Analysis of the Blade Element Momentum Theory, application to river current power extraction

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50 ans du LJLL - Roscoff, 4.3.19
Evaluation and design of propeller, Seminal models:

- **1865**: "Momentum Theory": William J. M. Rankine\(^1\), also Greenhill and Froude.
- **1878**: "Blade Element Theory": William Froude\(^2\), also Taylor and Drzewiecki.
- **1919**: The 1D-model of Betz and the Betz limit
  \[ C_{p,Betz} = \frac{16}{27} \approx 0.5926 \]
- **1926**: "Blade Element Momentum Theory": Glauert’s breakthrough.
  \[
  \begin{align*}
  1 & \text{ Combine "Momentum Theory" and "Blade Element Theory",} \\
  2 & \text{ Take into account the wake momentum.}
  \end{align*}
  \]

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1. The Glauert’s model
   - Local/Macro decomposition
   - Reformulation
   - Correction of the model
   - Existence of solutions

2. Classical solver
   - Usual algorithm
   - Convergence issues

3. Optimization
   - Functional
   - Usual algorithm
   - With correction?

4. Conclusion
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4. Conclusion
Hermann Glauert, 1892-1934.

Ideas:
- Decompose the blade into elements, considered to be independent.
- Coupling of two models:
  1. Local 2D model, describing the lift and drag forces on a 2D profile
  2. Macroscopic model, describing the evolution of a fluid ring crossing the propeler

*The Elements of Aerofoil and Airscrew Theory* - 1926
Local 2D model:
Using windtunnel, or Computational Fluid Mechanics, one use a 2D prototype or model to assess the Drag and Lift forces on a profile, assuming they are on the form:

\[ dL = C_L(\alpha) \frac{1}{2} \rho W^2 c(r) dr \]
\[ dD = C_D(\alpha) \frac{1}{2} \rho W^2 c(r) dr. \]

with:
- \( \alpha \) = angle of incidence,
- \( W \) = macroscopic velocity in \( x = -\infty \),
- \( c \) = is the chord distribution.

http://www.pilotwings.org/
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- \( \alpha \) = angle of incidence,
- \( W \) = macroscopic velocity in \( x = -\infty \),
- \( c \) = is the chord distribution.

"Wind Turbine Blade Analysis using the Blade Element Momentum Method", Notes by G. Ingram.
Macroscopic model: axial and rotational interference factors

\[ a = \frac{U_{-\infty} - U_{x=0}}{U_{-\infty}} \]

\[ a' = \frac{\omega_{x=0} + \omega_{x=0}'}{2\Omega} \]

"Aerodynamics for students",
http://www-mdp.eng.cam.ac.uk
Macroscopic model:
axial and rotational interference factors

\[ a = \frac{U_{-\infty} - U_{x=0}}{U_{-\infty}} \]

\[ a' = \frac{\omega_{x=0}^+}{2\Omega} \]

Macroscopic model: Angular relations

\[ \theta = \text{Blade angle} \]
\[ \alpha = \text{Incidence angle} \]
\[ \varphi = \text{Relative angle deviation} \]

"The element will work at \[ \alpha = \theta - \varphi. \]"
Macroscopic model:
Angular relations

Glauert motivation: aeronautics

\[ \Rightarrow a_{\text{Glauert}} \rightarrow -a, \]
\[ a'_{\text{Glauert}} \rightarrow -a' \]
\[ \theta \rightarrow \gamma \lambda. \]

\[ \tan^{-1} \varphi = \lambda \frac{1 + a'}{1 - a} \]
\[ \lambda = \frac{r \Omega}{U_{-\infty}} \]

16-2. Consider next the aerodynamic forces experienced by the blade element at radial distance \( r \). The blade element is subject to an axial velocity \( V(1 + a) \) and a rotational velocity \( W \). If \( W \) is inclined at an angle of incidence of \( \phi \), and if \( \theta \) and \( \phi \) give the corresponding lift and drag coefficients, \( C_L \) and \( C_D \), appropriate to the aerofoil section in two-dimensional motion. The components of these force coefficients, resolved in the direction of the thrust and torque, are respectively

\[ \lambda_1 = C_L \cos \phi - C_D \sin \phi, \]
\[ \lambda_2 = C_L \sin \phi + C_D \cos \phi, \]

and the elements of thrust and torque given by the blade element of area \( cd\alpha \) are

\[ dT = \lambda_1 \frac{1}{2} \rho W^2 cd\alpha dr, \]
\[ dQ = \lambda_2 \frac{1}{2} \rho W^2 cd\alpha dr. \]

