LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
FACULTY OF TECHNOLOGY
BIOENERGY TECHNOLOGY

MASTER'S THESIS

OPTIMIZATION OF WIND BLADE DESIGN INCLUDING ITS ENERGETIC CHARACTERISTICS

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ABSTRACT

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Optimization of wind blade design including its energetic characteristics

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The goal of the Master's thesis is to develop and to analyze the optimization method for finding a geometry shape of classical horizontal wind turbine blades based on set of criteria. The thesis develops a technique that allows the designer to determine the weight of such factors as power coefficient, sound pressure level and the cost function in the overall process of blade shape optimization. The optimization technique applies the Desirability function. It was never used before in that kind of technical problems, and in this sense it can claim to originality of research. To do the analysis and the optimization processes more convenient the software application was developed.

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Lappeenranta, May 2010
Daniil Perfiliev

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ABBREVIATIONS

HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
O&M	Operation and maintenance
RTM	Resin transfer molding
BEMT	Blade elements moments theory
TE	Trailing edge
Inf	Inflow noise
LFC	Loss factor correction

LIST OF SYMBOLS

a	Axial induction factor	
a'	Angular (tangential) induction factor	
A	Coefficient of Weibull distribution	
AEP	Annual energy production	[MW*h]
b_{rotor}	Fixed cost	
B	Number of blades	[units]
c	Aerofoil chord length	[m]
c_{av}	Average chord of the section	[m]
c_o	Speed of the sound	[m/s]
C_L	Lift coefficient	
C_D	Drag coefficient	
C_P	Power coefficient	
C_{rotor}	Relative cost of the blade	
COE	Cost of energy	
d_i	Desirability function parameter	
f	Frequency, function	[Hz]
i	Angle of attack	[deg]
I	Turbulence intensity	
k	Coefficient of Weibull distribution	
K	Empirical coefficient	[dB]
L	Turbulent length, section lengh	[m]
L_p	Noise level	[dB]
M	Mach number	
M_{tot}	Total mass of the original blade	[kg]
m	Section mass	[kg]
N	Number of blade elements	
P	Power, perimeter	[kW], [m]
$prof$	Profile type	[string], [numb]
Q	Tip loss correction factor	
r	radius and radial direction	[m]

R	Blade tip radius	[m]
Re	Reynolds number	
T	Annual working period of wind turbine	[hours]
S	Compressible Sears function, surface area	[m^2]
V	Absolute velocity	[m/s]
V_r	Sectional speed	[m/s]
w_i	Parameter's weight in the overall optimization	
w_{rotor}	Parameter of variable costs	
x	Axial coordinate	[m]
z	Height of measurement or tower	[m]
z_o	Surface roughness	[mm]
β	Relative flow angle onto blades	[deg]
γ	Twist angle	[deg]
λ	Tip speed ratio	
λ_r	Local Tip speed ratio	
η	Mechanical/electrical efficiency	
ρ	Density	
σ	Local Solidity	
Ω	Blade rotational speed, mathematical region	[1/s]
ω	Wake rotational speed	[1/s]
ε_a	Relative difference for axial factor	
ε_a	Relative difference for angular factor	
δ^*	Boundary layer displacement thickness	[m]
δ	Material thickness	[m]
μ	Air viscosity	[Pa*s]

1 INTRODUCTION

The goal of the Master's thesis is to develop and to analyze the optimization method for finding a geometry shape of classical horizontal wind turbine blades based on set of criteria. Nowadays the most used search criterion is a minimum cost of annually produced energy. Considerations of the wind turbine power and noise exposure so far have received less attention. The thesis develops a technique that allows the designer to determine the weight of such factors as power coefficient, sound pressure level and the cost function in the overall process of blade shape optimization.

The analyzing block of the optimization process includes calculations of aerodynamic parameters of the blade, sound pressure level, costs of materials needed for blades production, annually produced energy and analysis of wind conditions at a given site.

To determine the power coefficient we use the classical moment theory and blade is divided into sections. An important simplification is that this aerodynamical parameter assumed to be constant in the whole range of speeds, and that in fact, of course, untrue. A basis of the sound pressure calculation methodology is the semi-empirical model developed by British and Danish scientists. The cost calculation model takes into account the relative materials consumption needed for the blades manufacture, and the produced during the reporting period energy. It was also necessary to include a block of the wind condition analysis, so to find the parameters of Weibull wind speed distribution function and to consider the proposed wind turbine installation site. The optimization technique uses the Desirability function. It was never used before in that kind of technical problems, and in this sense it can claim to originality of research.

To do the analysis and the optimization processes more convenient the software application was developed. It allows to make analyzing and optimization calculations in the semi-automatic mode and to receive the results in tabular and graphical form.

2 STATUS AND TRENDS OF BLADES PRODUCTION FOR WIND GENERATORS

2.1 The evolution of rotor and blades design

The purpose of this paragraph is to present a historical view on the evolution of blade design during the last decades. This evolution has been a balance between economic, aerodynamic, noise, and aesthetic considerations.

For the last quarter of the past century the wind energy development gave the opportunity to experiment with the variety of turbine designs and materials that through trial and error, has lead to the trade-off, three-bladed composite blade configuration. The history of this evolution should be studied and documented to minimize negative regressions in the future blade prototypes.

The wind blade design process includes choices of materials, blade number, airfoils, chord and twist distributions. Each of these choices often involves conflicting situations that need to be prioritized. For example, thin airfoils are good for their high lift ratios and don’t care so much about roughness, whereas thick airfoils don’t have some of these qualities to provide greater blade solidity required for large machines. The pros and cons of these features have to be examined to understand the current state of blade design.

Some regular blade design trends that are provided by the increased blade radius are lower blade stiffness, increased airfoil chord, and maximum lift coefficient, along with additional growth in tip speed. The trend limits need to be explored in order to reach the best variant of the blade shape.

2.1.1 How it all began

The rise of the wind energy industry during the 1970s began with a trial-and-error experimental process with various blade configurations. Variety of horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) were built than. There were upwind and downwind HAWT prototypes with different diffuser and concentrator constructions. Among vertical-axis wind turbines there were machines of Darrieus and

Savonius type. The goal of wind industry development during the 1980s was cost effectiveness of energy production, which influenced on many of the early proposed wind turbine schemes. Although the vertical machines have the advantage of a drive train located on the bottom, their cost-effectiveness is below of that of the horizontal machines for reasons not fully documented. VAWT utilizes aerodynamically less efficient symmetric profiles that are worse than the twisted profiles with higher lift-to-drag ratio, used on HAWT. The blades of vertical turbines use constant chord distributions and thus have a negative effect on efficiency and start features. (Tangler, 2000)

Blade losses of the VAWT are greater than those of HAWT, because VAWT operates at the optimum lift-to-drag ratio and has a small rotation angle. That is why the excessive wind energy goes into fatigue loads rather than for useful energy production. The high power output provided by VAWT rotors also produces higher fatigue loads. In addition, the VAWT lack of tower height diminishes most of the additional energy available higher up due to wind distribution. In comparison to a HAWT, a VAWT also produces energy on a lower-rpm speed that gives power more from torque than rpm. That results in greater turbine weight and expenses. (Tangler, 2000)

For HAWT the increase in blade radius gave greater cost-effectiveness than the use of different concentrators or diffusers. Most of them made it difficult to cost effectively address the hurricane load conditions. Cost considerations also made the two- and three-bladed turbine configurations popular. The two-bladed rotor type has lower expenditures but more complicated load, which influence on reliability negatively. (Tangler, 2000)

2.1.2 Present time

Reliability, noise, and aesthetic considerations are one of the main features that push the evolution of HAWT wind industry nowadays. Based on these criteria, the choice for wind turbine configuration of the last several decades was the upwind, three-bladed rotor. The moderate-size, lightweight, two-bladed teetering rotors, may still, however, find a market niche in areas where installation equipment is not usually available.

Let's now consider the main drives in various fields of blade production process.

Number of blades

For large wind turbines projects, the upwind, three-bladed rotor is the most popular configuration. Almost all large aggregates installed during the last decades are of this type. The three-bladed rotor has several advantages over the two-bladed rotor. Although the upwind turbines are preferred because of the lower noise, it is also provides lower blade mechanical loads. Tower-shadow noise and unstable blade loads for the upwind rotor are lower than for a downwind rotor. For the upwind rotor the choice of blade number is a compromise between blade stiffness of tower clearance, aerodynamic efficiency, and unstable noise of tower shadow. The three-bladed rotor construction introduces the best variant. For a considered radius and profile thickness more blades have lower blade flap solidity. Three blades configuration has the flap stiffness that is enough to avoid tower breakdowns, and the loads of blades are low enough to avoid undesirable noise. Aerodynamic efficiency increases with increasing number of blades. But this dependence is not linear.

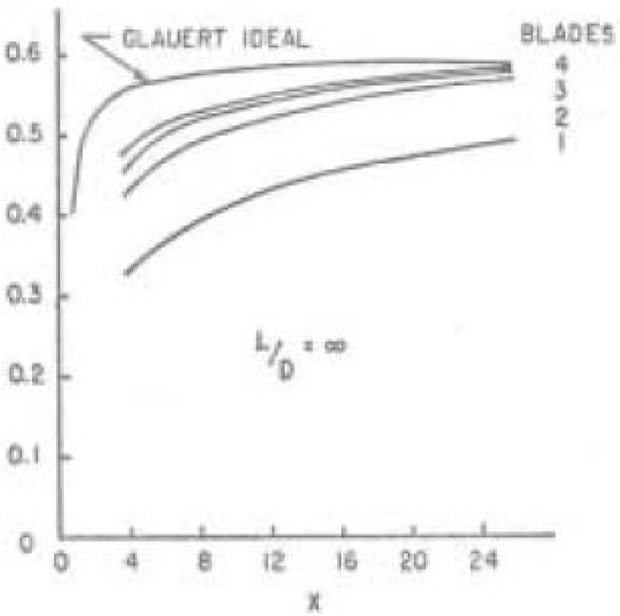


Figure 2.1.2.1 Aerodynamic efficiency versus tip-speed ratio (Tangler, 2000).

Blade number increase from one to two gives a six percent increase in aerodynamic efficiency, whereas increasing the number from two to three achieves only an increment for three percent. Further enlargement of blades number enlarges the blade stiffness too much, but slightly improves the aerodynamic performance. (Tangler, 2000)

The noise and visual considerations strongly insist on the choice of three blades rather than two or one. A three-bladed rotor has two benefits that relate to the noise exposure over another number of blades. For a fixed turbine diameter and stiffness, a three-bladed rotor will experience two-thirds of the blade loads of a two-bladed rotor and one-third that of a one bladed rotor. As a result, a three-bladed rotor will create lower unstable noise from blade rotation. In addition, for constant noise intensity at a fixed rotor rotation speed, the three per revolution sound is less disturbing than the two per revolution sound. (Tangler, 2000)

To have the same aerodynamic efficiency, one- and two-bladed wind turbines are constructed with lower blade solidity and higher tip speeds for a fixed diameter or power of the same three-bladed rotors. The higher rotational speed causes more noise. It is proportional to the fifth power of the tip speed. Some people also think the three-bladed rotor to be more aesthetically beautiful than a one- or two-bladed rotor. This is connected to the more unpleasant visual effect of fewer blades. The two-bladed rotor rotates with an unstable motion in contrast to a more smoothly motion of the three-bladed turbine. (Tangler, 2000)

Another fact that popularizes three blades is a more balanced rotation. As the interval between the blades is 120 degrees, the rotational physic is softer than for the 180 and 360 degree interval corresponding with two- and one-bladed rotors. Additionally, two-bladed rotors are more sensitive to one per revolution rotor mass-instable pulsation. Softer three-bladed rotor dynamics results in lower O&M cost.

Airfoils

Airfoils are one of the more difficult and misunderstood topics of wind blade design process. Performance characteristics and chords used for airplane profiles are not necessarily applied for wind turbine profiles. However, both the aviation and wind turbine profiles benefit from long laminar flow and the relative low drag coefficients. Experiments with commercial wind turbines during the 80s explored most of the unuseful operational characteristics of NACA 44XX, 63XXX, 230XX and NASA LS series profiles. The

NACA airfoils were introduced before the World War II, the LS (1) series during the beginning of 1970s. All these profiles are good in implementation with high Reynolds numbers and have a bad use in the cases of lower Reynolds numbers, because of extensive laminar separation bubbles. In various roughness conditions the large variations in profile performance can be caused by these bubbles. These airfoils also have inadequate chord distribution in the root region because of the mechanical loads requirements of high flap solidity for tower clearance and efficient use of the material to implement high twisting moments. (Tangler, 2000)

Another parameter desirable for wind turbine profiles is minimal sensitivity of the maximum lift coefficient to the conditions of roughness. That is especially important for stall-regulated wind turbines. Projecting for roughness insensitivity is only possible through the implementation of the modern profile design methods by the experienced profile designers. Airfoils designed not so long ago experience the turbulent flow along its upper surface almost until the maximum lift. Figure 2.1.2.2 shows an example of this design for the airfoils developed for large wind turbines.

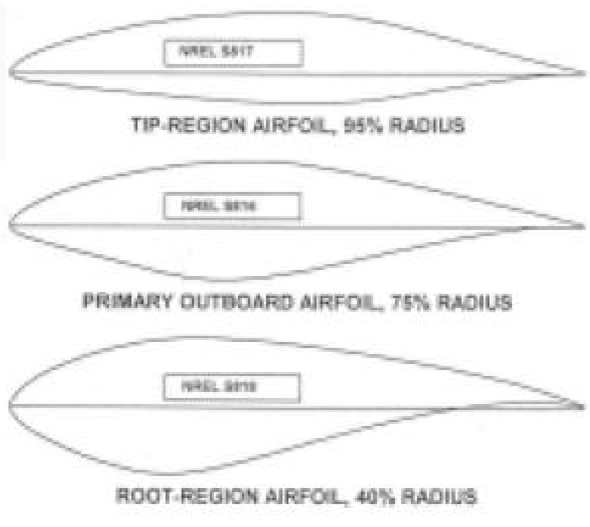


Figure 2.1.2.2 Profile family (Tangler, 2000)

It the 80s extra peak power was another difficult problem for fixed-pitch stall-regulated wind turbines that gave the high drive train mechanical loads and failures of generator. To transform the blades to more stall was not a satisfactory solution, because it controlled peak power along with higher blade mechanical loads, wake-induced losses and lower aerodynamic efficiency. A more useful approach is to apply the low-maximum-lift tip profiles to control peak power passively. It also increases the overall performance characteristics. (Tangler, 2000)

Additional lessons about ideal airfoil characteristics were implemented in the 90s. Desirable profile characteristics were found to be dependent on machine type and blade size. Small- and medium-size stall-regulated turbines benefit from the implementation of low maximum-lift coefficient in the blade tip to decrease the peak power. For very large turbines, blade weight and cost increase faster than energy production. (Tangler, 2000)

Weight and cost increase proportionally to the 2.4 power to the radius, while energy production increases proportional to the second power to the radius. Based on this, large rotors have to use profiles of greater chord and higher maximum lift to decrease the weight and cost of the blade. For constant-speed turbines, especially stall-regulated ones, there are expenses because roughness sensitivity increases while profile thickness and stall characteristics diminishing with increasing maximum lift coefficient. These unwanted factors are minimized with variable-speed rotors. For small turbines high maximum lift is not significant. Low maximum lift of profiles provides a soft stall, and the relative increase in blade stiffness has a minimal effect on blade cost. (Tangler, 2000)

Thin profiles can be used with small rotors, for variable-speed turbines that allows controlling peak power, thick profiles are used to avoid tower strikes and blade pulsation at high azimuth angles and the high speed of rotation. Small machine profiles must be developed for low Reynolds numbers to avoid undesirable laminar separation bubbles that cause the excessive drag, inconsistent maximum lift, and annoying noise. (Tangler, 2000)

Blade Geometry

Nowadays the blade geometry optimization criterion is based on minimizing the cost of energy production. In the past it was a maximum annual energy production. To reach a minimum cost of energy the design process implements multi-disciplinary methods that use an aerodynamic model, a material model for the blades, noise consideration, and cost models for the blades and all main wind turbine components. The blade design process also becomes dependent on the wind turbine and the installation site. As an example, it can be the design of a blade shape for given wind speed with a constraint on the maximum root-bending moment. (Tangler, 2000)

For very large machines optimization on the cost-of energy considerations can lead to a blade with lower stiffness than if it were under maximum annual energy considerations. Minimum cost of energy variant also can be gotten with higher rotational speeds, but the speed is limited under the noise considerations. The blade shape estimated with the aerodynamic considerations does not provide variants for an aerodynamic efficient kind of tip. Experiments show that rounding of the blade's leading-edge with a contoured edge (swept tip) gives good characteristics (see Fig.2.1.2.3). Other tip shape geometry (sword tip) is usually implemented for low noise, but it leads to the efficiency reduction. (Tangler, 2000)

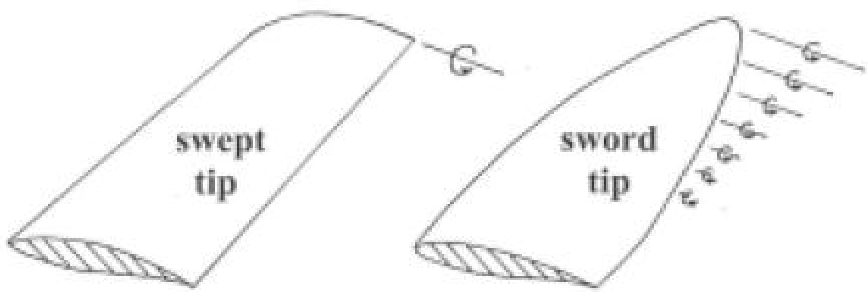


Figure 2.1.2.3 Blade tip shapes (Tangler, 2000).

Rotor Noise

A huge popularity of both small and big wind turbines has contributed to greater attention on minimizing their environmental impact, especially noise pollution. For large turbines, the two most important noise sources are pure tone noise and infrasound noise. Pure tone noise can be related to the design of the blade, while infra sound noise corresponds to large downwind machines. It is inversely proportional to the blades number. (Tangler, 2000)

Pure tone noise is typically related to the blade-tip shape and sometimes to the type of profile. A tip geometry that produces a strong tip vortex, which interacts with a thick trailing edge, generates a pure tone noise at the frequency about 2000 Hz. This noise can be avoided with the swept tip geometry (see Fig. 2.1.2.3) implementing a sharp local trailing edge. Other tips that push the trailing edge forward eliminate noise by diffusing the tip vortex. But the tip drag becomes increased. Profile shape generated pure-tone noise because of significant laminar separation bubbles influenced by the trailing edge. This kind of noise is more probable on small wind turbines, which operate at low Reynolds numbers and wind speeds. (Tangler, 2000). Current noise exposure model is discussed in this paper later.

Materials

During the past decades, blades for the large wind turbine were made from steel, aluminum, and composite materials such as wood, fiberglass, and carbon fibers. For a provided blade strength and solidity, the blade should have a weight as low as possible to minimize inertial and mechanical loads, which result blade fatigue. Steel and aluminum blades experience great weight and short fatigue life relative to the modern blades made from composites. Because of it during the past two decades almost all blades were produced from composite materials, particularly fiberglass.

