (100kW - 1000kW), modelling, and design tools validation.

- The major parameters of the system Wind-WT are identified, studied and understood in detail and the sensitivity of the system output (power, loads) to the system design parameters (design envelope of the machine) is studied and quantified for representative wind conditions at a complex terrain environment. This is accomplished with the development of a parameter identification methodology and evaluation of the machine's performance sensitivity to the Wind-WT parameters.

- Synthesis of the findings and investigation whether machines designed for flat terrains are suitable for complex terrains as well, and whether the complex terrain features can be faced by just trimming existing design concepts or if new design criteria concerning the individual machine components must be devised.

Based on the above objectives and identified work areas, the following work items were defined and implemented, and their results are presented in detail in the relevant chapters of the report. In the following an overall picture of the conclusions from the project is presented. These conclusions complement and enhance the MOUNTURB conclusions and provide a detailed picture of the complex terrain environment and its effects on the wind turbine operation.

I. 3D mean wind flow model development & application to selected complex terrain topographies.

NTUA performed numerical simulations for selected sites using a 3-D steady Navier-Stokes solver. Turbulence is simulated by the k - ε two equations transport model. A local grid refinement technique of telescopic type was employed, which allows for the treatment of extended areas with fine resolution of the order of a few meters over the spot-area of interest, enhancing the accuracy of the simulation.

LTL applied the AIOLOS-T code for the numerical simulations of the selected sites. AIOLOS-T is a 3-D, hybrid wind modelling numerical tool, which solves the incompressible mass-consistent equation (equation of the perturbation potential) and the compressible momentum conservation equation (Reynolds averaged Navier-Stokes) along the vertical direction, while implementing the two-equation k-ε scheme for turbulence closure. The simulation results obtained from this code render AIOLOS-T as an engineering tool, which can simulate a typical wind field in a reasonable CPU time. Its computational cost is one order of magnitude less than the cost of a full 3-D Navier-Stokes solver.

CRES developed and applied 3-D integral boundary layer method for the computation of the mean flow field over the selected sites. The application results and the comparisons against available experimental data show that the behaviour of the method is, in general, satisfactory mainly from the physical point of view, taking into account the complexity of the phenomenon and the level of approach. One of the major advantages of the method is its reduced computational cost requirements.

II. Experimental site characterisations - Wind structure

A number of differences were detected between flat and complex terrain values of the basic wind characteristics and previous knowledge on this issue acquired in the context of the MOUNTURB project was verified and improved.

At the mountainous sites, it is concluded that both the deterministic and stochastic characteristics of the wind and their correlation with the surface section analysis showed strong evidence of local topography effects. The profile shape, the speed-up, the direction change, the flow tilt angle and the turbulence ratios clearly follow the upwind terrain geometric features.

The wind profile is clearly affected by the upwind fetch inducing local speed-up regions which vary with wind direction. The logarithmic and power law are proved inadequate to describe the vertical wind shear which in complex terrain seems to be less intense than its flat terrain equivalent. The wind vector was found to be strongly inclined in mountainous terrain sites, following the local terrain slope. Vertical deviations of wind direction of considerable size have been observed. Depending on the actual site topography the mean flow field may be significantly distorted in the transversal direction. The effect is stronger at the side-boarders (with respect to the wind direction) of local hills. The turbulence ratios values show that in mountainous terrain, the kinetic energy of turbulence is split to its three components at ratios different than the 1:0.8:0.5 characterising flat terrain. More turbulence energy is now distributed to the transversal and lateral wind components. On the other hand, turbulence intensity seems to take a relatively low value (9% at 10m/s) compared with flat terrain cases and this should be attributed to the over-speeding of the mean wind vector. Noticeable is the variation of turbulence intensity with wind direction, which, however, may be observed in mountainous as well as in flat terrain sites, in the former case due to topography changes upwind, in the latter case due to roughness changes. The measured coherence was found to exhibit the typical exponential decay with increasing turbulence frequency. The decay rates obtained through the application of the Davenport exponential decay model exhibit significant scatter and considerable variation from site to site. The mountainous site of Tarifa appears to experience the more coherent winds (mean value of the decay factor around 2.3), while the corresponding values for Marmari (complex) and Lammefjord (flat) are 8.2 and 5 respectively.

