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Article

Implementation of a wind turbine blade design tool in an open source integrated development environment

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Abstract: This paper presents the implementation of a design tool, written in Pascal language, of a classic design method of wind turbines based on Blade Element Momentum Theory. The open source integrated development environment Lazarus was used. The software allows the user to visualize the changes in turbine geometry caused by the change in design parameters and the two design methodologies that are possible. Results that validate the algorithm according to the literature are shown. Characteristics of a wind turbine designed with a proper airfoil are also presented. The tool familiarizes the user with the open source philosophy and gives data to the construction of wind turbine models to experiments.

Keywords: Lazarus; Blade Element Momentum Theory; design; wind turbine; Kutta-Zhukovskii (Joukowski) theorem.

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1. Introduction

The need for clean and renewable energy sources in order to replace or complement the fossil fuels based energy matrix demands long and medium term changes in society. The industry, which requires several amounts of energy for its proper activities, is the most affected sector by this issue. To understand the demand caused by this change of paradigm the engineers' acting must be equally changed.

The renewable energy sources of greatest visibility and viability nowadays are: geothermal, solar, wind and biomass [1]. Brazil has a high energetic potential based on the three last ones and the Northeast region has high solar and wind potentials [2-3].

Ceará was one of the first Brazilian states to make an assessment of its wind potential [4]. Nowadays, the state has wind power plants in many cities and new ones are already in design or implementation phase. However, the technology used is majorly from abroad. To master the wind power generation it is necessary to prepare capacitated workers, which are able to design the devices involved in such activity.

The basic design of modern wind turbines is based on Blade Element Momentum Theory (BEM), which was developed by Hermann Glauert in 1926 and uses part of the actuator disc model described by Rankine. Though the BEM method is limited due its hypothesis, it conduces to fairly good results [5]. Many improvements were proposed and the most known one is the study of the drag induced by tip and root vortex, which was done by Ludwig Prandtl. Other methods use optimization algorithms.

The objective of this work was to implement the BEM method in a friendly graphic interface that allows engineers and any interested person to compare the design of different wind turbine rotors. Its concept includes giving to the user the freedom to vary the design parameters in a wide way in order to assess its effects in the rotor geometry. Else, it is desired that the program generates a text file with the geometric characteristics of the blades, in order to make easier the design of the rotor in a CAD tool and afterwards the simulation in a proper CFD tool.

2. Methodology

2.1. A Brief Introduction to Aerodynamics

2.1.1. Basic concepts

When a body is immersed in a flow there is a resultant force caused by the pressure and shear stress distributions over its surface. It is usual to split this force into two components. The first one is called Drag (D) and it is parallel to the direction of the freestream velocity V_∞, the flow far away from the body. The second force is called Lift (L) and it is perpendicular to the direction of the freestream. Figure 1 presents these forces and their directions.

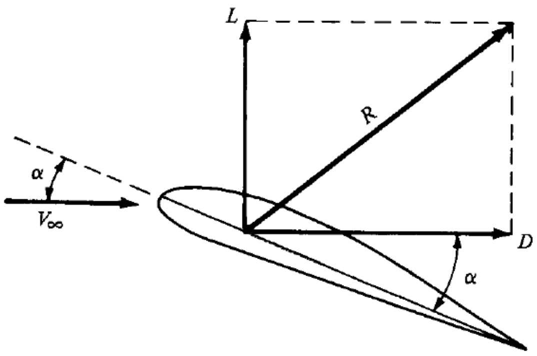


Figure 1. Resultant force over an airfoil. Adapted from [**6**]

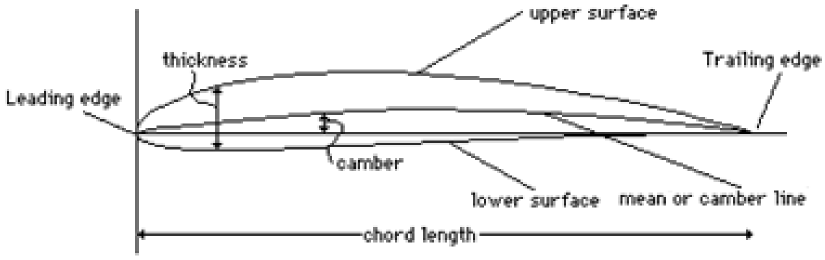


Figure 2. Airfoil geometry.