The Glauert’s model

Local/Macro decomposition

Using Bernouilli’s relation, one can find the elementary force and torque:

\[ dF_x = \rho U_x^2(4a(1 - a))\pi r dr, \]
\[ dT = 4a'(1 - a)\rho U_x^0 r^3\Omega \pi dr. \]

But the lift and drag coefficients definitions imply

\[ dF_x = \sigma(r)\pi \rho \frac{U_x^2(1 - a)^2}{\sin^2 \varphi} (C_L(\varphi - \gamma) \cos \varphi + C_D(\varphi - \gamma) \sin \varphi) r dr, \]
\[ dT = \sigma(r)\pi \rho \frac{U_x^2(1 - a)^2}{\sin^2 \varphi} (C_L(\varphi - \gamma) \sin \varphi - C_D(\varphi - \gamma) \cos \varphi) r^2 dr, \]

where we have introduced the **local solidity**, defined by:

\[ \sigma(r) = \frac{Bc(r)}{2\pi r}. \]
We end up with the Glauert’s system:

\[ \tan^{-1} \varphi = \lambda \frac{1 + a'}{1 - a}, \]

\[ \frac{a}{1 - a} = \frac{\sigma(r)}{4 \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \cos \varphi + C_D(\varphi - \gamma \lambda) \sin \varphi), \]

\[ \frac{a'}{1 - a} = \frac{\sigma(r)}{4 \lambda \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \sin \varphi - C_D(\varphi - \gamma \lambda) \cos \varphi). \]
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Simplification : we assume $C_D = 0 \rightarrow$ fits with the practical cases\(^3\)

\[
\tan^{-1} \varphi = \lambda \frac{1 + a'}{1 - a} ,
\]

\[
\frac{a}{1 - a} = \frac{\sigma(r)}{4 \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \cos \varphi) ,
\]

\[
\frac{a'}{1 - a} = \frac{\sigma(r)}{4 \lambda \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \sin \varphi) .
\]

---

\(^3\) "In the calculation of induction factors, [...] accepted practice is to set $C_D$ equal to zero [...]. For airfoils with low drag coefficients, this simplification introduces negligible errors." , Manwell et al. p.125.
\begin{align*}
\tan^{-1} \varphi &= \lambda \frac{1 + a'}{1 - a}, \\
\frac{a}{1 - a} &= \frac{\sigma(r)}{4 \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \cos \varphi), \\
\frac{a'}{1 - a} &= \frac{\sigma(r)}{4 \lambda \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \sin \varphi).
\end{align*}

Remarks:

- Also for practical cases, we are interested in solution such that \( C_L(\varphi - \gamma \lambda) > 0 \Leftrightarrow \gamma \lambda > \varphi, \)
- \((a, a', \varphi) = (1, a', \frac{\pi}{2})\) is always a (non-interesting) solution of this system.
Set $\mu_{CL} = \mu_{CL}(\varphi) := \frac{\sigma(r)C_L(\varphi - \gamma \lambda)}{4}$:

\[\tan^{-1} \varphi = \frac{\lambda}{1 - a} \left( 1 + a' \right),\]

\[\frac{a}{1 - a} = \frac{\sigma(r)}{4 \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \cos \varphi),\]

\[\frac{a'}{1 - a} = \frac{\sigma(r)}{4 \lambda \sin^2 \varphi} (C_L(\varphi - \gamma \lambda) \sin \varphi).\]
\[
\begin{align*}
\tan^{-1} \varphi &= \lambda \frac{1 + a'}{1 - a}, \\
\frac{a}{1 - a} &= \frac{\mu_{CL}}{\sin^2 \varphi} \cos \varphi, \\
\frac{a'}{1 - a} &= \frac{\mu_{CL}}{\lambda \sin \varphi}.
\end{align*}
\]
To study the solution(s) of Glauert’s system, we rewrite it:

\[
\tan^{-1} \varphi = \lambda \left( 1 + \frac{\mu C_L}{\sin^2 \varphi} \cos \varphi \right) + \frac{\mu C_L}{\sin \varphi}
\]

\[\iff \mu C_L = \sin \varphi \frac{\cos \varphi - \lambda \sin \varphi}{\sin \varphi + \lambda \cos \varphi} \]

\[\iff \mu C_L = \sin \varphi \tan(\theta \lambda - \varphi) =: \mu_G.\]