The coastal site of Näsudden was proved to experience a special wind regime, like all the near-shore sites in Northern Europe, where the seasonal variations of the sea temperature have major influence on the meteorological conditions. The wind characteristics vary with height due to the existence of an IBL, the transition height of which, depends on the atmospheric stability. Parameters describing the turbulence structure in the fully developed surface layer (i.e. turbulence ratios and length scales) have similar values to these reported for flat terrain. Near the transition height of the IBL, a large scatter is observed for most of the parameters.

The individual power spectra computed for the different measuring locations at Marmari, using the length scale value for normalising the frequency, showed evidence of transfer of turbulent energy in the frequency domain as the flow accelerates from the flat plate to sloping terrain and to the hill crest. A general remark is that the energy containing region potentially includes contributions from various in-homogeneity (turbulent - producing) sources which produce the observed flat distribution.

The von Karman spectra does not seem applicable in the fully developed surface layer at the Nasudden site whereas the Kaimal formulation fits quite well and this is also true for the flat Lammefjord site in Denmark.

III. WT characterisations on sites of operation - Experimental Complex terrain WT parameter identification

The experimental investigation of design aspects and design options for wind turbines operating in complex terrain was based on extended experimental research applied on the different project machines. The selected wind turbines cover a wide range of design options currently followed by the manufacturers. The applied experimental techniques are well beyond the current practices, as presented in existing standards or followed by certification bodies or the manufacturers, in terms of the quantity of the measured wind, operational and load magnitudes as well as the acquired experimental data volume. This strategy resulted in consistent, well defined, and totally comparable experimental data bases that supported the following tasks:

- description of the performance and loading characteristics of each type of wind turbine in full correlation with detailed description of the incoming flow

- research on parameter identification on the wind related magnitudes that affect wind turbine fatigue loading

- assessment of wind structure and wind climate effects on wind turbine loading in the macroscopic view of yearly based accumulated fatigue loading

- assessment of the design options, namely size and control strategy, in terms of loading

- calibration and verification of the numerical models that were used in parameter identification and design study research

Within the framework of the present project extensive wind measurements were performed and the resulting data bases allowed for the detailed description of wind structure models, specific for complex terrain sites. The models treat all the main parameters, namely mean wind speed, wind speed distribution shape, mean turbulence at high wind speeds, lateral and vertical turbulence components as related distributions of normal or Weibull type. The parameters that describe those distributions are estimated from the exact measurements and they are considered as descriptive of complex terrain sites. The variation of those parameters allow for the prediction of the changes, in wind turbine component damage terms, in relation to the level of complexity of a specific site.

Detailed results of the work are presented in the respective sections of the report and the main conclusions drawn are that the wind climate as described by the mean wind speed and the Weibull shape parameter k, along with the standard deviation of the longitudinal wind speed σ_u, and the turbulence ratios σ_w/σ_u and σ_v/σ_u are the main fatigue load drivers. Their effects are quantitatively comparable in most of the wind turbines and load cases. It is noted here that the site specific absolute value of σ_u is of importance and directly proportional to the fatigue loads. The turbulence ratios σ_w/σ_u and σ_v/σ_u were found to be higher than the values for flat terrain and directly proportional to the fatigue loading. In addition the Weibull shape parameter was less than the typical value of 2 (Raleigh) in all complex terrain sites examined and responsible for great increases in fatigue loading. The smaller the Weibull shape parameter value the greater the increase in fatigue loading on the wind turbines. This last conclusion is of major importance given the fact that it was discovered during the project research and that this is the first time that it is reported.

Finally, the results allow for the estimation of damage change, and consequently for the prediction of lifetime change, on a specific wind turbine component in case of implementation of the same machine on sites with a specific complex terrain wind structure. This outcome is a valuable tool for manufacturers and developers as well as for standardisation bodies as the issue of site dependent wind characteristics effects on wind turbine lifetime is documented with the experimental results of the present project.