Carbon fiber has the highest strength-to-weight ratio and solidity, but it has not been promoted because of its high cost, strain instability when it is used along with fiberglass, and some handling difficulties. General resin systems are used in composite materials. It usually includes polyester, epoxy and vinyl ester. Polyester and vinyl ester have popularity because of their lower cost. But currently more blade designers are using epoxy to provide better material features. Epoxy reduces shrinkages, does not brake with ages, and has better fatigue performance characteristics. (Tangler, 2000)

Structural Design

Many small turbines have blades which made from wood, either solid or laminated to avoid brakes over time. Other cost-effective variants made from fiberglass-reinforced composite material. For an example, it can be a pultruded blade that contains a solid cambered plate or a multi sectional profile. Injection molding has also been used in the production of small blades, but it is not so popular nowadays. This method applies resin injection, for example, polypropylene, into the aluminum mold of the blade shape. The blade length limited to less than two meters, because of solidity and thickness parameters. To acquit the high operational costs this process needs to have a big production volume. Small blades are mounted straight to the hub plate. A root joint that has an outer plate is the most used approach because it avoids submitting bolts to experience high bending moments and gives two shear load paths. (Tangler, 2000)

For big turbines blade weight and cost expenses are much more significant things. The larger blades mean lower rpm, reduced centrifugal solidity, increased weight, and greater root bending moments caused by the gravity loads. For large turbines, the edgewise root bending forces become an important design parameter. To minimize weight, the small-turbine, solid-blade construction uses a lightweight, cored blade design method with many load paths. Some structural types for large blades are presented in Figure 2.1.2.4.

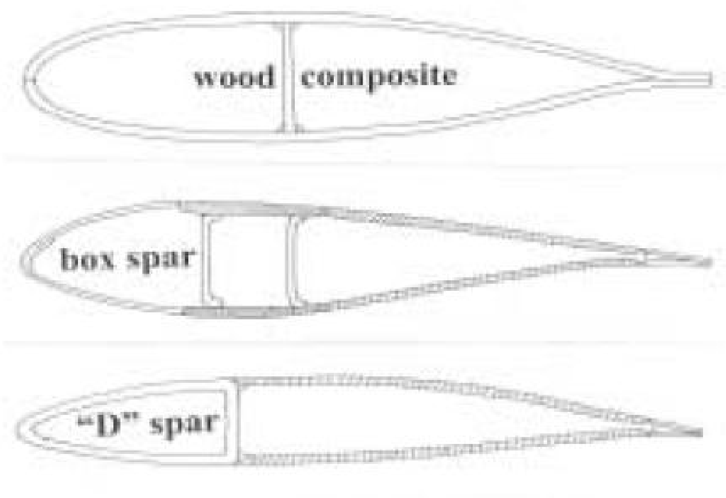


Figure 2.1.2.4 Structural design of large wind blades (Tangler, 2000)

Some blades that implement a monotone structure experience the particular loads along almost linear load path in the blade skin. Wood laminates are not promoted versus compound materials, although it has the advantage of lightweight and significant buckling resistance. It avoids big root twisting and chord variations to perform a better aerodynamic efficiency. (Tangler, 2000)

Another promoted method in the structural design is to apply the main loads to a composite box or "D" spar while the remaining load is experienced by the blade skin. For huge size turbines higher mechanical loads and a lower natural frequency will tend to new structural designs to better correspond the fatigue and dynamic considerations. An upwind twisting of the outer blade spaces may also provide the cost savings and to allow the tower clearance.

New structural design proposals have occurred after the large wind turbine installations in the Great Plains (USA). Fiberglass skin and the leading edge bond were damaged through the storms with large rain ice drops. Some problems may be solved by stopping of the turbine blades with minimum vertical exposure. Blades that have a solid "D" spar or a bond line on the pressure surface may be popular in the cases of the leading-edge bond separation reduction. (Tangler, 2000)

Root Joint

An important design region of any blade is the attachment to the hub. Design of the blade root attachment so far has been strongly depended by the cost considerations, which are typically estimated 20% of the blade cost. In many hub types used in the 80s, the tapered metal root cylinder has been used in various forms. Vestas, the world largest wind turbines manufacturer, designed their blades with an aluminum cylinder in the root. An example of such design and other current root designs are shown in Figure 2.1.2.5.

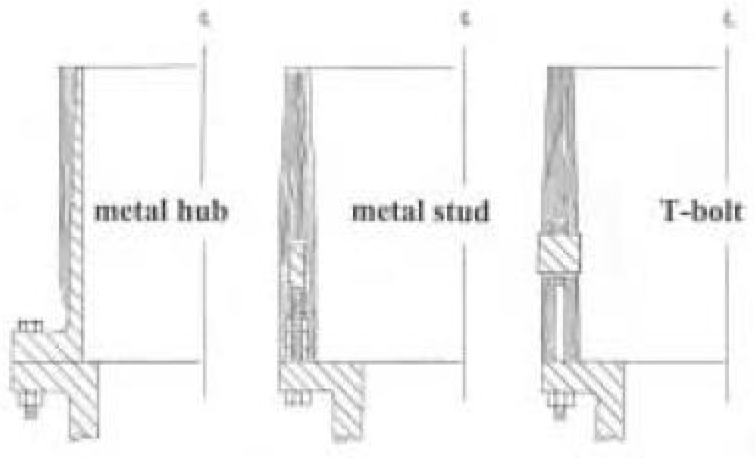


Figure 2.1.2.5 Root design for the large blades (Tangler, 2000)

For the last decades the embedded metal stud and T-bolt forms became more wide spread in the new blade designs. The metal stud root, which was used with the wood blade from composite material, is now applied to fiberglass blades. The metal hub and metal stud root attachment made the fiberglass to experience tension. For the T-bolt root attachment, fiberglass circular bolt inboard is under pressure while that outboard is under tension. Both the metal stud and T-bolt approaches are popular, because it uses a bigger root diameter for a fixed hub flange diameter. It gives more mechanically efficient blade-root attachment. Blades designed for outboard flap solidity, such as Vestas 1.65 MW wind turbine blades, allow to alleviate flap and yaw-drive fatigues. (Tangler, 2000)

A problem when using this attachment form with the upwind turbine is to ensure suitable tower clearance, which is reduces with time as a result of structural creep. In addition to low flap solidity, those used for downwind machines and pultruded blades, two bladed Carter 300kW wind turbine has low torsion solidity. Blades that have low torsion solidity become more probable to flutter, especially during turbine overspeed. To avoid it, the mass of the Carter blade is balanced in the direction of chord. Mass balance can be made by the lead bonding for the leading edge to move the chord wise gravity center forward to the airfoil aerodynamic center. (Tangler, 2000)

It was also interesting for researchers to use low tensional stiffness to have better flap/twist coupling as a way for passive peak power control. Good coupling can be made by fiber orientation and by the blade pitch axis move from the aerodynamic center. For most large wind blades, the pitch and twist axes are placed between the aerodynamic center and the profile maximum thickness. Flap/pitch coupling is found without balance of the chord wise mass because the achieved strong mechanical moment would largely diminish the wanted coupling. Consequently, it is better to avoid the blade flutter when the rotor is occasionally over speeded. (Tangler, 2000)

Manufacturing Methods

Hand Lay-Up

Hand lay-up was the most implemented manufacturing process for wind blades production during the 80s. The cost of such composite blade production approach was about half for labor and half for materials. Multiple fiberglass fabric layers were laid up by hand and filled up with resin separately. However this approach doesn't allow to achieve an optimum ratio of glass and resin. Fiber content was usually 60% of the weight or less versus the wanted 70%. Disadvantages of this method are air pollution and unsuitable work conditions because of the styrene gassing as the resin cures. (Tangler, 2000)

Filament Winding

The Kaman 40kW and WTS 4MW wind turbines were fabricated with filament wound 9.6m and 38m rotor blades. This production approach makes strong wind blades while has low labor cost, but it also has its disadvantages. Filament winding is automated and strands of fiber glass go to a resin bath and then they are placed with an angle around the core. The core is used to fabricate an internal spar or the external shape of the blade. This process applied well with production process of a tubular or "D" spar.

Concave surfaces of the blade, which is due to profile camber or twist, do not allow themselves to use filament winding. In addition, lightweight core shells of the external blade shape are used for filament winding. Filament winding also provides the rough tip surface which is not compatible with good profile performance characteristics. That is why filament winding is suited for tubular interior blade spars that are than molded into it. (Tangler, 2000)

Pultrusion

The costs reduction up to the 50 percent can be achieved by promise pultrusion production process. However, not very good aerodynamic and mechanical efficiencies limited its implementation for large blades production. Blades that were pultruded don't stand against nonlinear twist and tapered distributions of chord. Twelve percent of aerodynamic efficiency is reduced because of it.

Any cost savings are not for sure, although a big part of those losses can be negligee by inboard bonding, cuff twisting and a tip tapering. Secondary bonds may also influence on the blade material reliability. The bigger mechanical instability of pultruded blades makes them undesirable for their implementation in large, upwind commercial wind turbines for which tower clearance is very significant.

For bigger flap solidity and mechanical efficiency the external doublers should be implemented in the root region because there is the greatest bending moment. Pultruded blades produce a cost-of-energy savings in downwind and small machines constructions. There the rotor reliability is more important than the aerodynamic efficiency. (Tangler, 2000)

Resin-Transfer Molding

For labor and resin cost reduction the blades manufacturers use resin-transfer molding (RTM). It was adopted during the past twenty years. RTM provides the quality increase and compliance with air pollution standards. In this approach, the fiberglass layers are laid in the dry mold, which covered with the membrane. The membrane is sealed through the mold perimeter. Then the catalyzed resin is placed between the mold and the membrane. Process uses pressure, vacuum, or both of them. More complicated parts and those with higher quality may have seventy percent of fiber content. Twenty percent or more of the cost savings may be achieved by this production process.

Achieved properties of the material are comparable to expensive prepreg production process. Produced volatile gases are contained and are not released to the atmosphere. It doesn’t create an environmental danger. These are RTM advantages. It can be manufacturing approach for future large wind turbine blades production. (Tangler, 2000)

2.1.3 Prospects for the future

In the future the trended evolutionary processes toward three-bladed, upwind rotors probably will still the same. These design and construction technologies are rapidly growing. Further improvements and convergence toward the various configurations of the three options of stall-regulated, variable-pitch, and variable-speed, can be expected in this future. Blades for large, stall-regulated turbine with flexible, overspeed-control tips are changed for blades with flexible pitch. It provides better reliability and peak-power control.

Movements are being aimed toward improved construction designs, higher energy production with suitable control systems, profiles and power electronics. Higher-quality production processes are being implemented. They also provided the lower blade cost. These improvements should contribute to the reduction of vibrations and loads; to reduce operating and maintenance costs, and to eliminate the costly failures. The variable-speed type of turbine has taken greater market acceptance and share year by year. This approach has greater aerodynamic efficiency, minimal turbulence sensitivity and large coherent eddies, leading power factor, less aerodynamic noise, and lower weight of the tower top. Further development of power electronics and variable-speed generators will one day reach greater overall efficiency than two-speed rotor maintenance. Future improvements in weight of tower top are going through the implementation of a more reliable and single-stage gearbox.

To pursue these machine design trends in the future we need to develop a suitable balance between the controversial aerodynamic, mechanical, economical and noise considerations. This balance is dependent on the machine size, and it puts a huge emphasis on structural efficiency, aerodynamic and natural frequency considerations with increase of the blade size. Big commercial wind blades will require thick and high-maximum-lift profiles with profitable performance characteristics that are also insensitive to roughness effects and have tips with low-noise shapes that do not negatively affect on the performance.

RTM as the best existing manufacturing approach should give a cost-effective, environmentally friendly manufacturing process that results in fiberglass blade with a high strength-to-weight ratio. The potential of further development through solidity tailoring and flap/twist coupling has to be explored to better estimate their effect on O&M costs and the overall cost of energy. (Tangler, 2000)

2.2 Literature review on the optimization techniques of blades design

Global trends of technological progress incline search of the optimal solutions more and more to the simulation, going away from the experiments. The task of the modern practical science is to describe the processes mathematically and to allow the computer software to simulate different situations, and to find, therefore, the best option. This provides considerable savings in the design and introduction of any mechanisms that for sure influences on their production costs. The importance of the adequate preparation of the model can not be underestimated. Such a model is particularly important when designing large and costly mechanisms like wind blades, because the cost of production of one powerful windmill blade could amount to tens of thousands of dollars.

The existing calculation and optimization models allow to take into account some of the operational aspects of wind installation, such as produced power, in other words, power characteristics, noise characteristics and economic indicators of production and operation, as well as mechanical stresses and reliability. Many scientific research models take into account some of these factors, but not many offer a single optimizing technique, which consider all possible components. The applied optimization methods also differ in their complexity and convergence, in other words, in the cost of computer time.

From the author's point of view the most completed and developed methodology in that subject is offered by Danish experts P. Fuglsang and H.A. Madsen from the Danish National Institute RISO. They have been engaged in the design process and in the optimization of wind energy use for many years. In their works (Fuglsang, 1998; Fuglsang, 1999), they divide the design process for the following components:

- Block of initial data. Set the goal function, input parameters, limitations and preliminary design options; wind conditions and structural model of the wind turbine.
- Calculation block. Provides estimations of output parameters of wind turbine for given initial data. This unit will include consideration of operational (noise, power, mechanical loads) and design (economic) parameters.
- Design block. Makes changes in the input design data and provides an optimized variant.

Unfortunately, the format of their work did not allow a detailed explanation of each block and methods of calculation, so the author had to seek third-party sources. Thus, when calculating energy characteristics of the blade, namely the power coefficient, the classical theory of moments for the elements of the blade was applied. Using Grant Ingram (Ingram, 2005) publication the author of this study replicated the method of that calculation. In estimation of economic parameters a substantial assistance had the work of Wang Xudong (Xudong, 2009), which, referring to the publication of Fuglsang, discloses methodology, inherent in his model. The noise calculation model expressed in a scientific publication of Fuglsang and Madsen (Fuglsang, Madsen, 1996).

Unfortunately, the theory of wind turbine noise is still considered not fully investigated. However, assembled from several sources method of calculation, which is promoted by Fuglsang and Madsen, in practical calculations could well be applied. This technique is described in details in the dissertation of Wei Jun Zhu (Zhu, 2004). It states that noise can be decomposed into several, more precisely, into six components that can be calculated separately and then summed up, using physical laws of interference. However, in the earlier publication, Lowson (Lowson, 1993) argues that among these sources of noise there is only two of greatest importance, and practical calculations can be limited by considering only them. In this particular paper the author makes the noise calculations considering only these two sources and doesn’t focus on others.

Choosing the goal function and mathematical optimization model, the author faced with many approaches for solving this problem. In the above-mentioned publications by Fuglsang and Wang Xudong numerical methods for optimization are used. As an objective function they encourage to establish a minimum cost of energy production and the maximum energy produced per year.

Juan Mendez (Mendez, 2009) applies currently wide spread genetic algorithms for optimization process. As an objective function he maximizes the average annual wind turbine power, which is proportional to the produced energy. Moreover, he especially emphasizes that the optimal shape of the wind blade depends on the wind conditions, particular geographic point of use.

An attempt to optimize the distribution of wind blade chord and twist angle in terms of minimization of the produced noise was made by Fuglsang and Madsen (Fuglsang, 1996).

But, apparently, nowhere was the technique of optimization based on several assumptions, the so-called multiobjective optimization. To solve such a nonlinear problem the author of this work had to use the approach described and applied by Boulet et. all (Boulet, 2009) in the article on optimization of the operational activities of the factory. There he refers to the so-called desirability function, introduced by Harrington and further developed by the works of Derringer. From the author's point of view this technique, due to its universality, is the most suitable for considerable problem, because it provides the optimization process that is performed on several output parameters simultaneously.

2.3 Problem statement and methodology of research

The problems alleged to be discussed in this thesis cover a wide range of technical problems. In order to determine the most appropriate shape of horizontal wind turbine blades we need to have knowledge on the aerodynamic, noise, economic and optimization calculations. Applied computational models, although sometimes empirical, have been tested in practice.

Today, as mentioned earlier, there is at least one methodology for such calculations, but the process of optimization is made with single objective function conderation, for example, minimizing the cost of produced energy. The objectives of this study also includes the development and application of a universal optimization method, which could take into account many criteria and prerequisites.

The objectives of this thesis include:

- Description and analysis of the modern methods for calculation the wind conditions, aerodynamic, noise and economic parameters associated with the production and exploitation of wind turbine rotor.
- Development and application of the technique for finding optimized wind blade shape based on the desirability function.

- Design and analysis of the calculation software, which would allow a semi-automated search of an optimized blade shape on the basis of a given set of criteria.

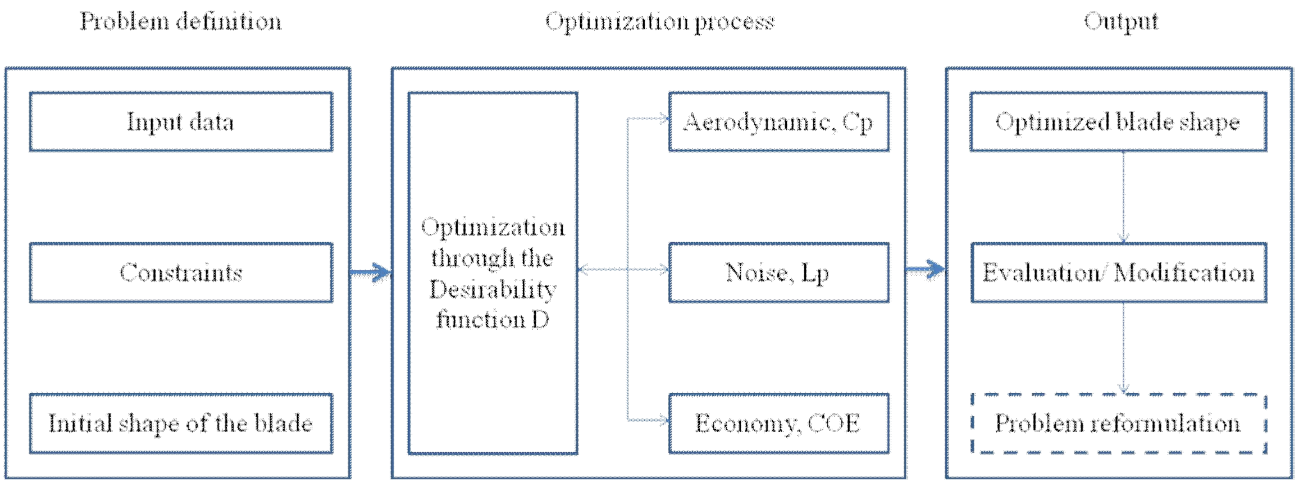


Figure 2.3.1 Block diagram of the wind blade shape optimization process

Each calculating block (aerodynamic, noise or economic) has its own set of initial data. Sometimes they intersect, i.e. used in more than one block. The spectrum of the given initial data is described for each block separately. The structural form of the search for optimum wind blade shape is shown in Figure 2.3.1.

3 MATHEMATICAL DESCRIPTION OF THE DESIGN METHODS

This chapter describes a technical methodology of aerodynamic, noise and economy parameters calculations that are connected to the wind blade production and operation. Those methods or models use approaches of classical and modern researches.