According to the Kutta-Zhukovskii (Joukowski in western spelling) theorem, all bodies generating lift have a net circulation different from zero over its surface. The circulation is defined as the line integral of the velocity around a closed loop which encloses the body:

$$\Gamma = \oint V \; cos\theta \; ds \tag{1}$$

Where C is the closed reference path, V is the velocity tangent to C and θ is the angle between V and ds.

An airfoil can be the cross section of a wing, propeller or blade. It is relevant to know some of its geometric characteristics, which are shown in Figure 2.

- Leading edge: Frontal extremity of the airfoil.
- Trailing edge: Rear extremity of the airfoil.
- Chord: Segment of line connecting the leading edge and the trailing edge. It is also the longest segment connecting any points of the airfoil's surface.
- Mean camber line: Curve connecting the points midway the upper and lower surfaces. For symmetrical airfoils the mean camber line and the chord coincide.

The biggest part of the lift that acts over buoyant bodies, as cylinders, is due to the pressure and can be evaluated quite well by the inviscid (zero viscosity) fluid model. Nevertheless, this model is unable to predict the shear stress component of the lift. Furthermore, the influence of shear stresses over an airfoil can be more relevant than the pressure along a wide range of flow conditions. Thus the inviscid fluid model is normally not an efficient way to predict the behavior of an airfoil.

The approach often used is empirical, by the determination of nondimensional coefficients to evaluate the airfoil performance. They are the lift coefficient (C_L) and drag coefficient (C_D), which are defined as:

$$C_L = \frac{L}{\frac{1}{2}\rho V_\infty^2 S} \tag{2}$$

$$C_D = \frac{D}{\frac{1}{2}\rho V_\infty^2 S} \tag{3}$$

Where ρ is the specific mass of fluid, V_∞ is the velocity far upstream and S is a reference surface area. For wings, propellers and blades, it is common t use the planform surface.

Under ordinary conditions the lift coefficient varies almost linearly with the incidence angle α. This is a good approximation for small angles. For large angles, the flow is no more attached to the upper surface of the airfoil, the lift decreases heavily and a big component of pressure drag is generated. This phenomenon is called stall. As in the present work the incidence angles are small enough, it is assumed that the flow is always attached to the upper surface and stall does not occur.

2.2. The BEM Method

The rotor is modeled as an actuator disc that induces velocity changes in the flow in its neighborhood. The induction is divided in an axial component and a tangential one, described by their respective factors. The axial flow induction factor (a) is the fraction of the axial speed which is lost by the fluid when it passes through the turbine. In an analog way, the tangential flow induction factor (a') is the fraction of the rotational velocity of the rotor which is transferred to the fluid as angular momentum.

The Blade Element Momentum Theory has as hypothesis bidimensional flow along the blades, i.e., the radial component of the velocity is ignored. This condition is achieved if the axial flow factor does not vary radially. For every radial position the velocity components can be determined as a function of the wind speed, the rotation speed of the rotor and the flow induction factors. Figure 1 shows the forces actuating upon a blade element. If the relation between the aerodynamics characteristics of the airfoil, lift coefficient (c_l) and drag coefficient (c_d), and the angle of attack is known then it is possible to determine the forces upon the blades. Such forces, of aerodynamic nature, are the drag (D) and the lift (L).

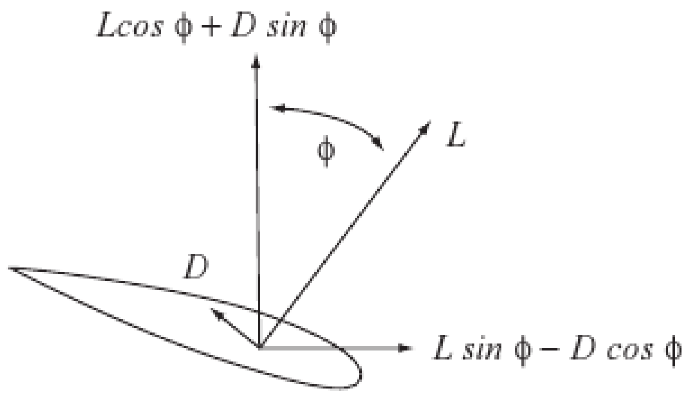


Figure 3. Forces actuating upon a blade element [7]

The BEM equations may be developed to obtain the maximum efficiency geometry for a speed controlled wind turbine. At this turbine type the rotational speed of the rotor is not constant, but the tip speed ratio (λ) is. This value is defined as the ratio between the speed in the blade tip ($\omega.R$) and the wind speed (U_∞). The rotor geometry is then completely defined by these two parameters: the incidence angle of the wind upon the blade (α) and the chord of the blade at every radial position (c). Figure 4 shows the relation between the incidence angle of the wind, the angle of attack and the pitch angle (β).