IV. 3D coupled wind field model (wind structure generation) development and semi-empirical Complex terrain WT parameter identification - Design Study

Three medium size machines and two large size machines of different control strategies (stall or pitch regulated, constant or variable speed) have been modelled in this project, in an attempt to evaluate the validity of the application of existing simulation codes in complex terrain and to quantify the influence of the wind conditions on the machine loading.

The code validation phase has shown that reliable results can be obtained if the machine data, structural and aerodynamic, are properly gathered and tuned. Failure, whenever encountered was always related to the limited understanding of the 3-D rotor aerodynamics.

The modelling and PI work on the wind turbines showed that apart from the standard deviation of the wind speed, which has been identified as the main fatigue driving mechanism, the length scale of the longitudinal wind speed is the only serious fatigue driving mechanism, among those describing the stochastic part of the wind inflow. This is not clearly supported by the experimental results where length scales have a secondary effect and the turbulence ratios σ_w/σ_u and σ_v/σ_u are of greater importance. No clear result could be drawn for the influence of the spatial cross correlation of the wind speed on the wind turbine loading.

The above imply that either the length scale calculation methods and the suitability of the von Karman spectrum in the low frequency part has to be re-examined, or that the way that the modeling was performed (i.e. changes in one parameter of the inflow while the other parameters were kept constant) is not representative of the reality in which all inflow parameters change together. The second argument is more appealing given the good agreement of WT model and measurement results obtained during the WT model development.

Finally, for the specific wind turbines no clear results can be drawn regarding the control strategies and the design concepts employed. The use of some “soft” components (tower, drive train, blades) contributes clearly to a redistribution of the fatigue loading of the wind turbine. However, if this is not taken into account from the design phase of the machine, it is not evident that posterior modifications can ameliorate the performance and the reliability of the wind turbine.

MAIN CONCLUSIONS OF THE PROJECT

The main conclusion of the project are summarised as follows:

- The modelling of mean wind field over complex terrain is feasible by various models, especially by those that incorporate more accurate physical descriptions like 3D N-S and 3D boundary layer models. The success of the models is strongly connected to the exploitation of COMTERID extensive wind measurement data base, in terms of model parameter definition and validation.
- The description of complex terrain regarding wind structure deterministic and stochastic parameters is, due to the work performed within COMTERID, mature enough in order to be exploited in terms of WT design, standardisation and systems application.
- The extensive experimental investigation of the load and power performance of WT of different control strategy and size revealed the sensitivity of the WT to complex terrain characteristics. The higher loading related to complex terrain is a combined result of wind structure parameters, among which the primary are the lateral and vertical turbulence components, length scale, wind shear, wind speed and wind component cross correlation factors, in addition to the effect of wind speed standard deviation.
- The application of advanced statistical analysis methods, like the multivariate regression analysis used within COMTERID, proved to be a valuable engineering tool for the:
  a) Parameter identification research on extensive experimental data
  b) Enhancement of the exploitation capabilities of experimental data with feasible projection to different WT operating conditions, that are not experimentally covered
  c) Potential use as part of typical WT testing, verification or certification tasks

   d) Definition of models that describe the correlated parameters of the complex terrain characteristic probabilistic distribution
   e) Correlation of WT component fatigue to wind structure distribution parameters and prediction capability of the expected fatigue at different sites
- The modelling of 3D turbulent wind field time series, using the wind structure parameters that were verified by the extensive COMTERID experiments, proved to be essential for the modelling of WT operating in complex terrain fields
- Aeroelastic codes, verified by extensive experimental data, proved to be capable of predicting the WT response at the desired conditions. The experience gained after the heavy use of aeroelastic codes will support the systematic and common practice within code verification, design and WT certification fields.
- The design aspects and options assessment, based on the experimental data and the associated statistical analysis results along with the aeroelastic simulations, revealed the specific behaviour of WT of different control strategies under complex terrain conditions. The assessment also showed that there is a large field of WT optimisation.
- The data bases collected within COMTERID is a valuable tool for WT industry, standardisation and certification bodies in terms of background information for complex terrain applications.