3.1 Model of aerodynamic parameters calculation

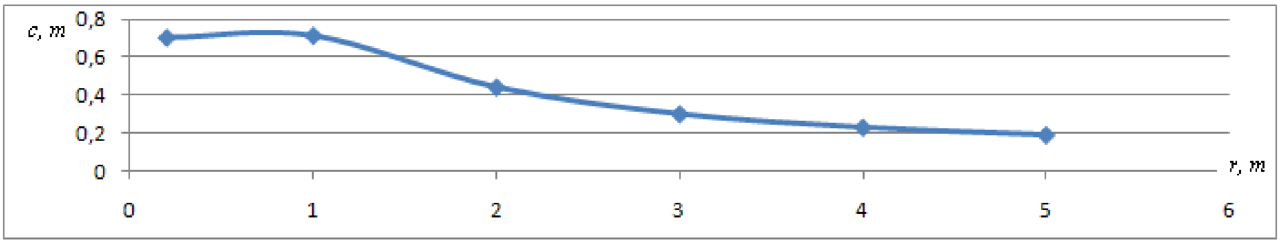
The classical approach to calculate the power factor and other aerodynamic characteristics of wind installation is to use the theory of moments applied to the blade elements (BEMT). It is based on the analysis of the wind wheel from two points. From the one hand the balance of moments in the ring rotating pipe passing through wind wheel is considered, and from the other hand the lift and drag forces acting on the different sections of the blades are analyzed. Using these two approaches we will be given a series of equations that can be solved iteratively.

The detailed derivation of equations and explanations for them are given in a publication by Grant Ingram (Ingram, 2005). Here only some practical results are mentioned that help to explain the process of calculation without going into details. Almost all the equations are taken from that source.

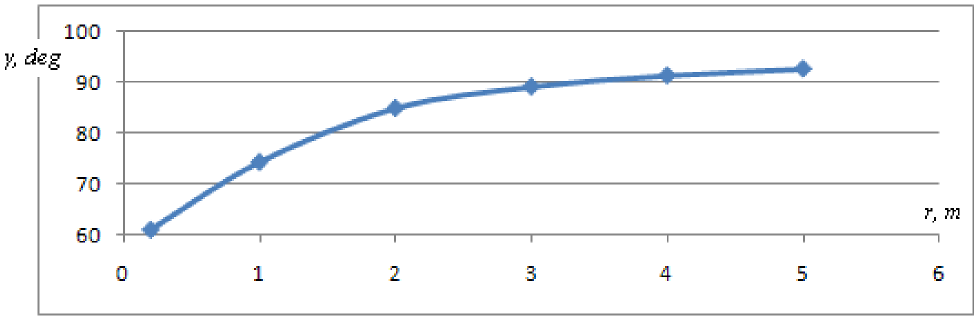
3.1.1 Description of the initial data

In order to carry out the analysis of the wind installation blades we must have a set of initial data. Number of wind installation blades B may vary, but in this paper we consider the classical three-blade horizontal wind turbine, i.e. the number of blades is three.

The entire length of the blade is divided into N sections, and after a certain distance the chord c, the rotation angle γ, as well as the profile of the blade in cross section are specified. Thus, we will be given the functional dependencies $c = c(r)$, $\gamma = \gamma(r)$, $prof = prof(r)$. The typical view of such dependencies is shown in Figure 3.1.1.1:



a)



b)

Figure 3.1.1.1 Example dependencies a) $c = c(r)$ and b) $\gamma = \gamma(r)$

The calculation is performed from the part of the blade where it has the greatest chord and is up to the most distant point. It is a so-called active part of the blade. This condition is necessary in drawing up an automatic process of calculation and optimization of the blade shape, which will be discussed in subsequent chapters.

The profile sections are described either through the name (e.g., NACA 0012), or by their number in the database. More information about the database of profiles will be given later.

3.1.2 Calculation of the induction factors and the relative angle of attack

BEMT is based on two main hypotheses:

- There is no aerodynamic connection between the elements of the blade. In other words, each element or section of the blade can be examined separately.
- The forces acting on the elements of the blade are determined only by lift and drag coefficients.

Therefore, it is possible to divide the blade along the length to the *N* independent sections. Figure 3.1.2.1 shows such a division with the indication of the main dimensional parameters:

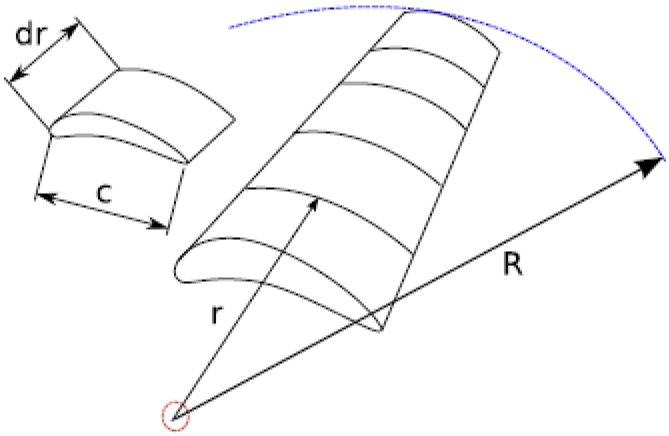


Figure 3.1.2.1 Model of the blade. (Ingram, 2005)

Each element of the blade will experience various effects, because it has a different speed (Ωr), chord (c) and twist angle (γ). Since the sections are independent, we can carry out the calculations of the wind flow for each of them separately, and then, using numerical integration, to obtain the final characteristics of the blade.

The angles in which we are interested are presented in Figure 3.1.2.2:

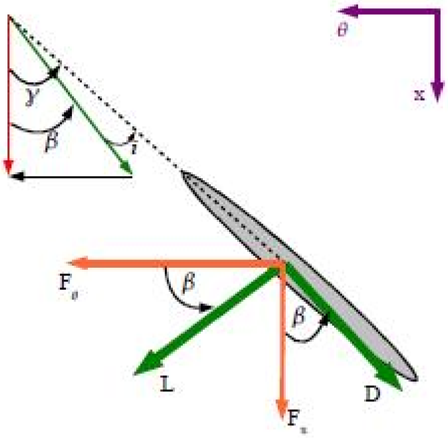


Figure 3.1.2.2 Flow angles and forces for the blade section (Ingram, 2005)

To calculate the characteristics of the blade we use the following two basic equations:

$$\frac{a}{1-a}=\frac{\sigma\left[C_L\sin\beta+C_D\cos\beta\right]}{4Q\cos^2\beta} \tag{3.1}$$

$$\frac{a'}{1-a}=\frac{\sigma\left[C_L\cos\beta-C_D\sin\beta\right]}{4Q\lambda_r\cos^2\beta} \tag{3.2}$$

where

a – axial induction factor

a’ – angular (tangential) induction factor

σ – local solidity, that can be calculated with equation:

$$\sigma=\frac{Bc}{2\pi r} \tag{3.3}$$

where

B – number of blades

c – blade chord

r – radial direction, distance from the blade root to the examine blade element

β - relative angle of atack

λ_r – local tip speed ratio

Q – tip loss correction factor, that is determined by equation:

$$Q=\frac{2}{\pi}\cos^{-1}\left[\exp\left\{-\left(\frac{B/2\left[1-r/R\right]}{(r/R)\cos\beta}\right)\right\}\right] \tag{3.4}$$

C_L, C_D - the lift and drag coefficients respectively. These coefficients are the main experimental parameters of the blade profile. They vary depending on the flow velocity, in other words, on the Reynolds number and the angle of attack *i*. Typical characteristics for the airfoil NACA 0012 is shown on Figure 3.1.2.3:

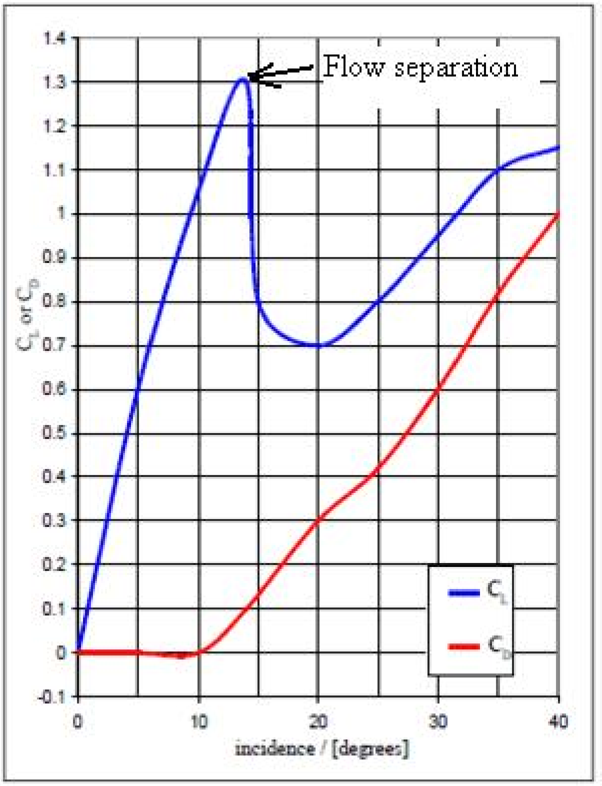


Figure 3.1.2.3 Lift and drag coefficients for the NACA0012 profile. (Ingram, 2005)

In the operational process and regulation of the blade twist angle we try to ensure suitable angle of attack to provide high lift coefficient and low drag. Section on which coefficient C_L is almost a linear function of attack angle is called a workspace. At this section the drag is almost zero. The sharp decrease in the lift at a certain angle of attack occurs at the time of flow separation from the upper part of the blade profile. A further increase in angle of attack leads to the fact that the separated flow in the upper part of the blade creates a great drag.

The calculation starts with the choosing of the wind wheel diameter on the basis of wind conditions and requirements for the output power. Having the power factor C_P equal to 0.4 (approximate ratio for the modern three-blade wind turbine) and the total electrical and mechanical efficiency η equal to 0.9, the radius of the blades can be estimated by using the standard equation:

$$R = \sqrt{\frac{2P}{C_p \eta \rho \pi V^3}} \tag{3.5}$$

where

P – output electric power of wind turbine

ρ – air density, equal under normal conditions 1,225 kg/m^3

V – wind speed on the tower height

Then we should set the tip speed ratio λ. For the three-blade wind turbine λ is given within 4-6 (Ingram, 2005). Choosing the profiles of the blade sections, which can vary along its length, we should provide the experimental characteristics for the lift C_L and the drag C_D coefficients.

Blade is usually divided to 10-20 sections, but some data may contain a larger number of divisions. This only affects on the accuracy of the calculation.

On the first step the preliminary parameters are used. The drag coefficient and losses set equal to zero (the tip loss factor Q in eq. 3.4 is equal to unity). The relative angle of attack, the local density and induction factors are determined by the equations:

$$\beta = 90° - \frac{2}{3}\arctan\left(\frac{1}{\lambda_r}\right) \tag{3.6}$$

$$a = \left(1 + \frac{4\cos^2\beta}{\sigma C_L \sin\beta}\right)^{-1} \tag{3.7}$$

$$a' = \frac{1-3a}{4a-1} \tag{3.8}$$

The lift and drag coefficients are determined from the experimental characteristics for the selected profile and the resulting angle of attack $i = \beta - \gamma$, where γ – the given twist angle of the blade for this section. The first step ends on this.

Then an iterative process begins. We find a relative angle of attack β and induction factors a and a'. To do this, first, determine the new value of the relative angle of attack from the equation:

$$\beta = \arctan\left(\frac{\lambda_r(1+a')}{1-a}\right) \tag{3.9}$$

Then a new angle of attack $i = \beta$-γ. From the profile characteristics we determine the coefficients C_D and C_L. Calculate the new values of induction factors:

$$a = \left(1 + \frac{4Q\cos^2\beta}{\sigma\left[C_L \sin\beta + C_D \cos\beta\right]}\right)^{-1} \tag{3.10}$$

$$a' = (1-a)\left(\frac{\sigma\left[C_L \cos\beta - C_D \sin\beta\right]}{4Q\lambda_r \cos^2\beta}\right) \tag{3.11}$$

The new values of induction factors are compared to those obtained in the previous step. The relative differences are given by:

$$\varepsilon_a = 1 - \frac{a_n}{a_{n+1}} \tag{3.12}$$

$$\varepsilon_{a'} = 1 - \frac{a'_n}{a'_{n+1}} \tag{3.13}$$

The taken accuracy of calculations for both parameters is equal to 5%. If the absolute values ε_a or $\varepsilon_{a'}$ are greater than the specified accuracy the iterative process continues until it is achieved.

If we imagine the process of calculation in the form of block diagram, it will look as it is shown on Figure 3.1.2.4

This process must be carried out for all N sections of the blade along its entire length and k sections. Thus, we obtain the functional dependence for the induction factors $a = a\ (r)$, $a'=a'\ (r)$ and the relative angle of attack $\beta = \beta\ (r)$.

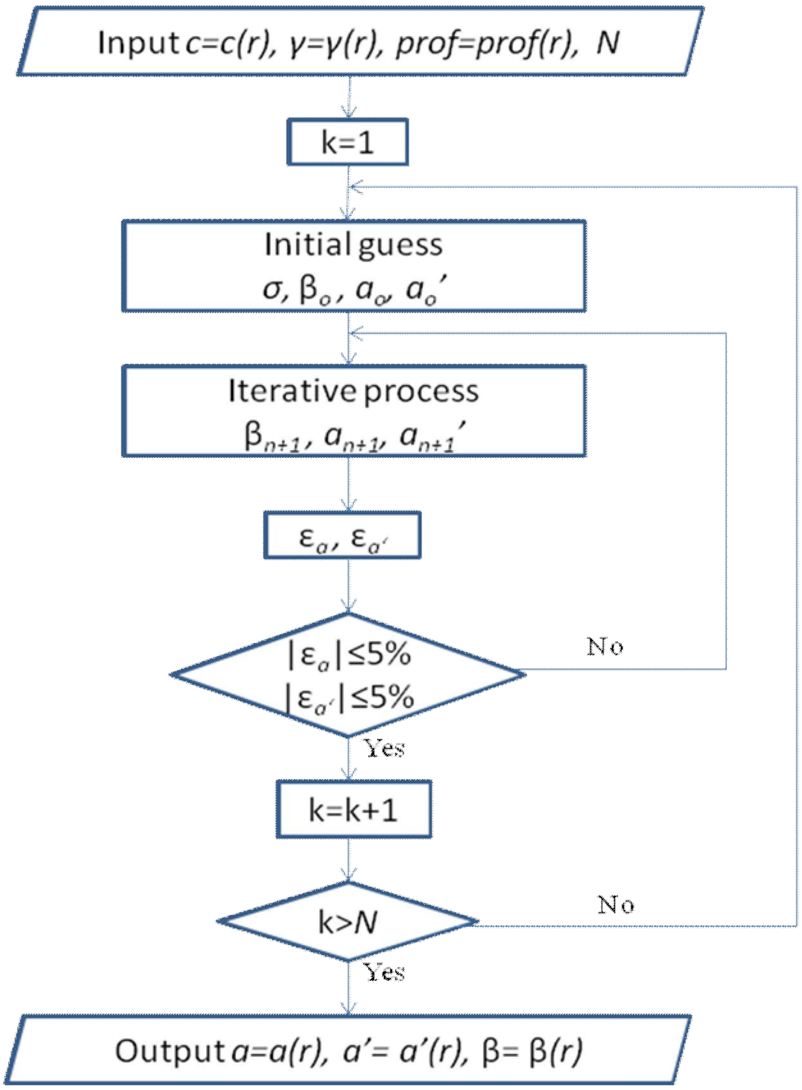


Figure 3.1.2.4 The algorithm for the calculation of blade sections parameters.

3.1.3 Calculation of the power coefficient

Power coefficient C_P is defined as the ratio of produced aerodynamic wind power P to the power of wind flow P_{wind}. Using functions and variables that were obtained in the previous section, we can determine the power coefficient with the following equation:

$$C_p = \frac{P}{P_{wind}} = \frac{8}{\lambda^2} \int_{\lambda_h}^{\lambda} Q\lambda_r^3 a'(1-a)\left[1-\frac{C_D}{C_L}\tan\beta\right] d\lambda_r \tag{3.14}$$

To take such a complicated integral recall the trapezoids rule (Ingram, 2005):

$$\int_{x_o}^{x_n} f(x)dx \approx \frac{x_n - x_o}{2n}\left[(y_o + y_n) + 2(y_1 + y_2 + \ldots + y_{n-1})\right] \tag{3.15}$$

In our case n = 1, x is replaced by λ_r, and function $f(x) = Q\lambda_r^3 a'(1-a)\left[1 - \frac{C_D}{C_L}\tan\beta\right]$. This rule applies to each blade section, and the overall sum gives the total power coefficient.

The above described method of calculation can be programmed and used to estimate the aerodynamic power coefficient of wind turbine for a given profile and shape of the blades, especially because the calculation is iterative and otherwise requires a significant time expenditures.

In the process of calculation we use the experimental characteristics of the profiles in question, but the above mentioned methodology does not take into account the change in the coefficients of lift and drag, depending on the Reynolds number, and it is assumed that change occurs only depending on the angle of attack. In fact it means that the power factor C_P remains constant at all speeds. This is a significant lack of accepted method, although it may be eliminated if the experimental curves will contain the dependence on the Reynolds number.

At the end of this paragraph the author would like to refer the interested reader to the publication of Grant Ingram (Ingram, 2005), where he can find a completed example for the described calculation, and thus it could help for better understanding of the process.

3.2 Model of sound pressure level calculation

The problem of noise exposure modeling is so far not completely solved. Despite the fact that there is at least one technique that allows to carry out such calculations, it still remains a semi-empirical and requires a substantial correction if initial conditions will slightly vary. In other words, the current understanding of the noise model is extremely low.

However, consideration of the noise exposure is an important task, since it is a key factor in public discussion when deciding on the wind station construction. And while the noise generated by wind turbines much less than established standard limits, it remains noticeable compared to the background noise in the remote regions.

The origin of the noise theory is solving the Naver-Stokes equations, and it is based on the Lighthill acoustic analogy (Lowson, 1993). A semi-empirical model described in the publication of Fuglsang and Madsen (Fuglsang, 1996), is applied for the blade profile NACA 0012, but in the practical calculations, for the lack of sufficient experimental data, this model is taken for calculations of other profiles either. Undoubtedly, this is a simplification.

In accordance with the existing model, noise can be divided into three components, which in its turn are subdivided into subclasses. Each source has its own properties, methods of calculation and control. These sources are as follows (Lowson, 1993):

- Discrete frequency noise at the blade passing frequency and its harmonics
- Self induced noise sources
    - Trailing Edge Noise
    - Separation-stall Noise
    - Tip Vortex Formation Noise
    - Laminar Boundary Layer Vortex Shedding Noise
    - Trailing Edge Bluntness Vortex Shedding Noise
- Noise due to Turbulent Inflow

In addition there is a mechanical noise that is created by turning mechanisms of wind turbine. However, it can be monitored by conventional methods (e.g., grease). This kind of noise impact is not considered in this thesis, especially because it is usually negligible.

In its publication Lowson (Lowson, 1993) argues that the self noise sources will prevail at low wind speeds, while at high speeds noise from the turbulent inflow will be the dominant. Analysis of the importance of each of the sources revealed that for adequate model of the noise exposure it is sufficient to consider two main sources: the noise from the trailing edge of the blade and the noise from the turbulent inflow. We will limit our calculation model with these two sources of noise.

3.2.1 Trailing edge noise

The described below semi-empirical method of calculation was proposed by Brooks, Pope and Marcolini and simplified by Lowson (Lowson, 1993). Almost all mentioned equations are taken from his publication.