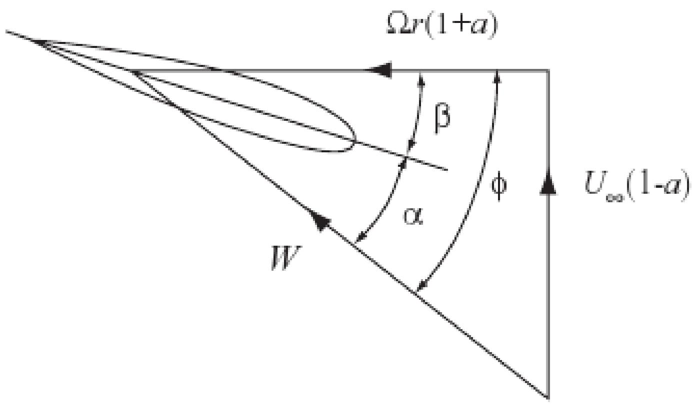


Figure 4. Angles upon the blade [7]

The geometry provided by the method follows the expressions:

$$tg\,\Phi = \frac{U_\infty(1-a)}{\Omega r(1+a')} \tag{4}$$

$$\frac{N}{2\pi}\frac{c}{R}\lambda C_l = \frac{4\lambda^2\mu^2 a'}{\sqrt{(1-a)^2+[\lambda\mu(1+a')]^2}} \tag{5}$$

where Ω is the angular speed of the turbine, r is the radial distance from the rotation axis, N is the number of blades, R is the rotor total radius, μ is an nondimensional radial coordinate, defined as $\mu \equiv r/R$.

It is proved that the maximum efficiency is achieved when the flow induction factors obey the following relations [7]:

$$a=\frac{1}{3} \qquad a'=\frac{a(1-a)}{\lambda^2\mu^2} \tag{6}$$

When the optimal values of the factors are replaced, it is found that:

$$\frac{N}{2\pi}\frac{c}{R}\lambda C_l=\frac{\frac{8}{9}}{\sqrt{\frac{4}{9}+\lambda^2\mu^2[1+\frac{2}{9\lambda^2\mu^2}]^2}} \tag{7}$$

$$tg\Phi=\frac{2}{3\lambda\mu\left(1+\frac{2}{9\lambda^2\mu^2}\right)} \tag{8}$$

The value *(Ncλ Cl)/(2πR)* is considered a geometric parameter of the blade. The way the blade's chord varies radially depends on this parameter. The designer can then adopt two different design methodologies.

2.3. Blade with constant angle of attack

This methodology consists in keeping every blade element deflected in a constant angle of attack and allowing the chord to vary. Such angle is the optimum angle of attack, the one which provides the maximum ratio between the lift and the drag. The blades designed in this way have bigger chords at the root and this usually difficults their construction.

2.4. Blade with linear taper

The second methodology imposes a linear taper to the blade, thus making easier its construction. The blade chord is defined [7] by the equation:

$$\frac{c}{R}=\frac{8}{9\lambda\, 0{,}8}\left(2-\frac{\mu}{0{,}8}\right)\frac{2\pi}{C_l\lambda N} \tag{9}$$

The angles of attack vary radially and can be determined by its relation with the lift coefficient, which depends on the chosen airfoil. If there is no stall in the flow around the blade elements, the relation between C_l and α can be approximated by a linear function:

$$C_l = f(\alpha) = m(\alpha - \alpha_{zero}) \qquad (10)$$

In the equation above, *m* is the angular coefficient of the line, which is experimentally determined, and α_{zero} is the angle of attack at which the airfoil lift is null.