Solving Glauert’s approach consists in solving:

\[
\frac{\sigma(r) C_L (\varphi - \gamma \lambda)}{4} = \sin \varphi \tan(\theta \lambda - \varphi)
\]

\[\iff \mu C_L(\varphi) = \mu_G(\varphi)\]
Example: river current power, ‘Hydrolienne H3’

→ A.N.R HyFloEFlu
The Glauert’s model
Reformulation
1. The Glauert’s model
   - Local/Macro decomposition
   - Reformulation
   - **Correction of the model**
   - Existence of solutions

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4. Conclusion
Recall that:

\[ dF_x = 4a(1-a)U^2_{-\infty} \rho \pi r dr. \]

The quantity

\[ C_T = \frac{dF_x}{\frac{1}{2} U^2_{-\infty} \rho 2\pi r dr}, \]

is called local thrust coefficient.

---

Figure 3.29  Fits to measured wind turbine thrust coefficients

Manwell et al, "Wind Energy Explained Theory, Design and Application", 2nd Ed., p.130
The Glauert’s model
Correction of the model

\[
dF_x = 4a(1-a)U^2_{-\infty} \rho \pi r dr \\
\downarrow \\
dF_x = 4\chi(a, a_c)U^2_{-\infty} \rho \pi r dr \\
= 4(a(1-a) + \psi((a-a_c)_+))U^2_{-\infty} \rho \pi r dr
\]

<table>
<thead>
<tr>
<th>Order</th>
<th>Author</th>
<th>(a_c)</th>
<th>(\psi((a-a_c)_+))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Glauert</td>
<td>1/3</td>
<td>(\frac{(a-a_c)<em>+}{4} \left( \frac{(a-a_c)</em>+^2}{a_c} + 2(a-a_c)_+ + a_c \right))</td>
</tr>
<tr>
<td>2</td>
<td>Glauert emp.</td>
<td>2/5 (a_c(1-a_c))</td>
<td>(\frac{(a-a_c)<em>+ + [F</em>\lambda(\varphi)(a-a_c)<em>+ + 2F</em>\lambda(\varphi)a_c - 0.286]}{2.5708}F_\lambda(\varphi))</td>
</tr>
<tr>
<td>2</td>
<td>Buhl</td>
<td>2/5</td>
<td>(\frac{1}{2F_\lambda(\varphi)} \left( \frac{(a-a_c)_+}{1-a_c} \right)^2)</td>
</tr>
<tr>
<td>1</td>
<td>Wilson et al.</td>
<td>1/3</td>
<td>(a-a_c)^2_+)</td>
</tr>
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</table>
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4. Conclusion
Lemma

Suppose that \((\varphi, a, a')\) satisfies Glauert’s model.

1. There exists \(\tau : \varphi \mapsto a = \tau(\varphi)\) satisfying:

\[
\frac{a}{1 - a} + \left(1 - \frac{\cos \theta \lambda \cos \varphi}{\cos(\theta \lambda - \varphi)}\right) \frac{\psi ((a - a_c)_+)}{(1 - a)^2} = g(\varphi),
\]

with

\[
g(\varphi) := \tan^{-1} \varphi \tan(\theta \lambda - \varphi) + \frac{\mu_{CD}}{\sin \varphi} \left(1 + \tan^{-1} \varphi \tan(\theta \lambda - \varphi)\right),
\]

2. The unknown \(\varphi\) satisfies

\[
\mu_{CL}(\varphi) - \tan(\theta \lambda - \varphi)\mu_{CD}(\varphi) = \mu_{\tilde{G}}(\varphi),
\]

where

\[
\mu_{\tilde{G}}(\varphi) := \mu_G(\varphi) + \frac{\cos \theta \lambda \sin^2 \varphi \psi ((\tau(\varphi) - a_c)_+)}{\cos(\theta \lambda - \varphi)} \frac{(1 - \tau(\varphi))^2}{(1 - \tau(\varphi))^2}.
\]
Expanding further, one finds
\[ a = 1 - \sqrt{\frac{\psi(1 - a_c)}{\mu_{CD}(0)}} \varphi^{3/2} \]