Noise from the trailing edge arises from the interaction of turbulent flow on both the pressure and suction, side with the trailing edge of the blade when the turbulent boundary layer near the blade turn into the wake. Figure 3.2.1.1 shows this source of noise:

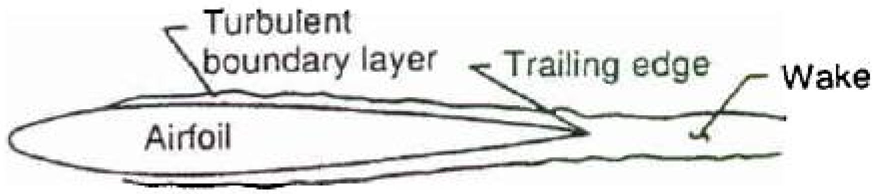


Figure 3.2.1.1 Trailing edge noise from both the pressure and the suction side of the airfoil section (Fuglsang, 1996)

The sound pressure level (L_p^{TE}) in dB can be found as follows:

$$L_p^{TE} = K + 10\log(M^5 \delta^* L / r^2) \tag{3.16}$$

where

K – empirical constant (=128,5dB)

$M = V_r/c_o$ – Mach number, defined as the ratio of speed of the blade section under consideration to the speed of the sound (in our case in the air, c_o=340m/s)

$V_r = V*\lambda*r/R$– rotational speed of the section, V – wind speed on the tower height

$\delta^* = \delta^* (i, c)$ – boundary layer displacement thickness

L – section lenght

r – distance to the noise receiver, in our case to the center of rotation.

The displacement thickness δ^* depends on the angle of attack i and chord of the blade c. This dependence is expressed by the equation:

$$\delta^* = 0{,}185 \cdot c_{av} \mathrm{Re}^{-0,2} \tag{3.17}$$

where

c_{av} – average chord of the section. It is a mean arithmetic chord at the beginning and at the end of the section.

Re – Reynolds Number, which can be found for the section from the formula explained in the publication of Cuerva (Cuerva, 2009):

$$\mathrm{Re} = \rho \frac{V c_{av}}{\mu} \sqrt{(1-a)^2 + \lambda^2 x^2 (1+a')^2} \tag{3.18}$$

where

a и *a'* – axial and angular (tangential) induction factors respectively

λ – tip speed ratio

c_{av} – average chord of the section

$x=r_{av}/R$ – relative distance of the section from the center of rotation

$\mu = 1{,}7 \cdot 10^{-5}$ Pa·s – air viscosity

$\rho = 1{,}225$kg/m^3 – air density (assumed constant)

After that we calculated the noise level from this source for each section of the blade along its entire length, we find the total noise impact with the help of physical laws of interference:

$$L_p^{TE} = 10\log\left(\sum_{n=1}^{N} 10^{0,1L_{pn}^{TE}}\right) \tag{3.19}$$

Thus, to find the noise impact from the trailing edge we need to know the following parameters of the blade:

- Axial and tangential factors
- Average chords of all section profiles
- The lengths of the sections
- Wind speed on the tower height

3.2.2 Noise due to turbulent inflow

Turbulence is an integral part of the wind flow. This phenomenon provokes unsteady and unequal distribution of the pressure along the entire length of the blade and causes the noise exposure. Noise is produced at all frequencies, providing a significant impact on the general background noise generated by the rotating blades of wind turbine.

Analyzing the impact of noise from the turbulent inflow it is necessary to consider the full range of perceived frequencies. In accordance with ISO standards this range of frequencies as follows: {63, 125, 250, 500, 1000, 2000, 4000, 8000} Hz. For each frequency from the spectrum the sound pressure is calculated by the formula:

$$L_{p-f}^{Inf} = 58,4 + 10\log\left[\rho^2 c_0^2 l \frac{L}{r^2} M^3 I^2 k^3 (1+k^2)^{-7/3}\right] + 10\log\left(\frac{LFC}{1+LFC}\right) \tag{3.20}$$

where

L – turbulent flow length

I – turbulent intensity

$K=\pi*f*c_{av}/V_r$ – wave number for the section, c_{av} – mean chord of the section profile;

$V_r = V*\lambda*r/R$–section linear speed, V – wind speed on the tower height

c_o=340m/s – speed of the sound in the air

S^2 – square of compressible Sears function, that is defined by the formula:

$$S^2 = \left(\frac{2\pi k}{\beta^2} + \frac{1}{1+2,4k/\beta^2} \right)^{-1} \tag{3.21}$$

where

$\beta^2=1-M^2$

LFC – correction factor for the low frequency, which is calculated by the formula:

$$LFC = 10S^2M\frac{k^2}{\beta^2} \tag{3.22}$$

After calculating the sound pressure level for each frequency we calculate the RMS, which will determine the level of noise generated by the blade section:

$$L_{pn}^{Inf} = \sqrt{\sum_{f=63}^{8000} \left(L_{p-f}^{Inf} \right)^2} \tag{3.23}$$

Finally, similar to the equation (3.19) we determine the sound pressure level from all sections of the blade that is caused by the turbulent inflow.

Thus, in order to determine the noise impact from the turbulent inflow for each section throughout the considerate length of the blade we need to know:

- Chord at the beginning and at the end of section
- The length of the section
- Wind speed at the height of the tower
- The length of the turbulent flow
- Intensity of turbulence

The total noise exposure received by applying the equation of physical interference (4) to the both considered sources:

$$L_p^{total} = 10\log\left(10^{0,1L_p^{TE}} + 10^{0,1L_p^{Inf}}\right) \tag{3.24}$$

The calculation process described above can be represented as a block diagram as it's shown on Figure 3.2.2.1.

In this case the author omits the consideration of the distance to a particular noise receiver, assuming that the noise impact is estimated at the center of rotation, i.e. at the height of the nacelle. Knowing this parameter as well as the distance to the selected receiver it is easy to calculate the sound pressure from the formula:

$$L_w = L_p^{total} - 6 - 10\log(4\pi R^2) \tag{3.25}$$

where R - distance to the receiver from the center of rotation.

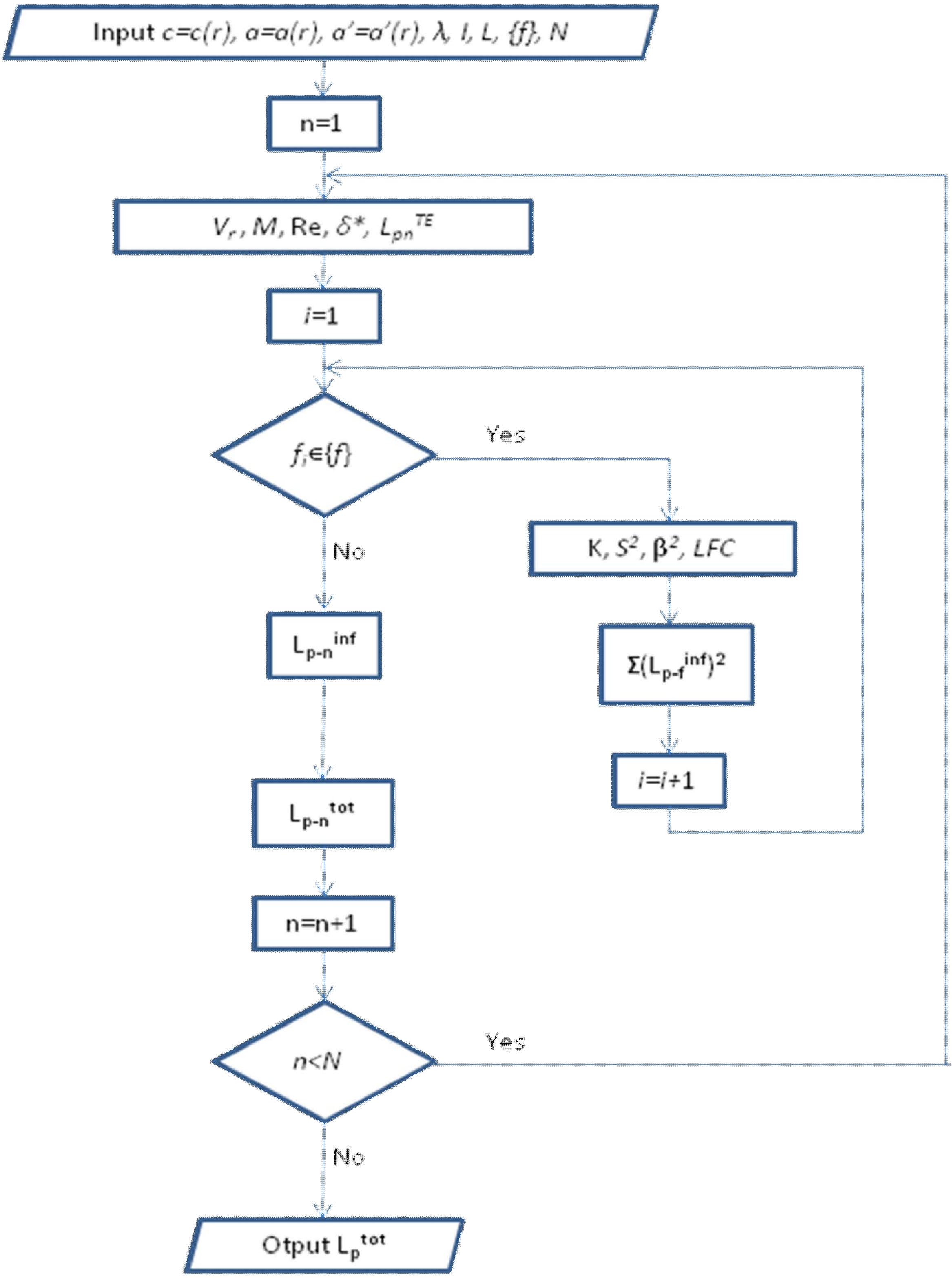


Figure 3.2.2.1 Calculation of noise exposure at the point of rotation created by the blade of wind turbine.

3.3 Model of economic parameters calculation

The main principle in the calculation of economic parameters of wind turbine, and in our particular case its blades, is a departure from the monetary calculus. We are interested in the relation between economic parameters of two blades: the original and the considered shapes. Methodology includes a calculation of the wind conditions in the proposed site, the annual output of energy, as well as the relative monetary and material costs of production and operation of the blades. Thus, we can avoid the introduction of a set of economic factors (inflation, monetary costs, profits, etc.) and bring the problem to a purely technical.

The underlying objective is to create a goal function which would allow to describe the production and maintenance costs and profits. Expenses can be attributed to the production of the blade, its transport and use; and profits - obtained energy through the work of wind turbine. It is natural desire to reduce the all possible costs and to increase the annual output of energy. This objective function can be defined by the following equation (Fuglsang, 1996):

$$f(x) = COE = \frac{C_{rotor}}{AEP} \tag{3.26}$$

where

COE – cost of energy in the relative units

C_{rotor} – relative cost of production, transportation, installation and operation of the blade

AEP – total annual energy production

Next we will consider the methodology of calculation of the required components.

3.3.1 Calculation of the blade production and operation costs

The cost of the blade can be divided into fixed and variable. For example, transportation, installation and operation of the blades can be considered as fixed costs. They are small compared to the cost of production, which vary due to the shape of the blade. The main part of variable costs accounted for the expenses of materials. Less significant role is played by development costs and direct labor associated with production.

Thus, the cost function C_{rotor} can be represented as (Xudong, 2009):

$$C_{rotor} = b_{rotor} + (1 - b_{rotor}) w_{rotor} \tag{3.27}$$

where

b_{rotor} – fixed costs

w_{rotor} – parameter of variable costs

Fixed costs typically represent a small fraction, and in this paper, as analogy to the publication of Wang Xudong (Xudong, 2009), taken as b_{rotor} =0,1 of total costs. Parameter of variable costs in our case of the blades production can be found by the formula:

$$w_{rotor} = \sum_{i=1}^{n} \frac{m_i \cdot c_i}{M_{tot} \cdot c_{i,or}} \tag{3.28}$$

where

m_i – mass of the *i*-th considered blade section

c_i – average chord of the *i*-th considered blade section

M_{tot} – the total mass of the original blade with respect to which a comparison is made

$c_{i,or}$ – average chord of the i-th section of the original blade

If the average chord of the section is easy to estimate because it is calculated as the arithmetic mean between the profile chords at the beginning and at the end of the section, to determine the relative mass we need to discuss a details.

Consider the blade divided into sections and its cross-section:

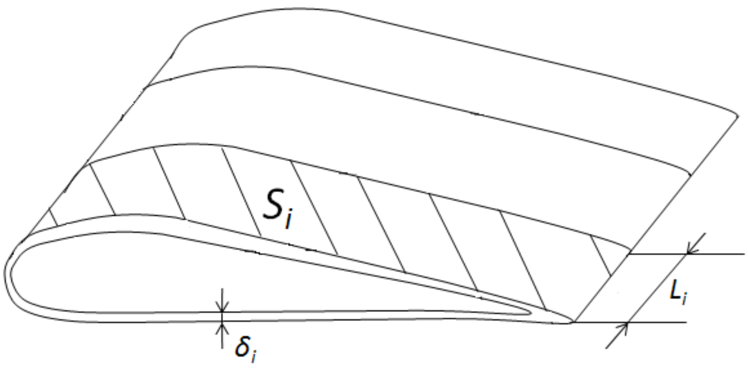


Figure 3.3.1.1 The geometrical parameters of the blade

The figure marked with the following parameters: δ_i - material thickness, L_i - length of the section, taking into account the twist angle $\Delta\gamma_i$; S_i - area of the sectional surface. The mass of i-th section can be determined by the formula:

$$m_i = S_i \delta_i \rho \tag{3.29}$$

where ρ is the density of the material from which section is constructed.

To simplify the calculation, as well as we don't have all relevant information, we make the following assumptions:

- We believe that the material density is constant for entire length of the blade.
- The thickness of the material δ_i also assumed to be constant.
- Material cost takes into account only production of the outer shell of the blade without internal reinforcing rod and other expenses.

Taking into account the made assumptions and drawing attention to the formula (3.29), it is possible to compare the same section by the relative difference in their areas. Thus, formula (3.28) can be rewritten as:

$$w_{rotor} = \sum_{i=1}^{n} \frac{S_i \cdot c_i}{S_{tot} \cdot c_{i,or}} \tag{3.30}$$

The surface area is approximately defined as:

$$S_i = P_i L_i \tag{3.31}$$

where

P_i – average perimeter of the cross section

L_i – section length.

As it was stated earlier, the value of L_i should consider twisting of the blade through it length, so the formula for its calculation is as follows:

$$L_i = \Delta r_i / \cos(\Delta\gamma_i) \tag{3.32}$$

where

Δr_i – section length in the projection to the radial axis of the blade

$\Delta\gamma_i$ – difference in the angles of twist at the beginning and at the end of the sections

The average perimeter of the section shall take into account the chord of this section and the unit perimeter of the profile. According to the rules of similarity we can write the following formula:

$$P_i = \frac{1}{2}\left(c_b P_b^1 + c_e P_e^1\right) \quad (3.33)$$

where the subscript «*b*» means the beginning of the section, the index «*e*» - its end. P^1 - the unit perimeter of the blade profile at the beginning or at the end of the section. For calculations this parameter is contained in the database of profiles and is estimated with the method of linear approximation by the unit coordinates.

3.3.2 Analysis of wind conditions and the calculation of annual power generation

The volume of the energy produced depends on two factors: the wind conditions and the used wind turbine. The wind conditions analysis includes the definition of frequency of wind speed occurrence by the grades, as well as the calculation of the Weibull distribution parameters for the wind speed. The technique outlined below was developed at the Danish Institute RISO and is given in the book of Haritonov V.P. (Haritonov, 2006).

A full range of wind speeds is divided into the grades of 1 m / sec. It is appropriate to consider the wind speeds that are not exceeding 25 m / sec. Furthermore, the higher speeds are unlikely even in the places with good wind conditions and for the most of installations the speed of 25 m / s is an extreme threshold of the wind turbine performance characteristics. At the higher speeds the wind turbine is switched off. By assuming the average values of gradation and the dismissal of 0,5 m / s we carry out the analysis of wind speeds (which are usually given with an interval from 10 minutes to 1 day as a data file). Programmed process is shown in Figure 3.3.2.1.

```
for ( m = 0; m < Vdt.Count; m++)
            {
                p = true;
                i = 0;
                while (p && i < f.Length)
                {
                    if (Vdt[m] >= (V[i] - 0.5) && Vdt[m] < V[i] + 0.5)
                    {
                        f[i] += 1.0 / Vdt.Count;
                        p = false;
                    }
                    i += 1;
                }
            }
```

Figure 3.3.2.1 Listing of the wind analysis program by the grades.

Here Vdt - downloaded dataset of wind speeds, given on the tower height, V - the array of wind speeds by the grades, V = {0.5, 1.5, 2.5,..., 24.5}, f - array filled with the wind speed frequency of occurrence. It is not complicated to understand the above mentioned listing even for those who are familiar only with the basics of programming.