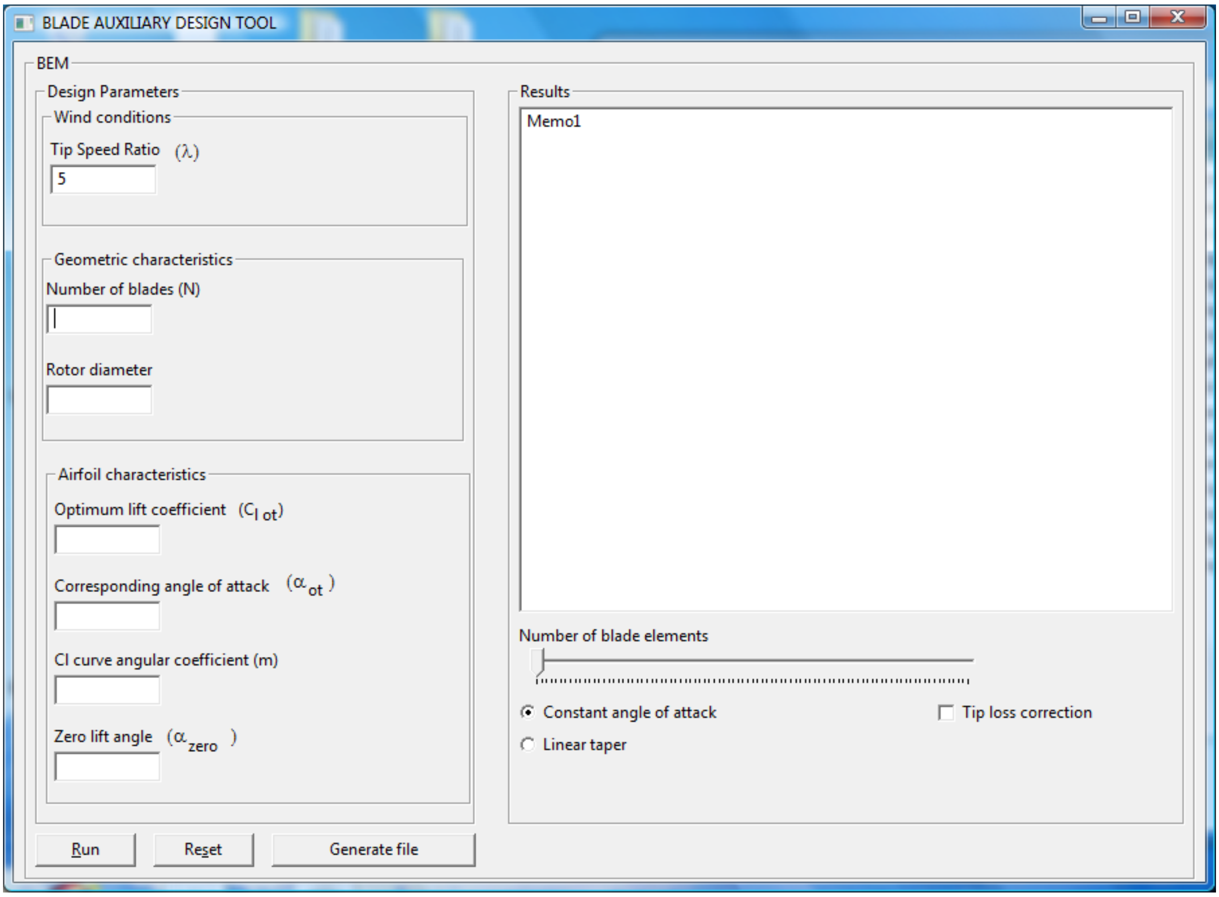


Figure 5. Graphic interface of the program

2.5. Characteristics of the developed code

To implement the algorithm the integrated development environment (IDE) Lazarus was used. Lazarus is an open source IDE based on Pascal language. Thus, the code developed is open and can be manipulated by the users with an open source tool. The program was developed in a way which allows the insertion of new methods of wind turbine design or improvements of the applied method.

The graphic interface is split in two groups: *Design Parameters* and *Results* (Figure 5).

In the *Design Parameters* group there are dialog boxes acting as input of the necessary values to the application of the BEM method. In the subgroup *Wind Conditions* there is the parameter tip speed ratio. In the subgroup *Geometric Characteristics* there are the number of blades of the rotor and its diameter. In the subgroup *Airfoil Characteristics* there are the airfoil optimum lift coefficient ($C_{l\ ot}$), the angle of attack at which this coefficient is achieved (α_{ot}), the angular coefficient of the line used to interpolate the curve C_l versus α for angles lower than the stall angle and the angle of null lift of the airfoil.