**Lemma**

The function $\mu_G^c$ satisfies
\[ \mu_G^c(\varphi) \approx \varphi = 0^+ \frac{\mu_{CD}(0)}{\varphi}. \]
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Usual way to solve this system :

airfoil characteristics. Thus, the total system of equation, which is both nonlinear and implicit, needs to be solved either by employing a nonlinear solution technique for the full system of equations or by using a simple iterative updating technique. For several reasons, the latter is the most convenient method to be used. A solution procedure may proceed as follows:

1. Divide the rotor blade into a number of spanwise elements (typically 20–30) and start an iterative procedure for each element.
2. Guess $a$ and $a'$. The guess may either be based on the values obtained at the previous element or, e.g., by putting $a = 1/3$ and $a' = 0$.
3. Compute the flow angle from the expression: $\phi = \tan^{-1}\left(\frac{1-a}{\lambda x(1+a')}\right)$, where $\lambda = \frac{\Omega R}{U_0}$ is the tip speed ratio and $x = r/R$.
4. Compute the angle of attack, $\alpha = \phi - \gamma$, and based on this, determine the airfoil characteristics, $C_l = C_l(\alpha)$ and $C_d = C_d(\alpha)$.
5. Compute $C_n$ and $C_r$.
6. Update $a$ and $a'$ and continue the process until convergence.

"General Momentum Theory for Horizontal Axis Wind Turbines", J. N. Sorensen
Usual way to solve this system:

\[ \tan^{-1} \varphi^{k+1} = \lambda \frac{1 + a'^k}{1 - a^k}, \]

\[ \frac{a^k}{1 - a^k} = \frac{\sigma(r)}{4 \sin^2 \varphi^k} (C_L \varphi^k - \gamma \lambda) \cos \varphi^k + C_D \varphi^k - \gamma \lambda) \sin \varphi^k, \]

\[ \frac{a'^k}{1 - a^k} = \frac{\sigma(r)}{4 \lambda \sin^2 \varphi^k} (C_L \varphi^k - \gamma \lambda) \sin \varphi^k - C_D \varphi^k - \gamma \lambda) \cos \varphi^k. \]
Theorem

Let

$$\mu_{CL}(\theta \lambda) \leq \mu_G(\gamma \lambda).$$

and

$$\frac{\|\mu'_{CL}\|_\infty h(\gamma \lambda)}{1 + \lambda^2} \leq 1$$

and

$$\frac{\|\mu_{CL}\|_\infty |h'(\gamma \lambda)|}{1 + \lambda^2} \leq 1.$$

Then, the sequence $$(\varphi^k)_{k \in \mathbb{N}}$$ defined by the classical solver converges to a solution of Glauert’s model.
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All the variant of the model may give rise to multiple solutions. More precisely:

1. With the simplification $C_D = 0$ and $C_L$ approximately linear around 0: two solutions.
2. Stall: possible other solution after the critical angle.
3. Corrected model: $\mu_G$ may change of concavity.

→ possible problem of convergence..
⇒ Bisection method will always work...
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Quantity to maximize:

\[ C_P = \frac{8}{\lambda^2} \int_{\lambda_r}^{\lambda_R} \lambda^3 a'(1 - a) \left( 1 - \frac{C_D(\varphi - \gamma\lambda)}{C_L(\varphi - \gamma\lambda)} \tan \varphi \right) d\lambda. \]

Design parameters: \( c(r), \gamma\lambda(r) \Rightarrow (\mu_{C_L}, \mu_{C_D}). \)

Indeed:

\[
\begin{align*}
\mu_{C_L} &= \sigma(r) \frac{C_L(\gamma\lambda(r) - \varphi)}{4} \\
\mu_{C_D} &= \sigma(r) \frac{C_D(\gamma\lambda(r) - \varphi)}{4} \\
\sigma(r) &= \frac{Bc(r)}{2\pi r}.
\end{align*}
\]
Mathematical formulation, for fixed $\lambda$:

$$\min J(\mu_{CL}, \mu_{CD}) = a'(1 - a) \left(1 - \frac{\mu_{CD}}{\mu_{CL}} \tan^{-1} \varphi \right),$$