EXPLOITATION PLANS AND ANTICIPATED BENEFITS

The deliverables of the project were according to the JOULE specification, ie 6 month interim progress reports, detailed yearly reports corresponding to the work according to the project schedule, and a final report detailing the research work and its achievements.

The knowledge of the Complex Terrain environment and its effects on different Wind Turbine Technologies in relation to the known results from Flat Terrains, will lead to the establishment of the required basis for the development of guidelines for the design adaptation, construction, maintenance and operation of the machines. The project produced output that indicate directions for new machine concepts, specifically for complex terrain operation, that will be both <u>technically and economically efficient</u>. Additionally the full 3D wind fetch acting on the rotor disk, based on the reality of these regions, will provide inputs to the basic assumptions of the design of these units.

- Knowledge of the *Full 3D Wind Fetch* acting on the rotor disk of different size WTs (driving force) on Complex Terrains. Knowledge of the *Operational Characteristics* (Power Production and Loading) of Wind Turbines of different design concepts and sizes operating in Complex Terrains.

- Knowledge of all the Operational Characteristics compared with operation in flat terrain, would form the basis for the establishment of *design standard guidelines* for Wind Energy Applications in *Complex Terrain Regions*. In addition it will provide inputs for *adaptations of existing WTs* which will ease the existing increased machine failure situation.

- *Measurements* reports containing all the relevant characteristics of wind turbine operation in highly complex terrains (Wind - Machine - Grid), for a number of wind turbine technologies and sizes, *will become available to both the Wind Industry and the Users*.

- The influence of the complex terrain environment to the machine response is *identified and quantified* through systematic experimentation and modelling. The sensitivity of the Wind Turbines performance in respect to the wind and machine design parameters is studied for the first time. Guidelines for a *complex terrain oriented design procedure* or *adaptation of existing designs* may be then established on a cost-effective basis.

- *Design options available to accommodate the complex terrain environment and its particularities*.

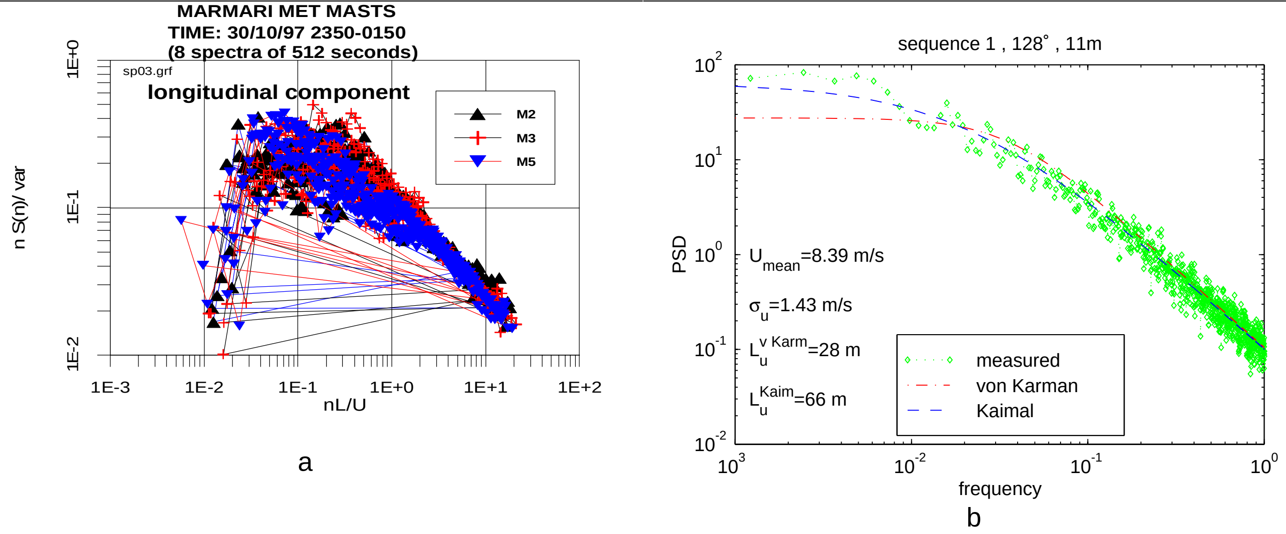
The results of the project will be of *great value to the certification centres* CRES, ECN and RISO and will be published so that every other certifying authority could have access to them. The interest shown by the manufacturers of the WTs shows the need for actual WT measurements operating on a multitude of terrains and environments.