In the *Results* group there is a text box, where the values of the chord and the pitch angle for discrete values of μ are presented. Below the box there is a roll bar to choose the number of displayed blade elements. Finally, two radio buttons were used to allow the user to choose which algorithm will be run: constant angle of attack or linear taper.

In the lower section of the interface there are three buttons: *Run*, *Reset* and *Generate file*. Their functions are respectively: run the chosen algorithm, clear all the fields and create a text file with the obtained results.

3. Results and discussion

3.1. Comparative analysis with literature data

In the case of a three bladed rotor, with 3 m diameter, constant angle of attack and optimized for a tip speed ratio $\lambda = 6$, the obtained geometric features for 20 blade elements are presented in Figure 6.

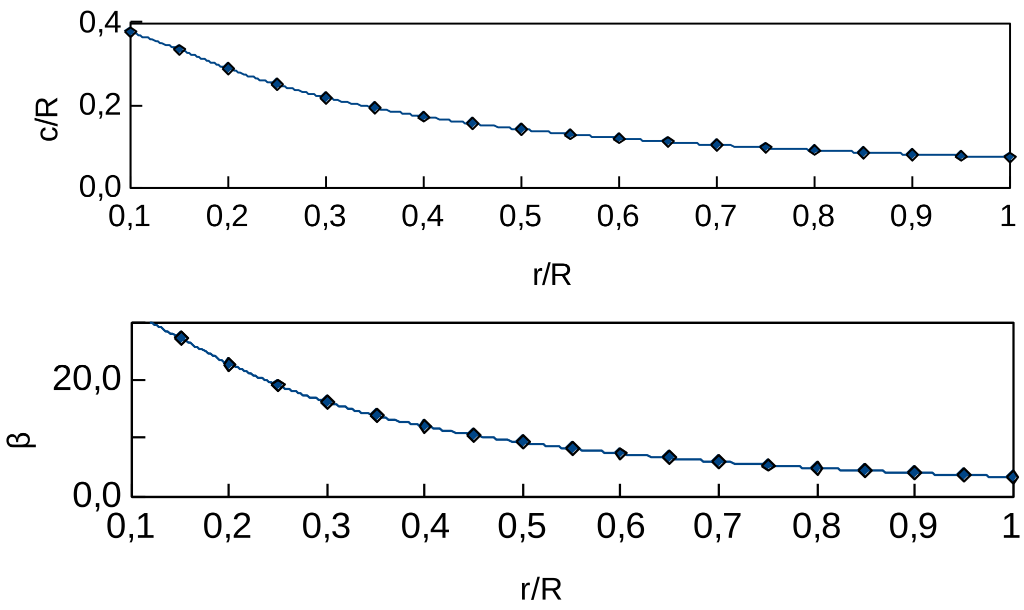
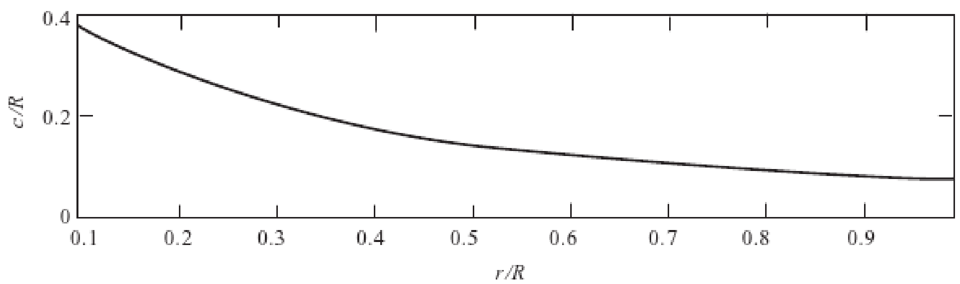


Figure 6. Geometric features of a three bladed rotor optimized to $\lambda = 6$ and constant angle of attack

The airfoil used was the NACA 4412 and its aerodynamic features are quite known. In the conditions above the airfoil has $C_{l\ ot} = 0{,}7$; $\alpha_{ot} = 3°$; m = 0,1 e $\alpha_{zero} = -4°$. These data were taken from the literature [8].