under the constraints

$$\tan^{-1} \varphi = \lambda \frac{1 + a'}{1 - a},$$

$$\frac{a}{1 - a} = \frac{1}{\sin^2 \varphi} \left(\mu_{CL} \cos \varphi + \mu_{CD} \sin \varphi \right),$$

$$\frac{a'}{1 - a} = \frac{1}{\lambda \sin^2 \varphi} \left(\mu_{CL} \sin \varphi - \mu_{CD} \cos \varphi \right).$$

and with

$$\mu_{CL} = \frac{\sigma(r)C_L(\gamma_{\lambda} - \varphi)}{4} \quad \mu_{CD} = \frac{\sigma(r)C_D(\gamma_{\lambda} - \varphi)}{4}.$$
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If the correction on $a$ is not included, the following procedure is used:

3.10.1.2 Define the Blade Shape

5. Obtain and examine the empirical curves for the aerodynamic properties of the airfoil at each section (the airfoil may vary from the root to the tip), i.e. $C_l$ vs. $\alpha$, $C_d$ vs. $\alpha$. Choose the design aerodynamic conditions, $C_{l,design}$ and $\alpha_{design}$, such that $C_{d,design}/C_{l,design}$ is at a minimum for each blade section.

\[ J(\mu_{C_L}, \mu_{C_D}) = a'(1 - a) \left( 1 - \frac{C_D(\varphi - \gamma \lambda)}{C_L(\varphi - \gamma \lambda)} \tan^{-1} \varphi \right) \]

\[ \Downarrow \quad C_D \approx 0 \]

\[ J(\mu_{C_L}) = a'(1 - a). \]

After this step $\alpha^* = \varphi - \gamma \lambda$ is fixed!
Consider then:

\[ J(\mu_{CL}) = a'(1 - a). \]

Taking into account that \( \mu_{CL}(\varphi) = \mu_G(\varphi) := \sin \varphi \tan(\theta_\lambda - \varphi) \), one can rewrite \( J \) only in term of \( \varphi \).

\[ J(\varphi) = \frac{1}{2\lambda} \frac{\sin^2 \varphi}{\sin \theta_\lambda} \sin(2(\varphi - \theta_\lambda)) \]

whose optimum is obtained for:

\[ \varphi^* = \frac{2}{3} \theta_\lambda \]
End of the design procedure:

Recall that $\alpha^* = \varphi - \gamma_\lambda$ and $\mu_{CL} = \frac{\sigma(r)C_L(\varphi - \gamma_\lambda)}{4}$, then

$$\gamma^*_\lambda = \alpha^* + \varphi^*$$

$$c^* = \frac{8\pi r}{BC_L(\alpha^*)\mu_C(\varphi^*)}$$
Summary:

\[
\min J(\mu_{CL}, \mu_{CD}, \varphi) \quad s.t. \quad Eq(\mu_{CL}, \mu_{CD}, \varphi) = 0
\]

\[
\downarrow (1)
\]

\[
\min J(\mu_{CL}, \varphi) \quad s.t. \quad Eq(\mu_{CL}, \varphi) = 0
\]

\[
\downarrow (2)
\]

\[
\min J(f(\varphi), \varphi)
\]

\[
\downarrow
\]

Explicit solution!
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Using the expansion:

\[ a = 1 - \sqrt{\frac{\psi(1 - a_c)}{\mu_{C_D}(0)}} \varphi^{3/2}, \]

we obtain

\[ J(\mu_{C_L}, \mu_{C_D}) \approx \frac{\psi(1 - a_c) \tan \theta}{\lambda} (1 - \mu_{C_D}(0)) \varphi^2. \]

**Theorem**

There exists \( a_c^0 < 1 \) such that for \( a_c \leq a_c^0 \), the optimal solution does not activate the thrust correction.
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4 Conclusion
The BEM is a $0D \times 2D$ coupled model.

- Condition on $\gamma_\lambda$ and $C_L$ to guarantee existence of solution of interest
- Possible multiple solutions
- Optimization: existence, definition of a research interval

Possible extension to $1D \times 2D$?
Une conférence Maths/Énergies Marines :
https://emrsim2019.sciencesconf.org/
4-7 Juillet
Une conférence Maths/Énergies Marines :
https://emrsim2019.sciencesconf.org/
4-7 Juillet

⇒ À Roscoff!!