The combination of the measurement results, will produce an extended range of regions and terrains (flat, simple, mountains, very complex topography), and operating conditions for probably the largest base of climates and conditions encountered in WT operation. The fundamental differences in wind turbine operation, thought to be the result of the complicated wind structure prevailing in mountainous terrains, can now be classified and will provide the basis for a new Design Load Spectra adhering to the reality of the regions. The application of design/modelling tools, after the extensive verification done by the partners, results to the classification of their scope of application as WT design tools and provide the required verified tools for the Design Investigation.

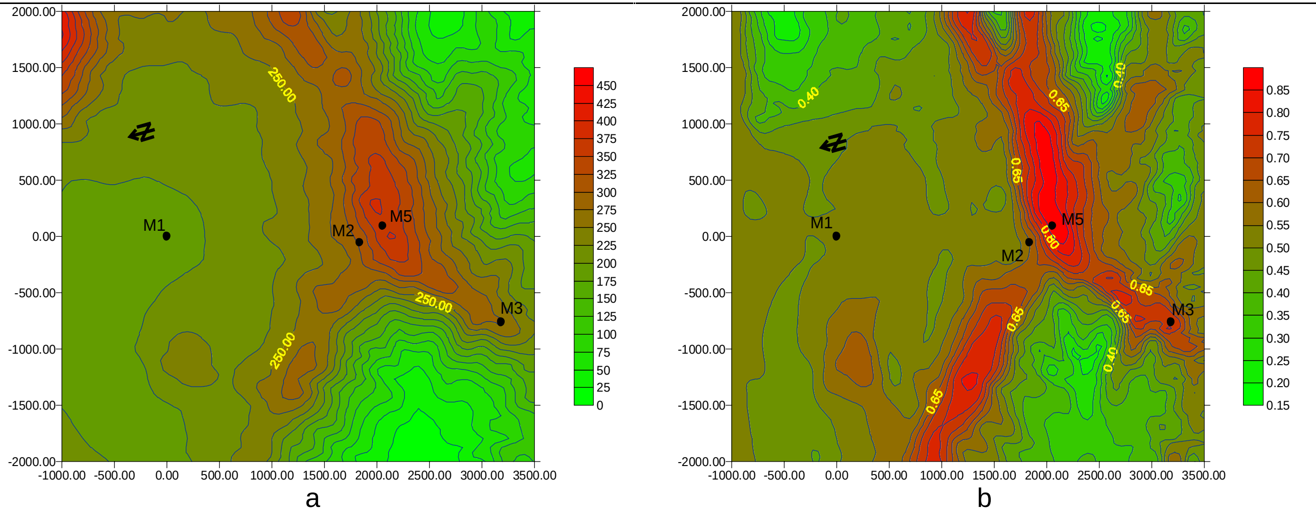
The project' *results will be directly applicable by the WT manufacturers* involved, on their respective WTs. In addition the project results will be made available to CEN/CENELEC to *support the European Standards Work*.

The *R&D outcomes of the project will be further disseminated* through Journal and Conference publications and will be reported through the regular meetings of the European Wind Energy Association meetings and conference proceedings.