The geometric features of a rotor designed by the same parameters are presented in Figure 7.



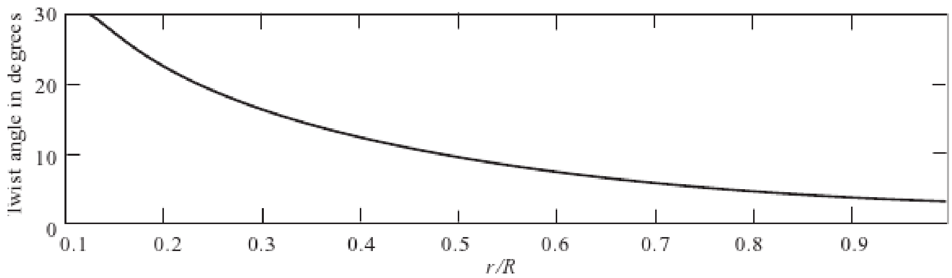


Figure 7. Geometric features of a NACA 4412 three blade rotor optimized to λ = 6 and constant angle of attack [7]

The accordance between the data can be observed.

Figure 8 shows the results for a rotor designed with the S809 airfoil, adequate to the use in wind turbines. The rotor has two blades, a diameter of 10 m and it is optimized to a tip speed ratio of λ = 5. In these conditions, the airfoil has $C_{l\ ot}$ = 0,86; α_{ot} = 6,2°; m = 0,13 e α_{zero} = -1°. These data were taken from the literature [9].

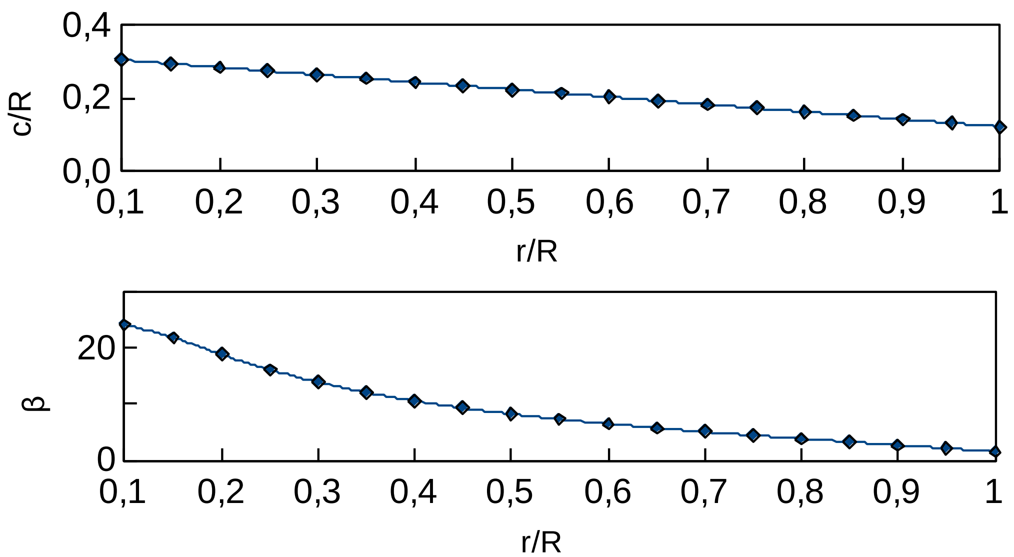


Figure 8. Geometric features of a S809 two bladed rotor with linear taper optimized to λ = 5

4. Conclusions

The BEM method has been used as one of the classic choices of wind turbine design. Its application has been efficient in the visualization and study of the wind turbine geometry.

The open source implementation of the method will allow the expansion of the program and the addend of any other wind turbine design method. Therefore, it familiarizes the user to the open source philosophy. The result achieved is an easy to use design tool able to visualize the geometry of a wind turbine either to supply the user with necessary data for the construction of an experimental or study model. The source code and a compiled version can be found at:

http://www.posmec.ufc.br/~laero/SDPA/1.0/Fontes%20-%20Pascal%20BEM%201.0%20-%20Ingles.zip
(English version)

http://www.posmec.ufc.br/~laero/SDPA/1.0/Fontes%20-%20Pascal%20BEM%201.0%20-%20Port.zip
(Portuguese version)

Conflict of Interest

"The authors declare no conflict of interest".

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