Usually, the wind speed is measured at the standard heights, for example, 10 meters. To find the wind speed at the height of the tower it is necessary to apply an equation that links it with the measured at a certain height wind speed. This formula is as follows (Haritonov, 2006):

$$V_z = V_{ref}\left(\frac{z}{z_{ref}}\right)^{\gamma} \tag{3.34}$$

where

V_z – wind speed at the height of the tower

z – tower height

V_{ref} – measured wind speed

z_{ref} – height of the measurements

γ – parameter of wind speed change due to the height

Parameter of wind speed change varies depending on certain arguments. For our calculation we set that it depends on the surface roughness of the adjacent territory of the wind turbine installation and can be determined by the formula:

$$\gamma = 0,24 + 0,096 \log z_o + 0,016(\log z_o)^2 \tag{3.35}$$

Surface roughness z_o and the relative γ parameter for different terrains are given in Table 1:

Terrain Description	**z_o, mm**	γ
Very smooth, ice or mud	0.01	0,112
Calm open sea	0.20	0,181
Blown sea	0.50	0,213
Snow surface	3.00	0,289
Lawn grass	8.00	0,340
Rough pasture	10.00	0,352
Fallow field	30.00	0,417
Crops	50.00	0,449
Few trees	100.00	0,496
Many trees,hedges	250.00	0,562
Forest and woodlands	500.00	0,616
Suburbs	1500.00	0,706
Centers of cities with tall buildings	3000.00	0,767

Table 3.3.2.1 The level of surface roughness for different terrains. (Zhu, 2004)

After performing this procedure, we will have an array of wind speed values by the gradation and a corresponding array of frequency of occurrence of these velocities. At this stage we can determine the average wind speed during the covered period by the formula:

$$V_{av} = \sum_{i=1}^{N} f_i V_i \tag{3.36}$$

To determine the parameters of Weibull distribution function it is also necessary to estimate the mean square speed by the formula:

$$V_1^2 = \sum_{i=1}^{n} f_i V_i^2 \tag{3.37}$$

As it is known, the Weibull wind speed distribution function has the form (Haritonov, 2006):

$$f_i(V_i) = \frac{k}{A}\left(\frac{V_i}{A}\right)^{k-1} e^{-\left(\frac{V_i}{A}\right)^k} \tag{3.38}$$

In accordance with the methodology developed by the Danish experts, the coefficients *k* and *A* can be found graphically. For this purpose we use the curves shown in Figure 3.3.2.2:

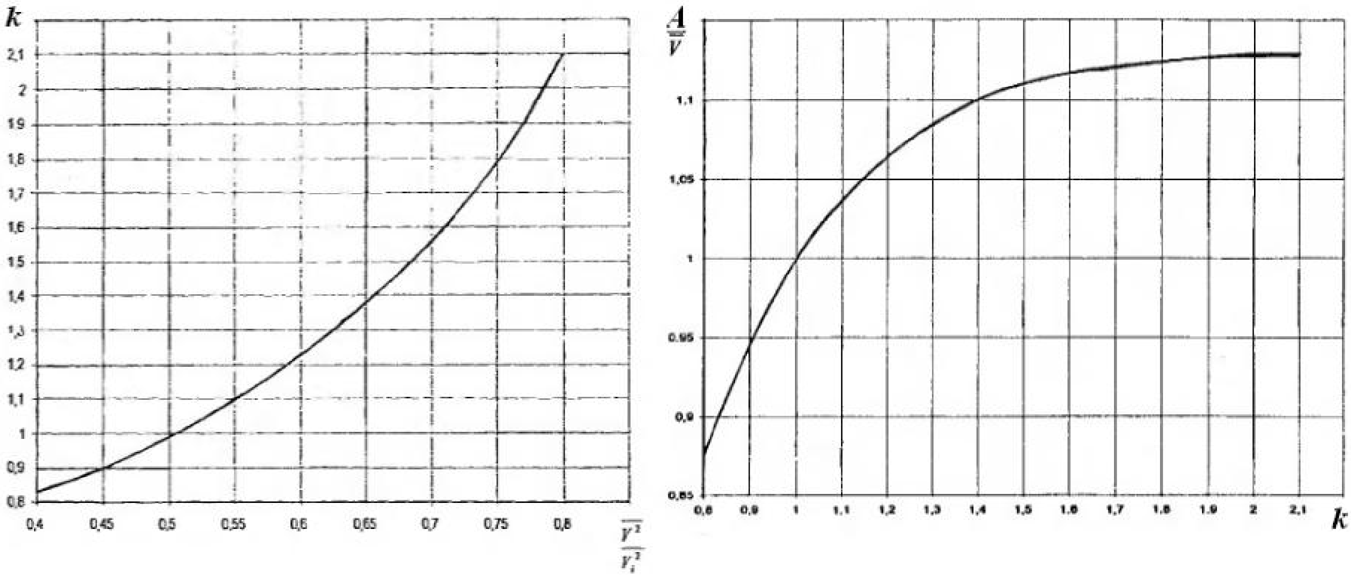


Figure 3.3.2.2 Determination of the *k* and *A* parameters of the Weibull wind speed distribution function (Haritonov, 2006)

Now all the necessary parameters are found, and we can determine the coefficients of the distribution function.

After analyzing the wind condition, and knowing the power characteristics of the corresponding wind turbine, it is easy to determine the annual energy production. To do this, use the following formula (Haritonov, 2006):

$$AEP = \sum_{i=1}^{N} P_i(V_i) \cdot f_i(V_i) \cdot T \tag{3.39}$$

where

$f_i(V_i)$ – recurrence rate of V_i

T – annual working period of wind turbine

$P_i(V_i)$ – wind turbine power issued to the network at the speed V_i and defined by:

$$P_i(V_i) = \frac{\rho V_i^3}{2} \pi R^2 C_p \eta \tag{3.40}$$

where

ρ=1,225кг/м^3 – air density (taken to be constant)

R – radius of the area swept by the wind turbine, in other words, the length of the blade

C_p – power coefficient of wind turbine with considered blades shape and obtained after aerodynamic analysis (see paragraph 3.1)

η – total electric and mechanical efficiency, taken equal to 0,9.

For different reasons the features of wind turbines performance are such that the power granted to the network confined within the speeds from 0 m / s to the V_1 and from V_2 to infinity and in these areas is equal to zero. V_1 and V_2 are called starting and storm speed respectively. In his calculations, we take the values of these velocities constant and equal to 3m / s and 25m / s, which correspond to a large number of modern wind turbines.

The value of energy production has the dimension of W*h / year. For ease of presentation it is easy to bring this figure to dimension MW*h / year by dividing it for one million.

Now we have all the necessary variables to determine the objective function by the formula (3.26). The obtained relative economic value *COE* has a dummy dimension [1/MW*h/year]. With its help, without knowing the real monetary value of the blades production and operation, we can compare two wind turbines between each other.

4 MULTIOBJECTIVE OPTIMIZATION

Sometimes in the calculation process it is necessary to find maximum or minimum of some objective function. In this case we choose an interval, use different methods (enumeration, the golden section, etc.) and identify the appropriate local extreme value. However, we can face a problem in which there are several objective functions and the need is to find the optimal solution for each of them. Such optimization problems are called multiobjective. Often the search for optimal solutions for one of the functions leads to a simultaneous distancing from the optimal solutions for other functions. For example, reliability increase of any system requires the investment of funds. Thus, we can not fully maximize reliability without increasing costs, which we typically want to minimize in the contrary. Multiobjective optimization methods help to find a good correlation between the parameters of objective functions.

4.1 Objectives and methods of optimization process

In this paper, we consider three objective functions: the power factor C_p, which characterizes the efficiency of wind energy use and is directly related to energy generation; the sound pressure level L_p at the height of the wind turbine tower, and energy cost function *COE*, related to the blade cost and annual produced energy. Obviously, the wind turbine efficiency associates with the expenses from the production of more massive and complex blades (and other parts, which are not considered in this work). The same applies to the problem of noise exposure reduction. The purpose of the optimization process is to find a compromise between maximization of the power efficiency and minimization of the sound pressure and energy costs. Let's consider the most common methods of multiobjective optimization:

- *Goal programming.*

The basis of this method is to minimize the deviation between the desired value of the objective function and its actual value at the given restrictions:

$$f(x) = \text{goal} - \text{what can be achieved} \rightarrow min \tag{4.1}$$

The main difficulty in the application of goal programming for the multiobjective tasks is to create an adequate mathematical model of a single objective function. In this case, it means that we have to find a connection between all the specified goals and to determine the single function for all objectives. This task is difficult and uses static data processing.

- *Analytic hierarchy process* (AHP)

This method is used to divide complex and unrelated tasks into component parts, which are considered in a hierarchical order in the accordance to their importance and weight in the overall solution. For each part we consider all their options and later we make the choice from them. Analytic hierarchy process is used mainly in difficult situations. The method is able to take into account countable (cost, efficiency, time, etc.) and uncountable (customer satisfaction, motivation of employees, etc.) factors.

In our case the all target parameters (power efficiency, sound pressure level and energy cost) are countable and their values or options are previously unknown, thus the use of AHP in this case is impossible.

- *Desirability function*

This approach allows to convert a multi-purpose optimization problem to maximization of a single aggregate measure. The desirability function deals with relative parameters and provides an opportunity to combine optimization problems for the variables with different units. The proposed approach uses a codification system for goal parameters from 0 to 1 and takes into account the purpose of optimization: maximization or minimization - for each parameter. Desirability function is simple and universal. It is the most suited for salvation of the optimization problem considered in this paper.

4.2 Desirability function D

The ideal case when the all objective functions are simultaneously has their optimal values is usually impossible because the input parameters that optimize a first objective function do not necessarily equal to those that optimize the other. In the present work the goal functions are power efficiency, sound pressure level at the height of the tower and the relative function of energy cost. Distribution of the blade chord, twist angle and relative profile shape are the input parameters of the goal functions.

Desirability function was introduced by Harrington and further developed in the works of Derringer. It is determined by the following equation (Boulet, 2009):

$$D = \left(d_1^{w_1} \cdot d_2^{w_2} \cdot \ldots \cdot d_r^{w_r} \right)^{1/\sum_{i=1}^{r} w_i} \tag{4.2}$$

where

w_i – parameter's weight in the overall optimization process

d_i – desirability function parameter that has a value from 0 to 1.

To set the parameter of desirability function for the specific correlation values of objective functions, first we must consider each of them. At the same time we find the maximum y_j^{max} and the minimum y_j^{min} values of the goal functions and the corresponding values of the relative input parameters on the considered interval Ω (Boulet, 2009):

$$\begin{aligned} y_j^{\max} &= \max_{x \in \Omega} \left\{ y_j(x_j) \right\} \\ y_j^{\min} &= \min_{x \in \Omega} \left\{ y_j(x_j) \right\} \end{aligned} \tag{4.3}$$

where x_j – set of input data of the objective function y_j

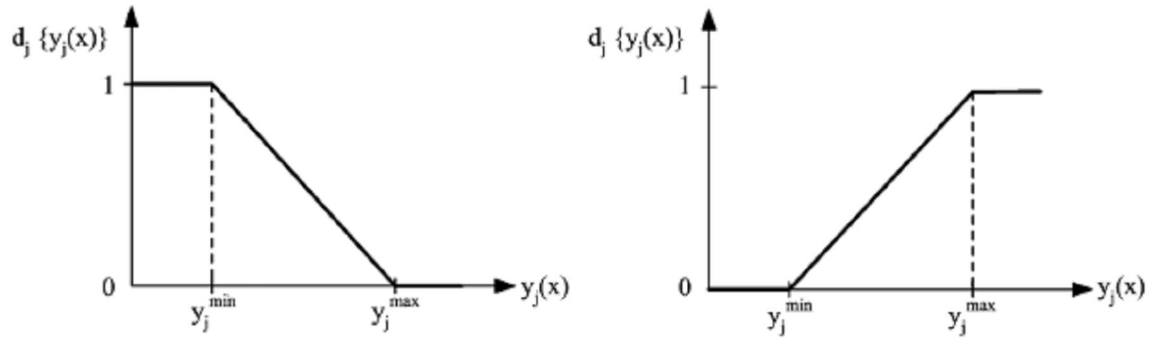
At this stage the input parameters x_j for different goal functions y_j may have different values. Thus, we solve the one-optimization problem separately for the each objective function. On the next stage this problem is converted to multiobjective.

To do this, we consider the effects of change of the input parameters x_j on each of the objective function and determine how the value of these functions is far from their corresponding optimal value. “Distance" is encoded by the value from 0 to 1.

For example, if for some distribution of chord, twist angle and profile shape of the blade, on the considered interval Ω, the power efficiency takes its *maximum* value, than the parameter d_i, responsible for the setting of desirability function of power efficiency, takes the value 1. If in the other case of a different set of the parameters x_j the power efficiency of the blades will be reduced to a *minimum*, then this parameter d_i will have the value 0. In the intermediate values parameter d_i varies linearly.

It means that for the power efficiency the higher value is preferable, and the purpose is to get the maximum. In contrast, for the sound pressure level and the cost of energy the desire is to get the lowest value and the goal is a minimization. In the case of such controversial optimization targets we use different coding rules to set a desirability function.

Graphically, depending on the optimization search direction, the value of encoded parameter d_i can be represented as follows:



a) Minimization b) Maximization

Figure 4.2.1 Encoding of desirability function parameter d_i. (Boulet, 2009)

Mathematically the encoding task can be represented by the following equations (Boulet, 2009):

$$d_1 = \frac{y_1 - y_{1\min}}{y_{1\max} - y_{1\min}} \tag{4.4}$$

$$d_{2,3} = \frac{y_{\max} - y_{2,3}}{y_{2,3\max} - y_{2,3\min}} \tag{4.5}$$

In this paper, the parameter d_1 encodes the value of power efficiency and its closeness to its maximum. d_2 and d_3 encode the values of sound pressure level and the cost of energy and their proximity to their minimum respectively.

Considering the all possible variants of the input parameters x_j from the interval Ω, we find the desirability function by the equation (4.2). The maximum value of the desirability function will respond to the set of input parameters with which the objective functions get their optimal solutions. The introduced problem will be solved.

It remains to mention about the weight parameter w_j. This parameter determines the importance of the objective function in the overall process of optimization. It is advisable to limit the value of the weighting parameter. In this paper we adopted a ten-point rating system for optimization priority.

For example, if an employee, engaged in the design process, was given the task to make the blade as efficient as possible and to consider the issues of ecology and economy to a lesser extent, he can set the weighting parameters of the objective functions as follows: $w_1 = 10$, $w_2 = 1$, $w_3 = 2$. Where w_1, w_2, w_3 are the weights of the power efficiency, sound pressure level and the cost of energy in the overall optimization process respectively.

Generally speaking, this option provides an opportunity for experimentation. It doesn't standardize the approach of the optimal solution selection. As the world situations today are various in terms of energy, economy and ecology, it is useful to be able to vary the approach to such a choice on a case by case basis. The beauty and universality of the desirability function is precisely in that it allows it.

5 INVESTIGATION OF THE OPTIMIZATION PROCESS

5.1 Software description

Modeling and optimization process requires a repetition of a set of identical operations. It is more rational to realize it with the help of computer. For that purpose the author of this thesis developed Windows application BSDesign on the C# program language. It offers a convenient interface and meets the necessary functionality for solving the optimization and calculation tasks of the wind blade shape. General view of one of the program window is shown in Figure 5.1:

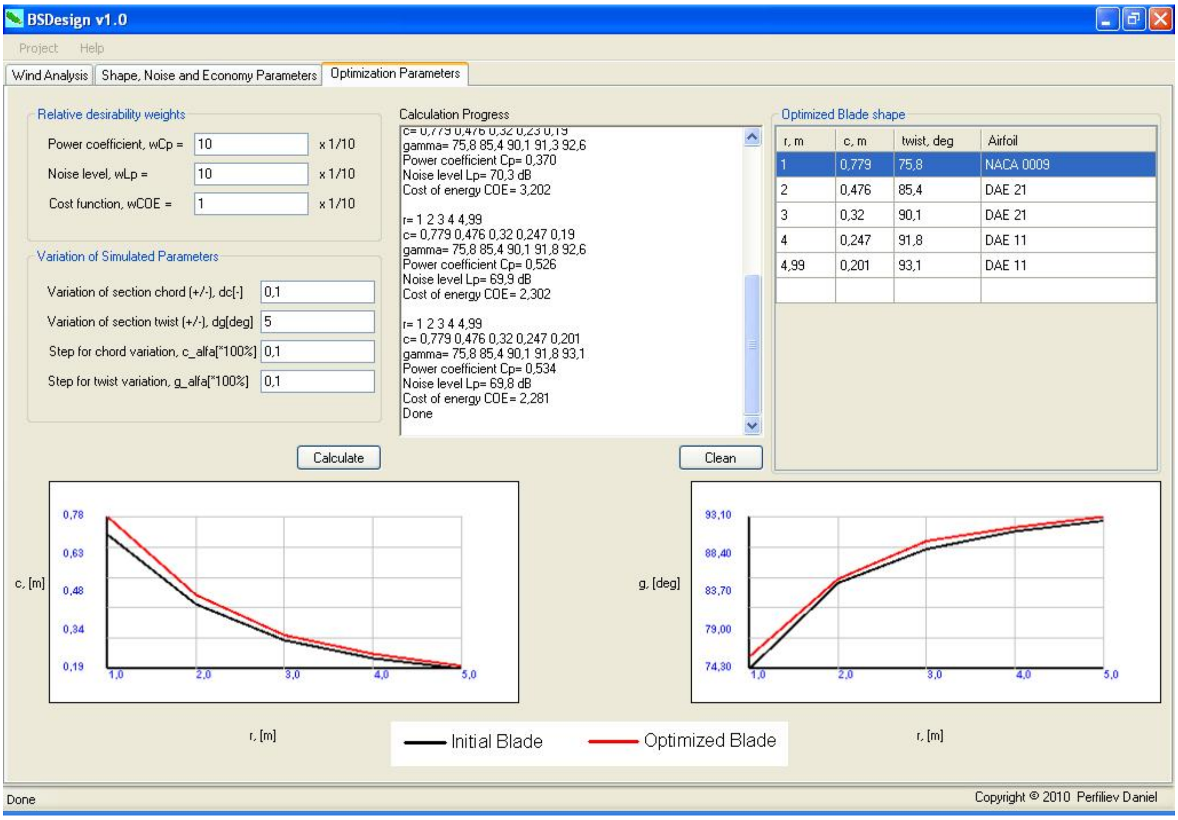


Figure 5.1. General view of the results window.

The software application is capable to:

- Conduct an analysis of wind data
- Optimize the shape (chord, twist angle) and the cross section profile of the wind turbine blades
- Show the results of calculations in a tabular, text and graphic form.

This version of the program doesn't allow to save the projects.

The initial data for the project is:

- Measurements of wind velocities at the proposed installation site. Excel file format (.xls, .xlsx).
- Initial distribution of chord, twist angle and profiles of the blade along its length. Data on the blade the shape of which must be optimized.
- Other necessary design parameters (coefficients, optimization limits, etc.).

Let's consider the actions being done in the typical project calculation.

5.1.1 Analysis of the wind conditions

In order to optimize the blade shape and to consider the specific site of wind turbine installation, we have to analyze the wind speed data. To do that, in the Wind Analysis tab it is possible to download the Excel file with the values of wind speeds (see Figure 5.1.1.1). We have to add the full file path to or to open it by clicking the button Browse.

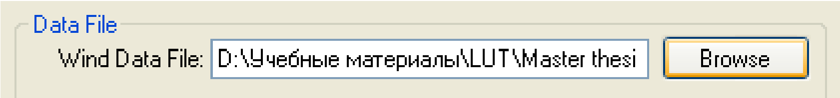


Figure 5.1.1.1 Opening a file with the measured wind speeds.

After that on the same tab we have to specify the limits of data reading (addresses of the extreme cells), and the following parameters: the height of the measurement H_{ref}, the height of the wind turbine tower H and surface roughness z_0 which forms the law of the wind speed variation with the height.

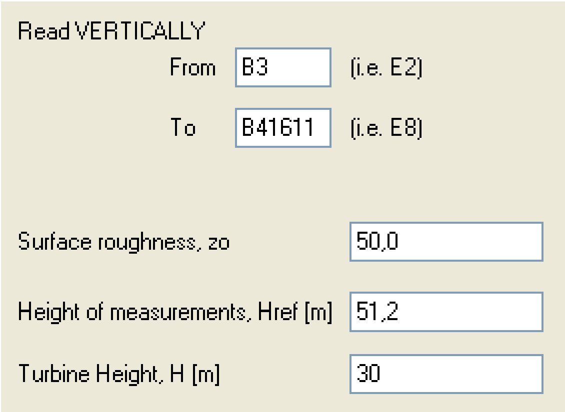


Figure 5.1.1.2 Parameters of the wind speeds analysis.

Note that the file is considered down vertically and extreme cells must be in the one column.

After pressing the Calculate button the statistical analysis of the wind speeds data is conducted by the method described in Chapter 3. As the result program gives *A* and *k* parameters of the Weibull wind speed distribution. In addition it provides graphical interpretation of graded histogram of wind speed distribution, as well as the Weibull distribution function. The calculated parameters of the distribution may be transferred to the next block by pressing the “Transfer to Other blocks” button.