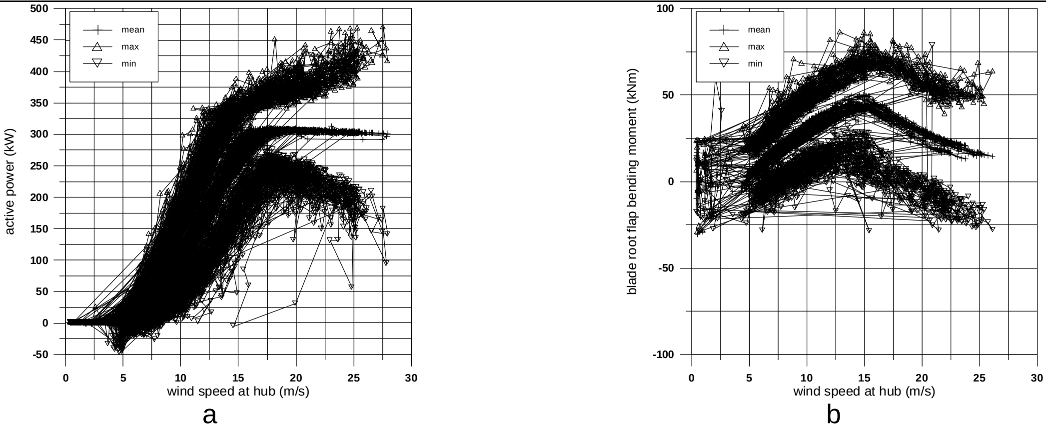
ILLUSTRATIVE FIGURES



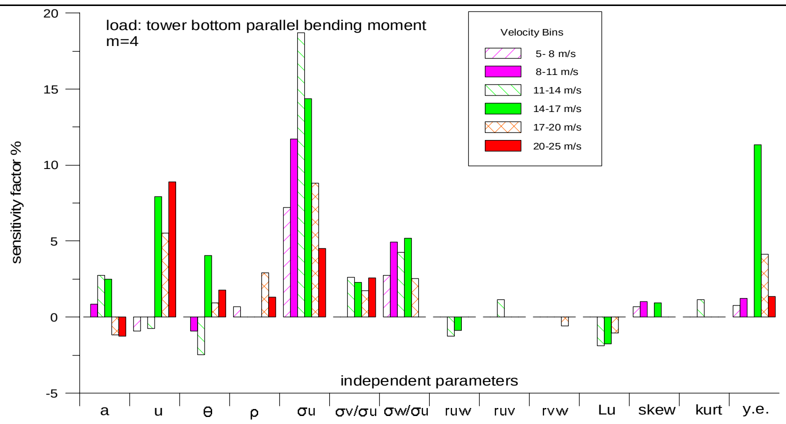
Samples from Marmari complex site (a) and Nasudden flat site (b) wind measurements data bases.



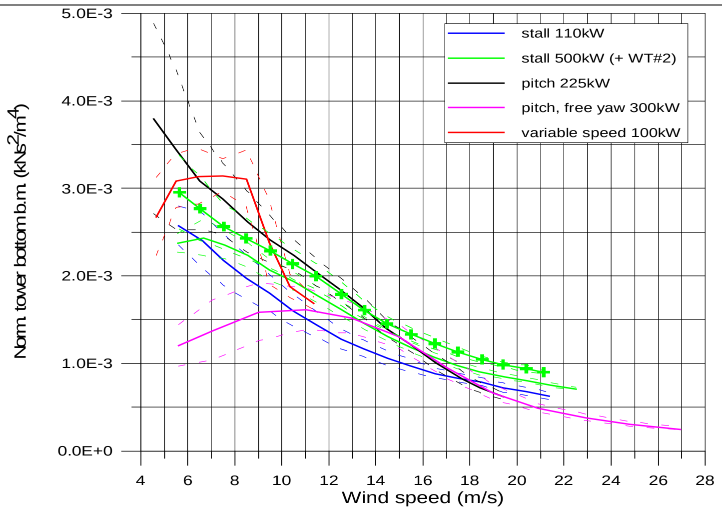
Boundary layer simulation of the flow field over Marmari site
(a. topography contours, b. normalised longitudinal velocity contours at 34m a.g.)