5.1.2 Input data for calculation

On the next step we switch to the tab Shape, Noise and Economy Parameters. The main parameters of calculation are set exactly at this point. It is necessary to describe the initial shape of the blade, namely the distribution of chord and twist angle along the length of the blade and to indicate the type of profile in the cross section (see Fig. 5.1.2.1 left)

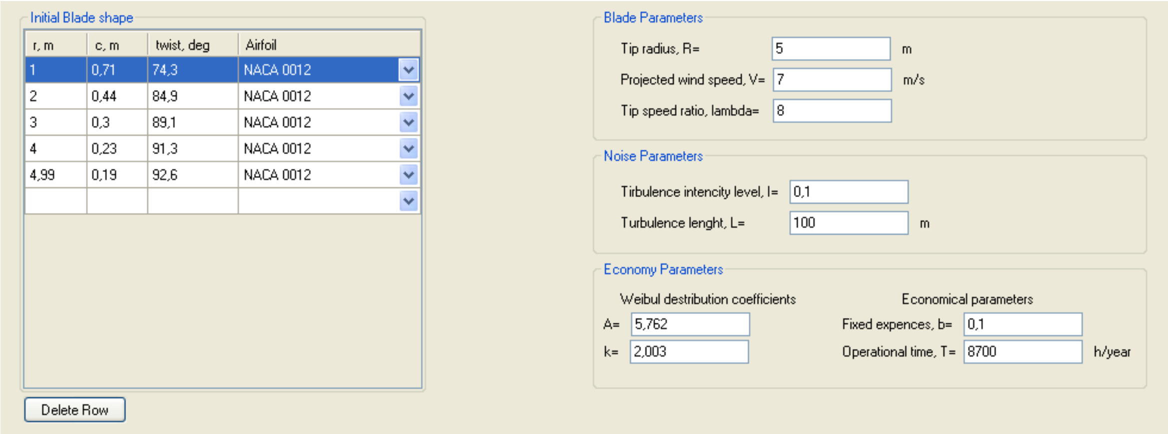


Figure 5.1.2.1 The tab Shape, Noise and Economy Parameters.

The profile type can be chosen from those for which the information in the database is available. Figure 5.1.2.2 shows the spectrum of the profiles in question.

In the right part of the tab the technical parameters are defined. They are subsequently involved in the calculations by use of the methods described in Chapter 3. By the way, the coefficients of the Weibull wind speed distribution function, participating in the economic calculation block, can be set based on the statistical data analysis of wind resource of the considerate area. How this can be done was mentioned above.

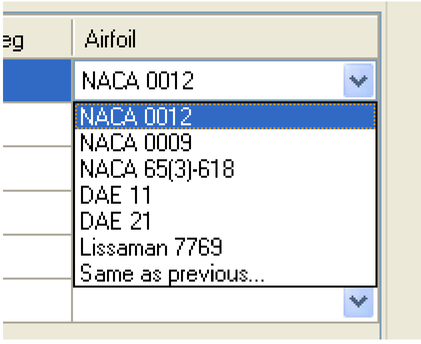


Figure 5.1.2.2 Considered blade profiles.

Finally, to perform the calculations we have to go to the Optimization Parameters tab and set the appropriate values of optimization criteria weights. In addition in the left side of the tab we have also to specify the limits of optimal solutions search interval and steps for chord and twist angle of the blade.

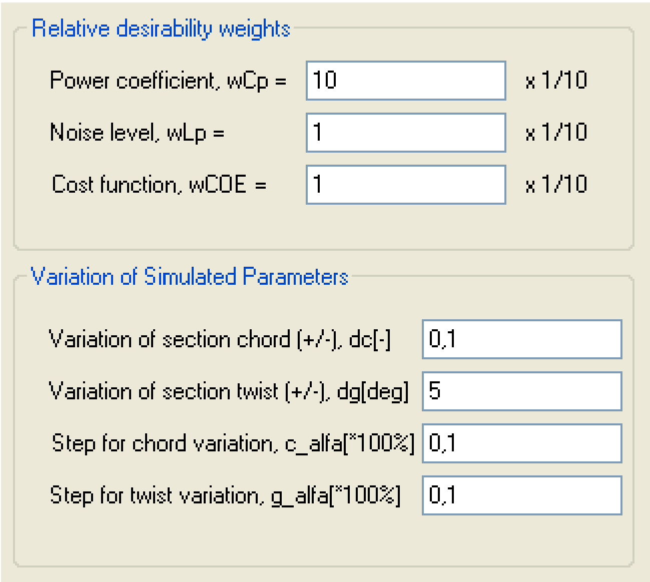


Figure 5.1.2.3 Set of optimization parameters

5.1.3 Results of the optimization process

After that all the initial parameters are set we press the Calculate button. It starts the calculation process information about which can be seen in the Calculation Progress window. The simulation process and the optimal solution search will be described later.

As a result the program displays data for the optimized blade. Distribution of chord, twist angle and cross section profile type along the blade are displayed in the right corner of the tab. In graphical form curves are constructed for the chord and twist angle and are performed at the bottom of the tab.

Optimized Blade shape

r, m	c, m	twist, deg	Airfoil
1	0,779	75,8	NACA 0009
2	0,476	85,4	DAE 21
3	0,32	90,1	DAE 21
4	0,247	91,8	DAE 11
4,99	0,191	93,1	DAE 11

Figure 5.1.3.1 Parameters of the optimized blade

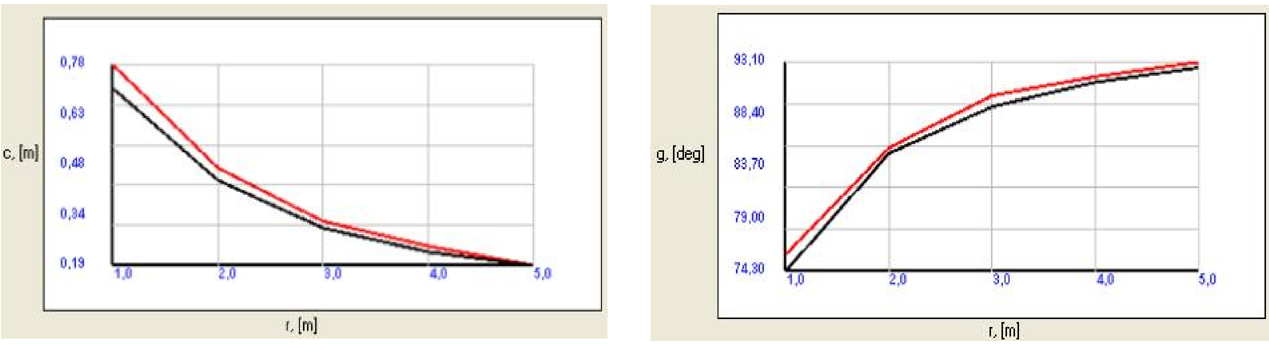


Figure 5.1.3.2 Graphical performance of the calculation results.

The functional part of the program ends on it. For further versions it is useful to make several changes and additions:

- Expand the database on the blade profiles.
- Implement the possibility of the data transfer to the image editors such as AutoCAD for constructing 3D models of the optimized blades.
- Make possible to save the projects.

5.2 The purpose of the study and initial data

Objectives of the study asserted in the title of the thesis. It is needed to find the optimum shape of wind turbine blades based on the adopted input data and developed software, as well as to analyze the sensitivity of software output parameters on the original information. All the parameters that are available for input to computer application can be varied.

Background information for the calculations, namely the initial shape of the blade, was taken from open sources. Scientists from Britain, Denmark, the USA, the Netherlands and some other countries, did a joint research work on experimental determination of characteristics of the different blades. This paper presents an open data on the distribution of chord and twist angle of the blades. For this thesis we use the information provided for the pilot test blade of Denmark Research Institute RISO. Here's some information that is presented for the blade (Schepers at all, 1997):

<u>Rotor:</u>

- Hub height: 29.3 m
- Number of blades: 3
- Rotor diameter: 19.0 m
- Swept area: 284 m
- Tilt: 5 deg
- Coning: 0 deg
- Blade tip angle (measured):
    - – 1.8 deg
    - – 1.5 deg
- Power control: stall
- Direction of rotor rotation (seen in front): anti-clockwise

<u>Blades:</u>

- Type: LM-Glasfiber 8.2 m, cantilevered GRP
- Spar material: GRP
- Shell material: GRP
- Blade length: 8.2 m
- Profiled blade length: 6.8 m
- Blade extensions: 1 m

- Root chord: 1.09 m

- Tip chord: 0.45 m

- Blade twist: 15 deg

- Blade profile: NACA 63n-2nn series

- Air brakes: Spoilers positioned on the suction side

<u>Gearbox</u>

- Gear ratio: 1:21.063

The blade uses the NACA 63n-2nn family profiles, but in our database there is only information for the NACA 65(3)-618 profile. Although these profiles are slightly different from each other, the calculations assume that the blade is made using the profile, information for which we have. In tabular and graphic form the distribution of chord and twist angle of the blade is presented in the following table and figure:

Table 5.2.1 Distribution of blade chord and twist angle, as well as the type of profile for RISO test blade (Schepers at all, 1997)

r, m	**c, m**	**γ, deg**	**Airfoil**
2,70	1,090	75,00	NACA 65(3)-618
3,55	1,005	80,50	NACA 65(3)-618
4,40	0,925	83,90	NACA 65(3)-618
5,25	0,845	86,10	NACA 65(3)-618
6,10	0,765	87,60	NACA 65(3)-618
6,95	0,685	88,50	NACA 65(3)-618
7,80	0,605	89,10	NACA 65(3)-618
8,65	0,525	89,60	NACA 65(3)-618
9,50	0,445	89,80	NACA 65(3)-618

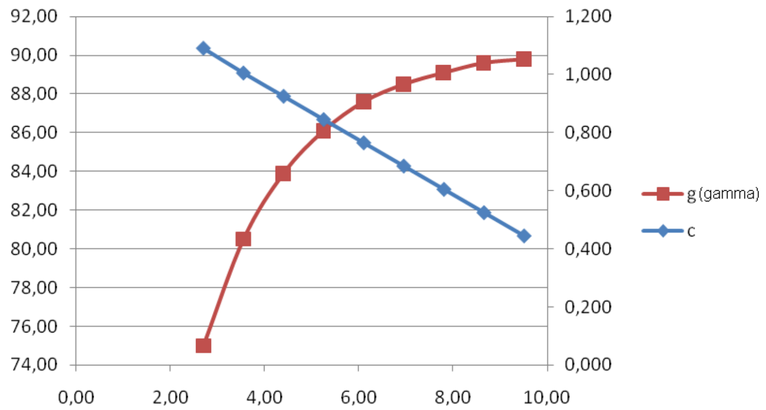
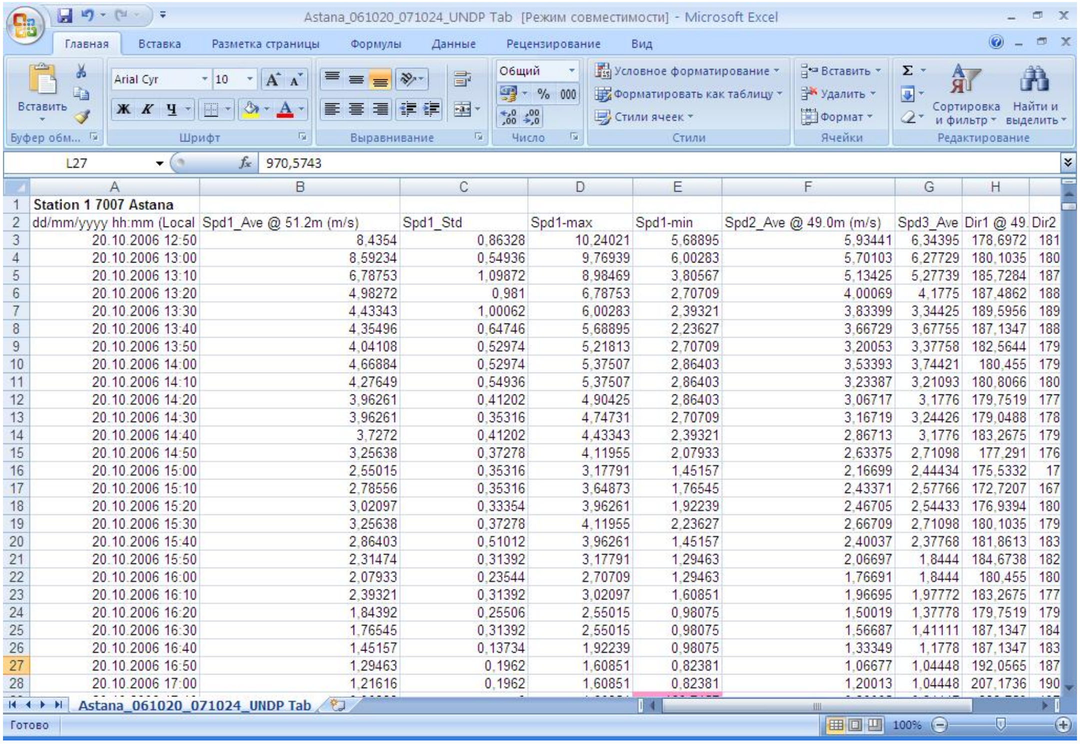


Figure 5.2.1 Distribution of chord and twist angle for RISO test blade.

For the economic calculations we need the data on wind conditions for the proposed site of installation. For that purpose we use measurements of the wind velocity near the city of Astana (Kazakhstan) during the period from 20.10.06 to 24.10.07. The observation period of one year with an interval of 10 minutes gives the reason to believe that the provided information is reliable and sufficient to calculate the preliminary parameters of the site wind conditions. Measured data of wind speeds is presented in the format of Excel file, and are taken from the public sources of Internet. A small observation interval is shown in Figure 5.2.2:



	A	B	C	D	E	F	G	H	
1	Station 1 7007 Astana								
2	dd/mm/yyyy hh:mm (Local	Spd1_Ave @ 51.2m (m/s)	Spd1_Std	Spd1-max	Spd1-min	Spd2_Ave @ 49.0m (m/s)	Spd3_Ave	Dir1 @ 49.	Dir2
3	20.10.2006 12:50	8,4354	0,86328	10,24021	5,68895	5,93441	6,34395	178,6972	181
4	20.10.2006 13:00	8,59234	0,54936	9,76939	6,00283	5,70103	6,27729	180,1035	180
5	20.10.2006 13:10	6,78753	1,09872	8,98469	3,80567	5,13425	5,27739	185,7284	187
6	20.10.2006 13:20	4,98272	0,981	6,78753	2,70709	4,00069	4,1775	187,4862	188
7	20.10.2006 13:30	4,43343	1,00062	6,00283	2,39321	3,83399	3,34425	189,5956	189
8	20.10.2006 13:40	4,35496	0,64746	5,68895	2,23627	3,66729	3,67755	187,1347	188
9	20.10.2006 13:50	4,04108	0,52974	5,21813	2,70709	3,20053	3,37758	182,5644	179
10	20.10.2006 14:00	4,66884	0,52974	5,37507	2,86403	3,53393	3,74421	180,455	179
11	20.10.2006 14:10	4,27649	0,54936	5,37507	2,86403	3,23387	3,21093	180,8066	180
12	20.10.2006 14:20	3,96261	0,41202	4,90425	2,86403	3,06717	3,1776	179,7519	177
13	20.10.2006 14:30	3,96261	0,35316	4,74731	2,70709	3,16719	3,24426	179,0488	178
14	20.10.2006 14:40	3,7272	0,41202	4,43343	2,39321	2,86713	3,1776	183,2675	179
15	20.10.2006 14:50	3,25638	0,37278	4,11955	2,07933	2,63375	2,71098	177,291	176
16	20.10.2006 15:00	2,55015	0,35316	3,17791	1,45157	2,16699	2,44434	175,5332	17
17	20.10.2006 15:10	2,78556	0,35316	3,64873	1,76545	2,43371	2,57766	172,7207	167
18	20.10.2006 15:20	3,02097	0,33354	3,96261	1,92239	2,46705	2,54433	176,9394	180
19	20.10.2006 15:30	3,25638	0,37278	4,11955	2,23627	2,66709	2,71098	180,1035	179
20	20.10.2006 15:40	2,86403	0,51012	3,96261	1,45157	2,40037	2,37768	181,8613	183
21	20.10.2006 15:50	2,31474	0,31392	3,17791	1,29463	2,06697	1,8444	184,6738	182
22	20.10.2006 16:00	2,07933	0,23544	2,70709	1,29463	1,76691	1,8444	180,455	180
23	20.10.2006 16:10	2,39321	0,31392	3,02097	1,60851	1,96695	1,97772	183,2675	177
24	20.10.2006 16:20	1,84392	0,25506	2,55015	0,98075	1,50019	1,37778	179,7519	179
25	20.10.2006 16:30	1,76545	0,31392	2,55015	0,98075	1,56687	1,41111	187,1347	184
26	20.10.2006 16:40	1,45157	0,13734	1,92239	0,98075	1,33349	1,1778	187,1347	183
27	20.10.2006 16:50	1,29463	0,1962	1,60851	0,82381	1,06677	1,04448	192,0565	187
28	20.10.2006 17:00	1,21616	0,1962	1,60851	0,82381	1,20013	1,04448	207,1736	190

Figure 5.2.2 Measured wind speed data for the site near the city of Astana (Wind industry of Kazakhstan, 2010)

We are interested in the second column which includes the wind speed data with an interval of 10 minutes on the vane height of 51,2 m. This information will be used in the analysis of wind conditions and determination of the Weibull distribution coefficients for the wind speed (see paragraph 3.3).

For the economic, noise and optimization calculations we need the following input data and their values that are setted by the designer:

- Surface roughness, z_0 = 50 mm (corresponds to the crops)
- Height of wind speed measurements, H_{ref} = 51,2 m
- The height of the wind tower, H = 29,3 m
- The length of the blade, R = 9,51 m (it is taken a little longer than a given in specification for the correct solution of the aerodynamic calculation equations)
- Design wind speed, V = 7 m / s
- Tip speed ratio, λ = 4,5
- The turbulence intensity, I = 0,1
- The length of turbulent flow, L = 10 m
- Rate of permanent economic costs, b = 0,1
- Annual operating time of wind turbine, T = 8700 h / year
- Variation of parameters:
  - Blade chord, dc = ± 0,1 (10%)
  - The twist angle, dg = ± 50
- Step variation:
  - Chord, c_alfa = 0,1 (10% dc)
  - Twist angle, g_alfa = 0,1 (10% of the dg)

5.3 The calculation process and sensitive analysis

Calculation process begins with the analysis of wind conditions of the given area. The input data, as mentioned above, is a file with a tabular performance of the measured wind speeds. We carry out the actions described in paragraph 3.3.2.

The distribution coefficients have the following values: A=5,695 and k=2. The average speed for the considered period at the height of the tower is 5,06 meters per second. Parameters of the Weibull distribution of wind speeds are assumed to be constant for the all further calculations. Before considering different variations of input parameters, let's study the characteristics of the initial blade shape. To do this, besides the previously mentioned input data, we will submit to the input of the optimization calculation block the following variation parameters: dc = 0,00001; dg = 0,00001. The values must be nonzero for the correct calculation. Remove a tick from the item «Include airfoils variation». Other parameters remain unchanged. We obtain the following operational parameters of the initial blade: C_p = 0,267; L_p = 65,8 dB; COE = 1,13; AEP = 88,5MWh.

If to multiply the COE and AEP we'll received approximately 100%. Indeed, recalling equation (3.26), COE = C_{rot} / AEP, where C_{rot} - relative flow of the material for the blade manufacture in percentage. In this case, the material consumption is equal to one hundred percent of the initial shape, which indicates proper operation of the program.

The aerodynamic power coefficient value of wind turbines is usually about C_p = 0,4. The obtained above without the optimization process value is much smaller. This is evidence that the geometry of the blades and type of profiles do not correspond to the operating conditions. We should consider other variants of the chord and twist angle distribution, as well as different types of profile. The set of combination should allow to use blade with a suitable angle of attack, with more lift and less drag. But first let's consider the variation of geometrical parameters.

Now we define the limits for the blade chord and twist angle variation in accordance with those mentioned in the previous paragraph, but restrict the possibility of the profiles change. Consider series of calculations, changing the weight of aerodynamic, noise and economic parameters (wCp, wLp, wCOE). The results are presented in the tabular form:

Table 5.3.1 Sensitivity analysis for the fixed profile type

Case	w_{Cp}	w_{Lp}	w_{COE}	C_p	L_p,dB	*COE*	*AEP*,MWh	Comments
1	10	1	1	0,272	65,9	1,231	89,9	Cp max, AEP max
2	1	10	1	0,272	65,6	1,259	90,0	Lp min, COE max
3	1	1	10	0,255	66,6	1,062	84,4	COE min, Lp max
4	1	10	10	0,265	66,1	1,169	87,8	Best case for Lp and COE
5	1	1	1	0,268	66,0	1,191	88,6	Equal
6	3	5	7	0,265	66,1	1,156	87,8	Cp ↓; Lp↑; COE↓
7	7	5	3	0,269	65,9	1,221	89,2	Cp ↑; Lp↓; COE↑
8	1	5	10	0,262	66,3	1,132	86,8	Cp ↓; Lp↑; COE↓
9	10	5	1	0,272	65,6	1,257	90,1	Cp ↑; Lp↓; COE↑
10	1	10	5	0,268	65,8	1,210	88,8	Cp ↓; Lp↑; COE↓

Analysis of the results shows that the program gives logical values of technical and economic parameters. In addition, it is clear that considered options and the results are mixed. Thus, if the designer is focused on obtaining the maximum energy production it is better to choose case №1. If the goals are to minimize the noise impact or cost function of the energy production, it is better to select cases №2 or №3 respectively.

The modern approaches for the blade shape optimization are based on consideration to minimize the cost function. It is preferably with all this to choose case №3. Obtained distribution of the blade chord and twist angle are presented in the graphical form (see Fig. 5.3.1). Recall that in these experiments the type of the blade profile did not change. Black line on the figure denotes the original blade, red - optimized.

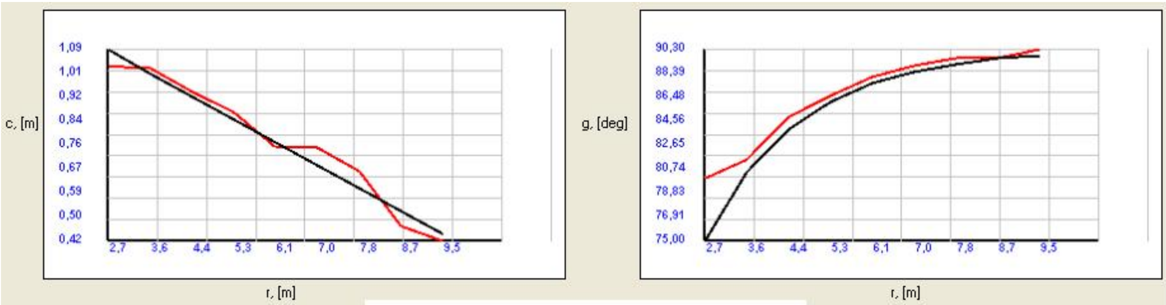


Figure 5.3.1 Dependence c(r) и γ(r) for the case №3 with fixed type of blade profile.

The optimization process is carried out without consideration of mechanical loads. Thus, these results may be unenforceable because of their instability to mechanical stresses. However, this paper was not targeted to take into account the mechanical stresses and to determine the optimized shape of the blade which could be made by the all rules of design.

Now let’s add the possibility of profiles type variation. Thus we will consider the options with various combinations of profiles for which information is contained in the database. The resulting series of calculations are summarized in the table:

Table 5.3.2 Sensitivity analysis with changeable type profile

Case	w_{Cp}	w_{Lp}	w_{COE}	C_p	L_p,**dB**	***COE***	***AEP*,MWh**	**Comments**
1	10	1	1	0,535	65,6	0,422	177,1	Cp max
2	1	10	1	0,535	65,6	0,422	177,1	Lp min
3	1	1	10	0,534	65,9	0,406	177,0	COE min
4	1	10	10	0,535	65,6	0,422	177,1	Best case for Lp and COE
5	1	1	1	0,535	65,8	0,422	177,1	Equal weights

As it can be seen, the values of obtained blade parameters are much better than those which the blade has initially. Thus, the power coefficient can be increased by almost half;

noise exposure slightly lowered and the cost function reduced almost thrice. These results are obtained through the optimal distribution of chord and twist angle of the blade, as well as through the use of more appropriate profiles. The blade is experiencing the best conditions for the lift and less drag.

Calculations showed that when considering various options for the blade profile, the results are roughly the same regardless of variations in the aerodynamic balance, noise and economic parameters. We select case №4 for more detailed consideration. Distributions of chord and twist angle as well as the types of profiles obtained along the length of the blade are presented in tabular and graphical form:

Table 5.3.3 Distribution of the blade chord and twist angle with an indication of the profile type.

r, m	**c, m**	**γ, deg**	**Airfoil**
2,7	1,031	80,0	Lissaman 7769
3,55	1,025	81,5	DAE 11
4,4	1,013	84,4	DAE 21
5,25	0,921	86,6	DAE 21
6,1	0,749	88,1	NACA 0012
6,95	0,747	89,0	DAE 11
7,8	0,665	89,6	NACA 4412
8,65	0,473	89,6	NACA 4412
9,5	0,471	90,3	NACA 0012

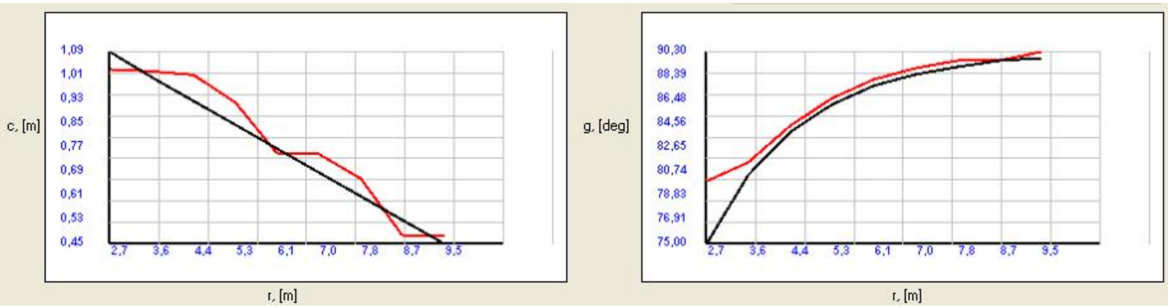


Figure 5.3.2 Dependences c(r) and gamma(r) for the case of variable profile type (black line - the original blade, red - optimized).

Thus, a series of calculations have allowed to find a suitable shape of the wind blade and types of preferred cross-section profiles. Sensitive analysis showed performance capacity of the software used and the calculation methods laid down in it.

Various combinations of weights of the objective functions (Cp, Lp, COE) correspond to different situations. Program testing shows that by varying these parameters the attitude of the designer to the blade shape optimization process can be simulated. In today's world, when not one but many factors play a role in the overall decision, we should be able to analyze different options.

6 CONCLUSIONS

Wind power is one of the most promising areas for energy production from renewable sources. History of the intensive development of this industry has a slightly over fifty years. Thus, one could argue that we are almost at the beginning of this sphere. Technological progress of wind power which occurred in the previous decades as well as its rapid growth nowadays suggests that the process of improving the techniques and equipment is far from complete and much remains to be done. At this stage of development the industry modernizes and improves individual wind turbine nodes. Engineers of all branches combine their efforts in finding the optimal geometric forms and modes of operation of each node. Individually optimized, for example, the wind turbine tower height and materials of which it is made, its shape. The same applies to the remaining parts.

In this regard, for the optimization problem was chosen one of the main elements of wind turbine - its blades. Considering the aerodynamic, noise and economic parameters associated with the production and operation of the blades, there was a try to develop universal method of finding the optimal blade shape. This shape depends on the set of input criteria, and necessarily takes into account the wind conditions of proposed installation site.

For calculation of various operating parameters we used well-known classical or modern methods. Aerodynamic parameters were determined through the classical theory of moments, the blade was divided into sections, and the total response was obtained by adding the characteristics of each section separately. Experimental dependences of the lift and drag forces coefficients on the angle of attack are taken to be independent on the wind flow velocity (Reynolds number), which led to calculations inaccuracies and simplifications. Also the mechanical fatigues are not taken into account, so the obtained blade geometrical parameters may be not suitable for the real blade production. However, these nuances are reduced to simplifications and assumptions.

The basis of the noise calculations is the semi-empirical model which determines the level of noise exposure. Noise pressure in dB was determined at the height of the wind tower. The experimental coefficients of the equations, although they were given for the

NACA0012 profile, showed its applicability to study the possible use of other profiles families. For that purpose there was created a database of profiles that provided the information for them. In the database such families as NACA, DAE and Lissaman are included.

The applied economic model departs from the real monetary terms and presents the cost function in relative units. It considers the relative consumption of materials for the wind blades manufacture, fixed costs, including transportation, maintenance, labor costs, as well as the annual energy production and wind conditions of the proposed installation site. Although the two blades, original and current, were compared only on the condition that they do not differ greatly (since it is assumed that the dependence of material consumption is linear in nature), this economic model was quite suitable for preliminary and optimization calculations.

Method of blade shape optimization uses the desirability function which has never before been used in such technical calculations. The universality of this method in that it is possible to introduce the necessary (and, in principle, unlimited) number of criteria. Each criterion had the appropriate weight in the overall process of optimization, thus it was possible to simulate different life and technology situations. To make the simulation comfortable and functional the special software was developed. Methods of calculation and informational database were laid down into it.

For the analysis of the optimization process was taken the test wind turbine of the Danish National Institute RISO. Its length is 9.5 meters, the tower height 29.3 m. The considered location of wind turbines – the region of Astana city (Kazakhstan). Analysis of the wind conditions allowed to determine the wind speed Weibull distribution coefficients: A=5,695 and k=2. For wind turbine with the primary shape of blades were obtained the following characteristics: C_p=0.267; L_p=65.8 dB; COE=1.13; AEP=88.5MWh.

After the optimization process with a fixed type of considered profiles we obtained the following parameters: C_p=0,255; L_p=66,6dB; COE=1,062; AEP=84,4MWh. It was based on a prerequisite to minimize the cost of production and operation of wind turbine. After analyzing the process of optimization and simulation of different weight distributions between the parameters of the blade and the consideration of options with different types of profiles has been chosen a compromise under which we focused on price and noise level. In this case the wind turbine blades and wind turbine itself have the following parameters: C_p=0,535; L_p=65,6dB; *COE*=0,422; *AEP*=177,1MWh.

Obviously, when used other types of profiles than those from which the blades were made initially, we greatly improved each parameter. Thus, the aerodynamic power coefficient increased more than twice and almost approached its maximum value by the Betz criterion (Cp=0.595). Noise exposure was reduced not much, only by 0,2 dB, but it's still a positive result. And most importantly, the cost function is decreased by more than 2,6 times. This is probably the main advantage of the optimized blade shape. With the increase of power coefficient the annual energy production has also increased.

This work provides a method for solving complex research problems. Further expansion of the database, consideration of other important parameters of the blades, particularly mechanical properties, improvement of the software functionality and much more - all this is the task for the following research and development, which surely will find its application in our science and technology.

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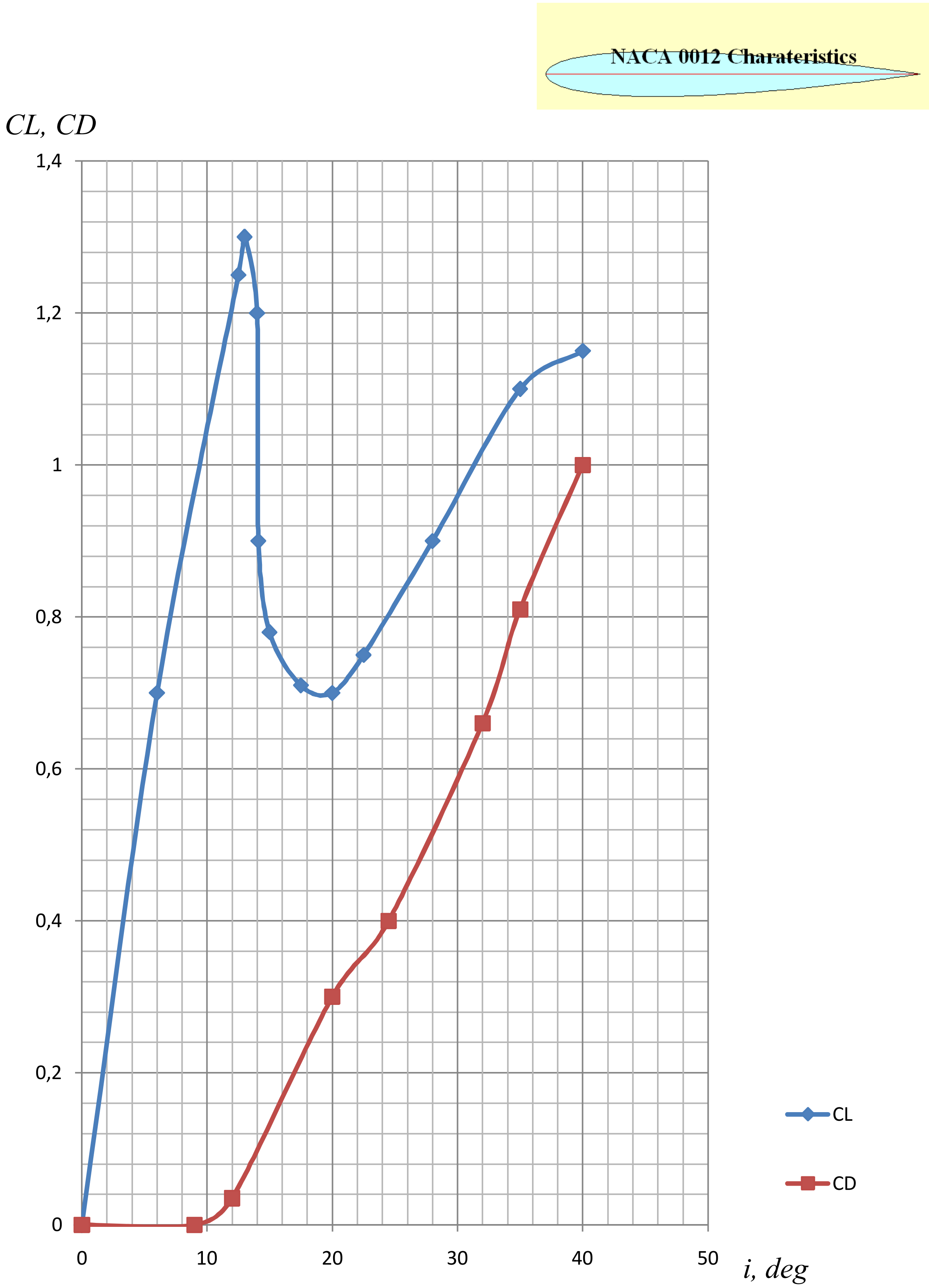
Appendix 1. Profiles data



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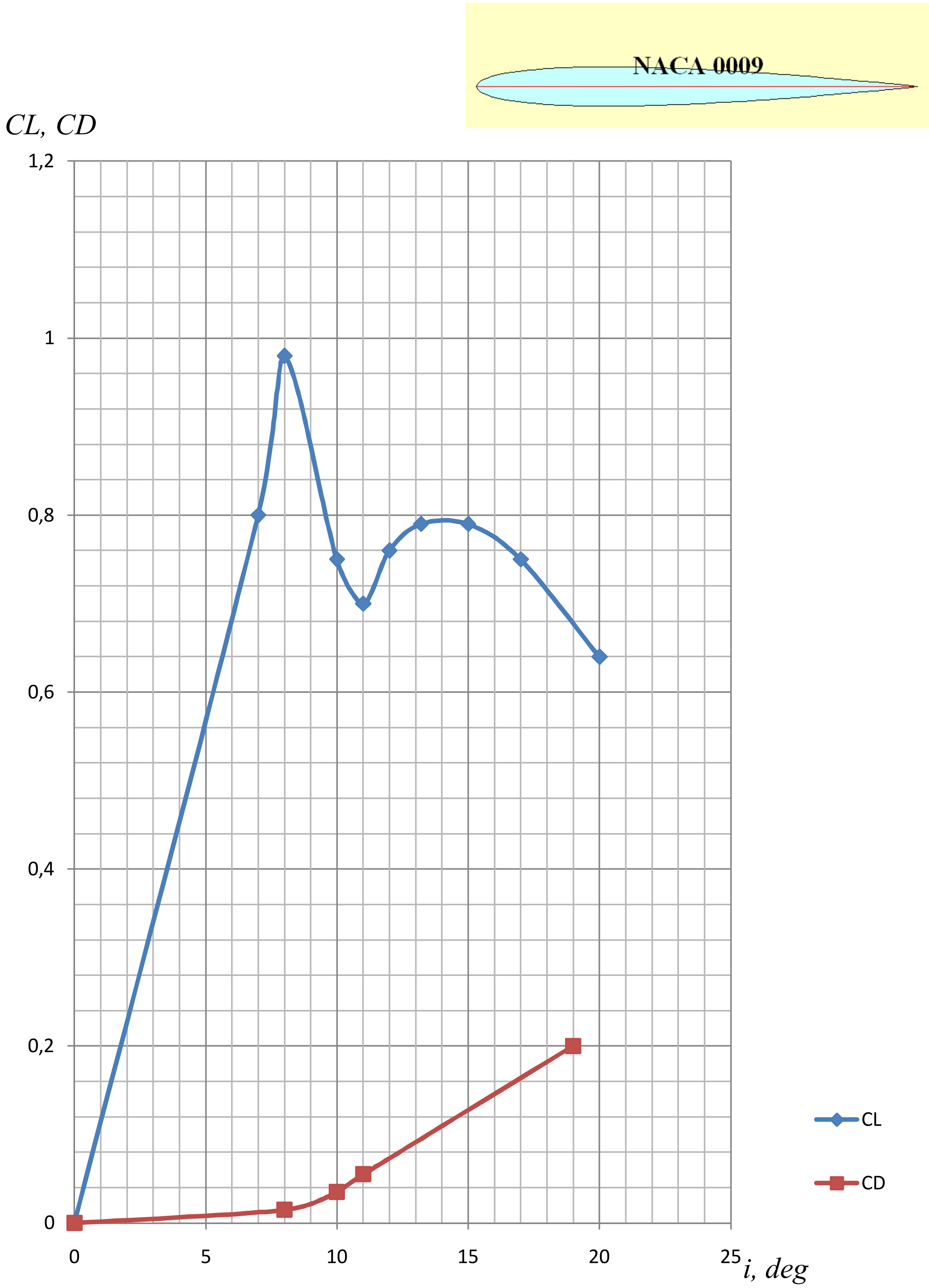