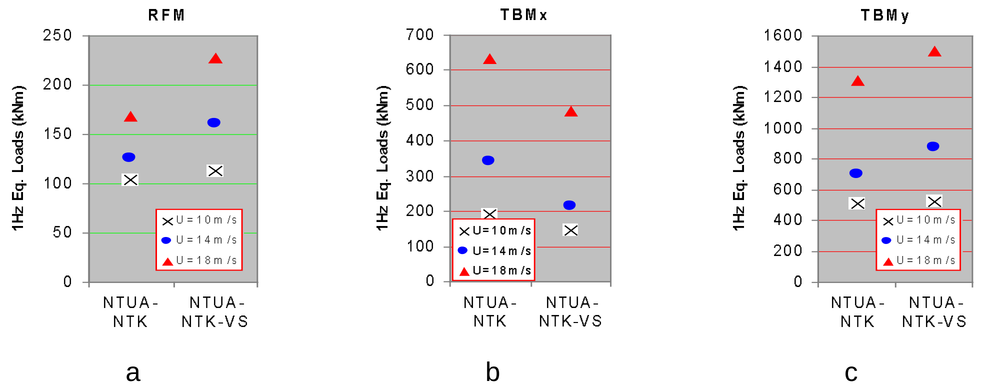
Sample from the experimental campaign for the 300kW pitch regulated, passive yaw wind turbine operating at Marmari complex terrain site. (a. power , b. blade root flapwise bending moment)



Sample from parameter identification procedure for 300kW pitch regulated, passive yaw WT. Sensitivity of tower bending fatigue loads to wind characteristics.



Sample of assessment of design options in terms of tower bottom bending moment.



Sample comparison of fatigue loading for a 500kW stall regulated wind turbine for different design option (variable speed version).
(a. flapwise b.m., b. tower bending moment lateral, c. tower bending moment axial)

ANNEX A: LIST OF ISSUED REPORTS AND PUBLICATIONS

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Carlen I. et al. (1998): "Characterisation of the Nasudden site in Sweden", Teknikgruppen AB report.

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Cuerva A. et al. (1996a): "AE-30 Wind turbine operating at Tarifa site", CIEMAT internal report.

Cuerva A. et al. (1996b): "Fuerteventura as flat terrain, Tarifa as complex terrain Wind structure analysis", CIEMAT internal report.

Cuerva A. et al. (1996c): "MADE AE-30 Power performance assessment", CIEMAT internal report.

Cuerva A. et al. (1996d): "Multivariable analysis on Power in complex terrain", CIEMAT internal report.

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Foussekis D. (1996): "Characterisation of the WINCON 110XT wind turbine at Lavrio", CRES internal report.

Ganander H. (1998): "Nordic 1000 characterisation at the Nasudden site", COMTERID report, Technikgruppen AB.

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Kossivas T., Morfiadakis E. (1997): "Characterisation of TACKE 550kW WT operating at Toplou site", CRES internal report.

Ladakakos P., Chaviaropoulos P., Vionis P. (1997): "Level crossing theory for estimating the frequency of wind turbine start-ups, shut-downs and other extreme wind conditions", CRES internal report.

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Mouzakis F., Morfiadakis E. (1996a): "Characterisation of NORDTANK NTK500/37 operating at Toplou site", CRES internal report.

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Mouzakis F., Morfiadakis E., Fragoulis A. (1996c): "Characterisation of VESTAS V27 operating at Andros site", CRES internal report.
Papadopoulos K., Morfiadakis E. (1998): "Characterisation of HMZ-300kW operating at Marmari site", CRES internal report.
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Petersen S.M. et al. (1997): "Load Measurements on a Pitch Regulated Wind Turbine in Inhomogeneous Terrain Sky River - Vestas V39", Risø-I-835(EN).
Riziotis V., Voutsinas S. (1999): Fatigue loads on wind turbines of different control strategies operating in complex terrain", Submitted to the Journal of Control.
Voutsinas S. (1998): "COMTER.ID: Investigation of design aspects and design options for wind turbines operating in complex terrain environments", Final Report, NTUA, Fluid Section.
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