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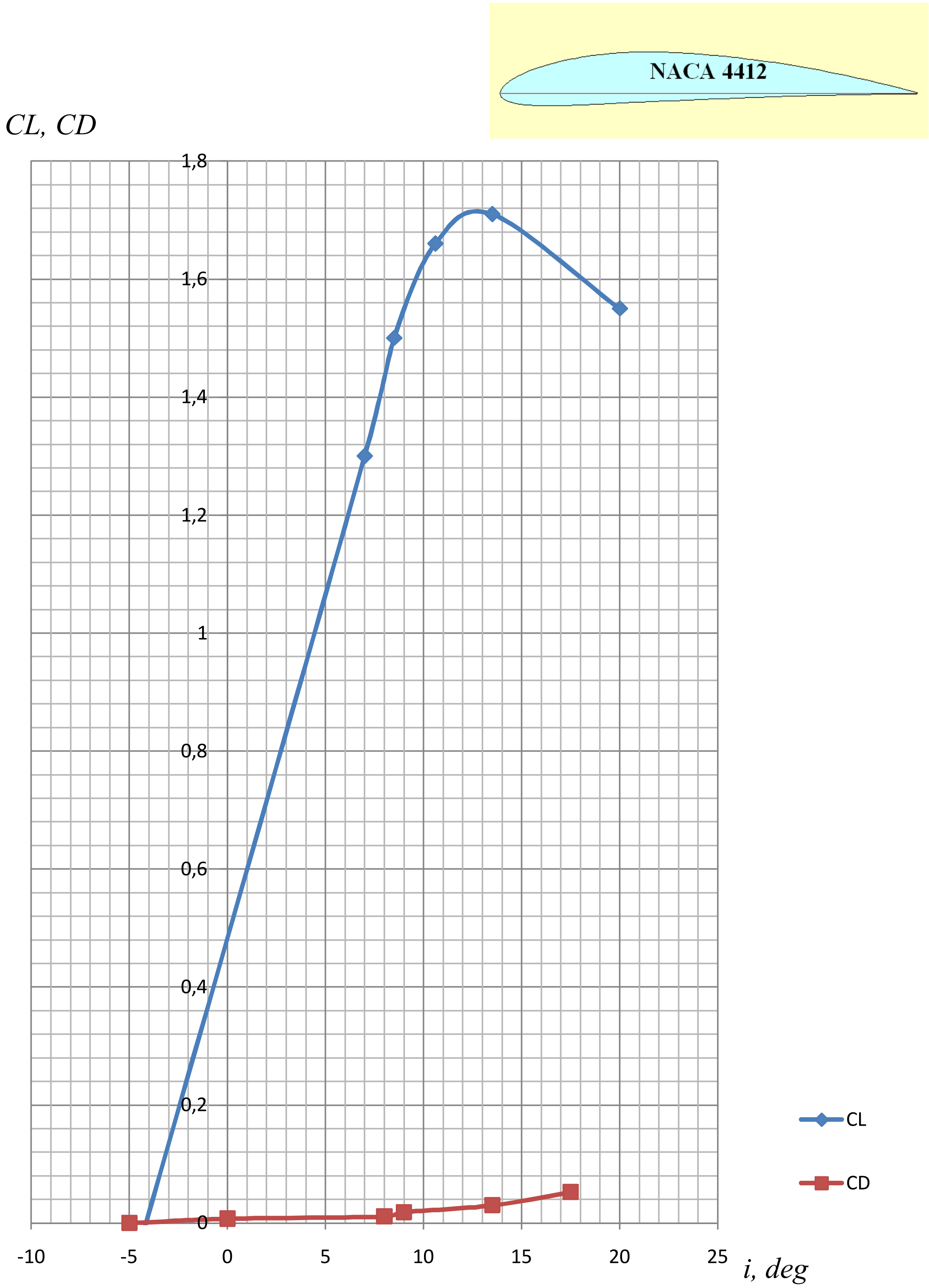
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1,4
1,2
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0,4
0,2
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10
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20
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i, deg
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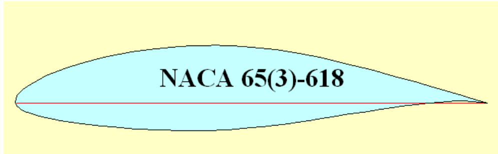
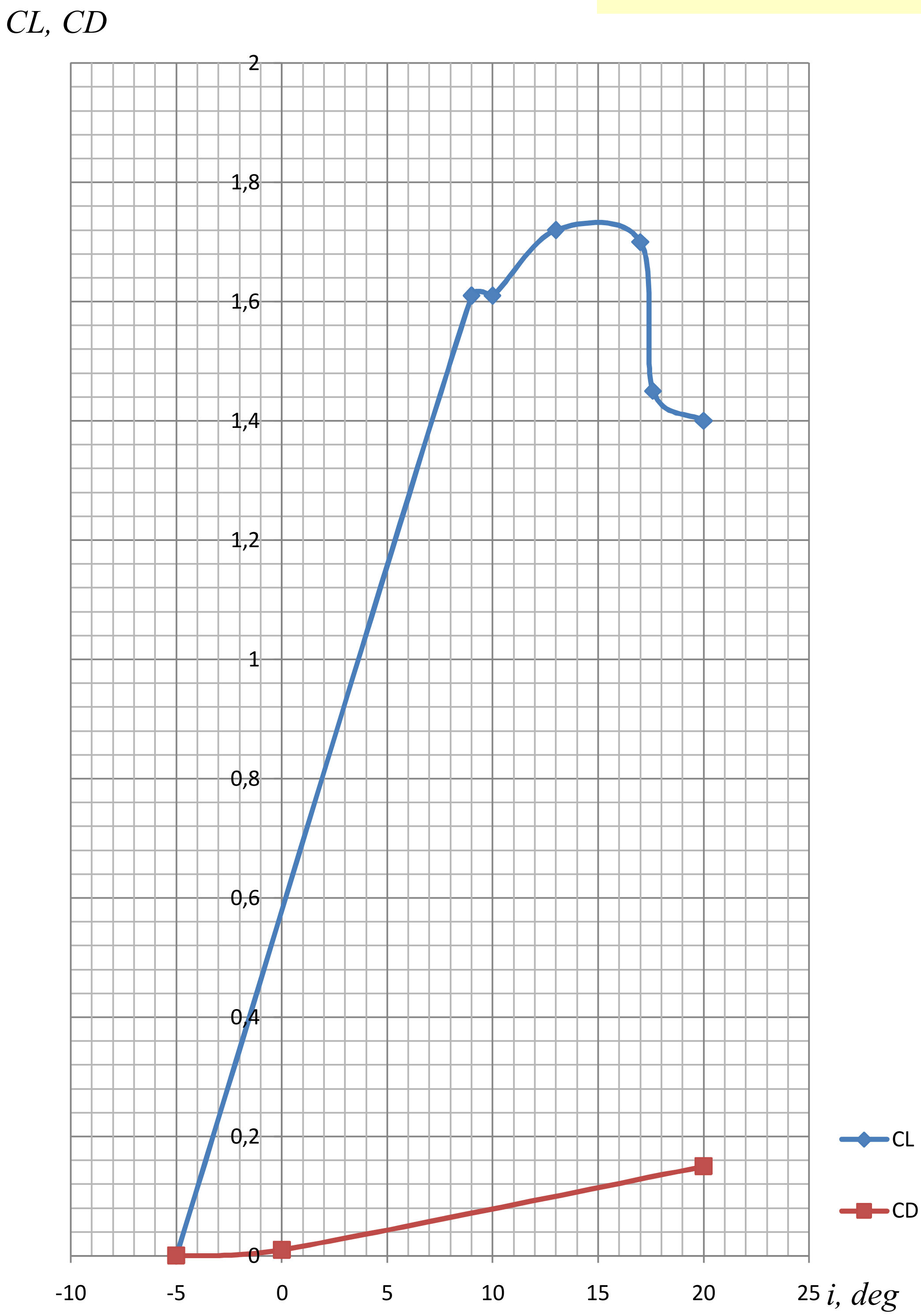

NACA 65(3)-618


CL, CD
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i, deg
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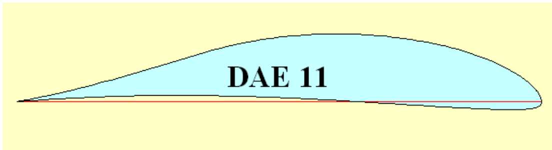

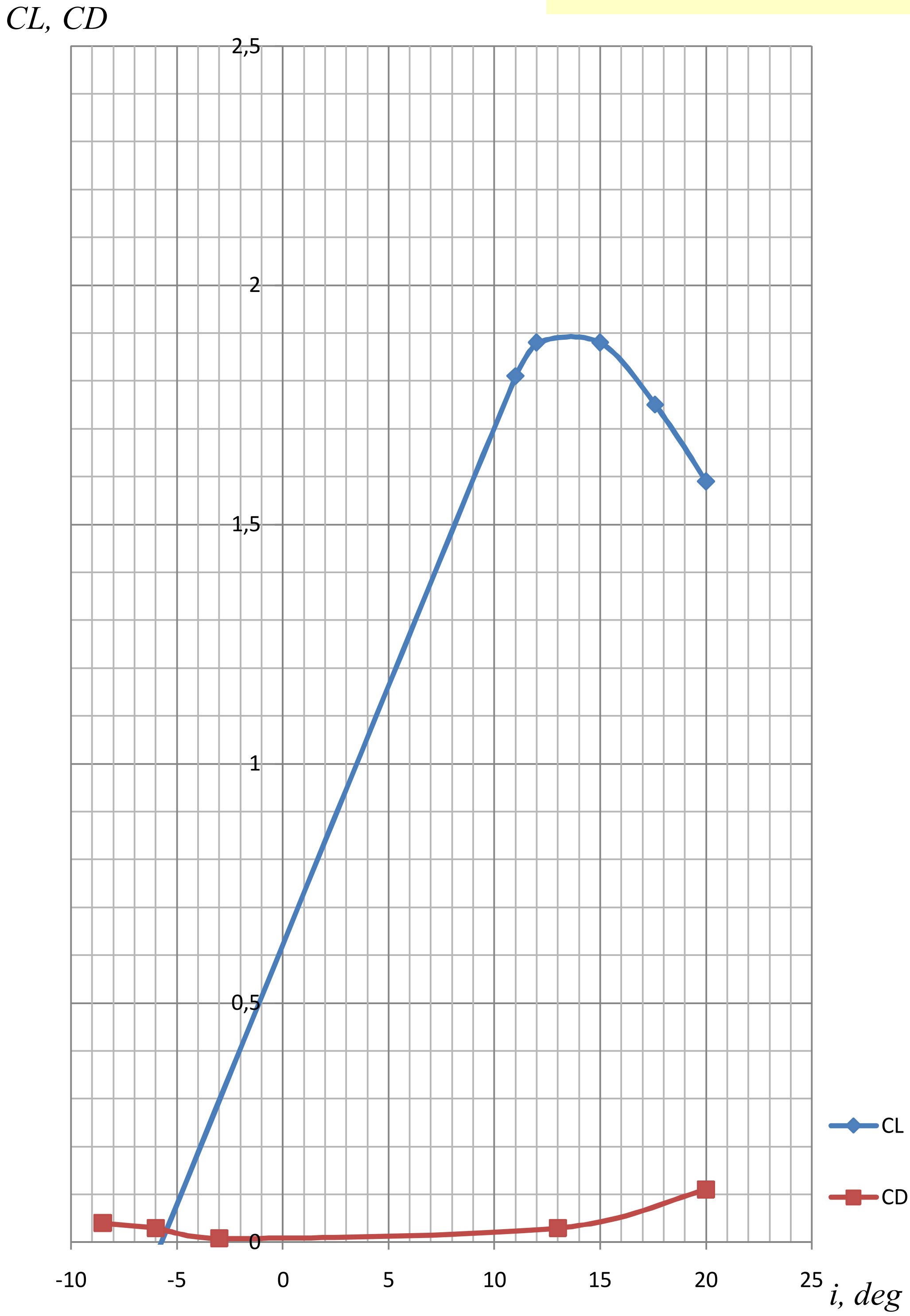

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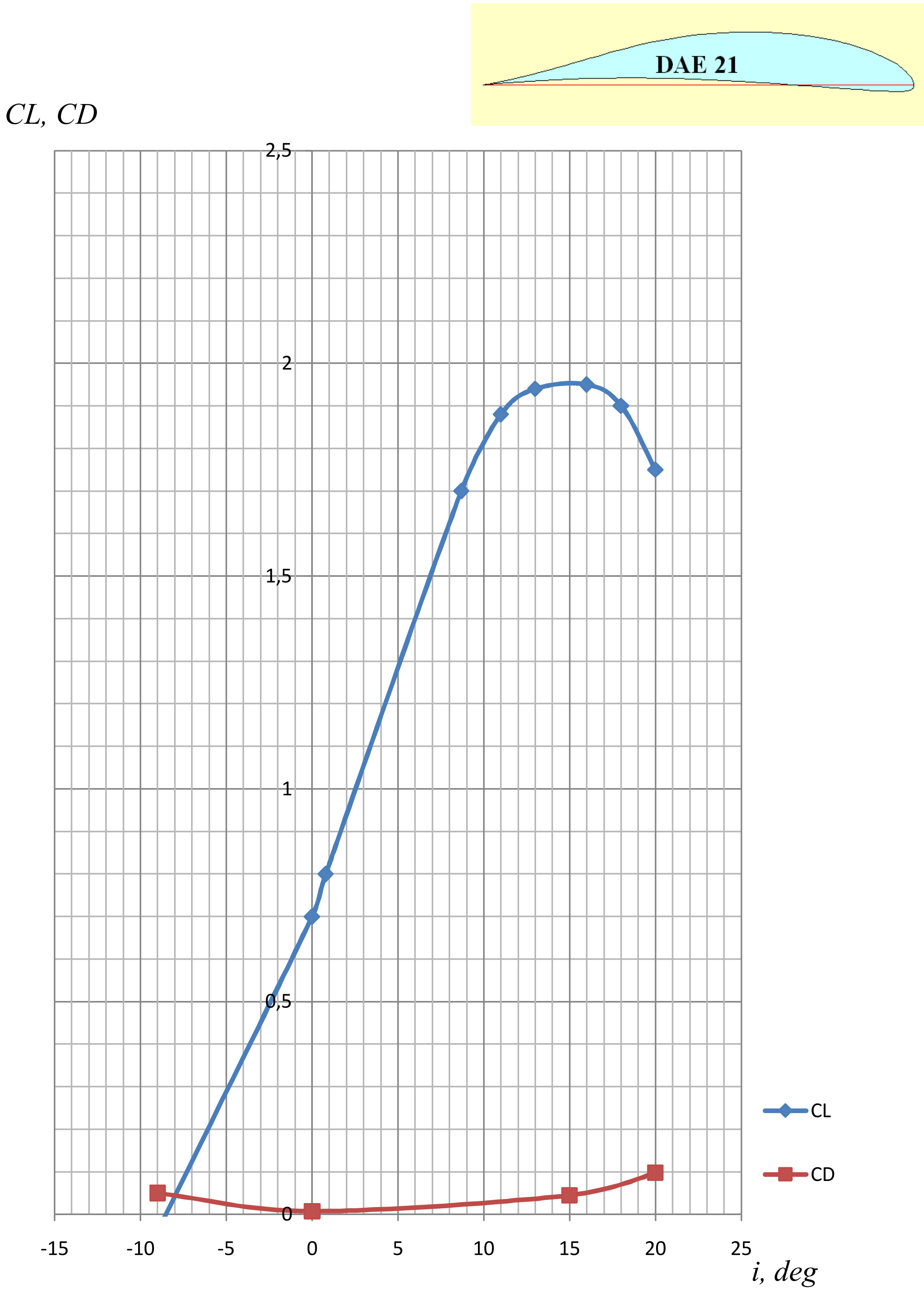

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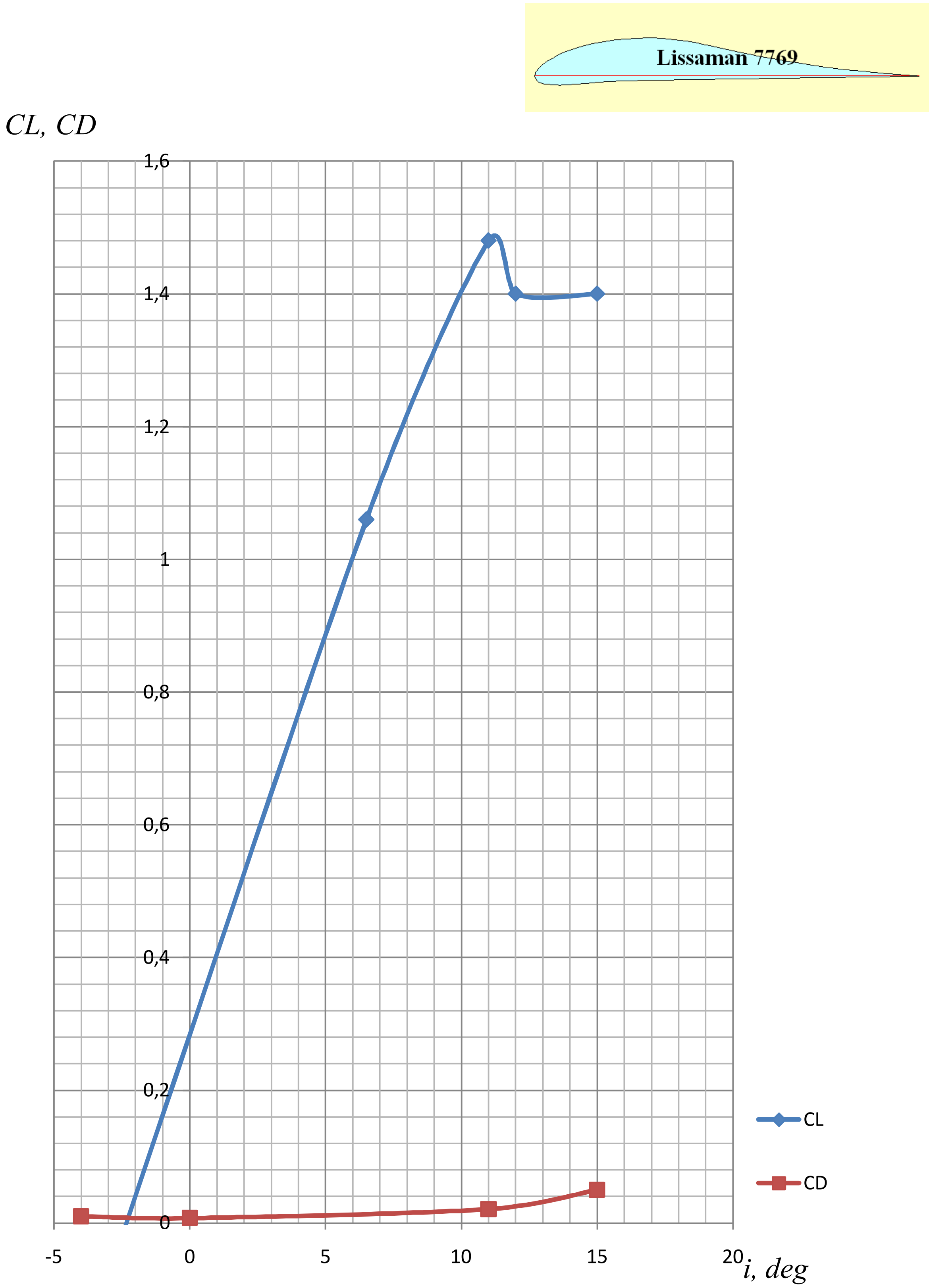

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