Aeroelastic analysis of membrane blade via panel-BEM coupling

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Abstract. This paper aims at introducing a methodology for aeroelastic analysis of membrane blades using panel-BEM coupling. The proposed methodology is used for evaluating the performance of a membrane blade with the baseline platform similar to the NASA-Ames Phase VI blade. The performance of the membrane blade is compared with the rigid baseline blade. The studied membrane blade has certain aerodynamic advantages over its rigid counterpart. For the studied blade and at higher wind speeds, the axial induction factor for membrane blade is nearer to the Betz optimum value of 1/3 and as a result the membrane blade is more efficient in producing power. The performance of the membrane blade is further examined via high fidelity FSI analysis. The same trend as in panel-BEM coupling is also observed in the high fidelity model, namely for higher wind speeds the studied membrane blade is more efficient than its rigid counterpart.

1. Introduction
This paper studies the performance of a new concept for a flexible wind turbine blade. Different concepts have been utilized to add flexibility to wing structures like morphing wings [1] or wing frames with telescopic spars [2]. The membrane blade concept utilizes pre-stressed membranes to construct the surface of the blade, which facilitates lightweight construction of the blade. It is inspired by the sailwing concept proposed by Ormiston [3] during the 70s. Schematic representation of the membrane blade concept is shown in Fig. 1. The leading edge and the root region are assumed to be rigid. Four ribs support the membranes along the blade and at the leading edge the membranes are attached to a pre-stressed trailing edge cable.

The blade element momentum (BEM) method is the most common approach for calculating aerodynamic loads on a wind turbine and analyzing its aerodynamic performance [4]. The method is very fast and provides good results if accurate lift and drag coefficient data as a function of the angle of attack are available. Obviously, the classical BEM cannot be used for the analysis of a blade with deformable cross-section.

A novel approach for low fidelity analysis of the membrane blade concept is proposed based on panel-BEM coupling. The proposed method uses a three-dimensional panel code solver for calculating the pressure distribution over the surface of the blade in order to estimate the aerodynamic loading for calculating the shape of the blade, combined with a two-dimensional panel method solver for polar calculations of the 2D blade sections. The 2D vortex panel method replaces the look-up tables for the lift and drag coefficients and calculates these coefficients on the run during the FSI iterations.
The panel-BEM coupling approach provides a very fast and robust tool for the analysis of the membrane blade at a reasonable computational cost, which specializes facilitates the early design stages. Its major drawback is that because of the fact that the panel method neglects viscous effects it does not predict stall and consequently over-predicts power generation. Final designs of the membrane blade must therefore be examined in more detail using high fidelity models. The studied blade in this contribution is furthermore studied via high fidelity FSI simulation based on coupling between OpenFOAM and Carat++ (the in-house Finite Element Method (FEM) based structural solver at the chair of structural analysis, TU Munich). Results from both modeling levels have predicted the same trend. For the studied blade, the camber of the membrane blade increases with the increase of wind speed and the membrane blade becomes more efficient than the rigid baseline blade at higher wind speeds.

![Membrane blade planform (without twist)](image)

**Figure 1:** Membrane blade planform (without twist)

2. Method
A typical FSI analysis using the staggered approach consists of a fluid solver and a structural solver with the two solvers exchanging information at the fluid-solid interface. Evaluating the aerodynamic performance of the membrane blade via BEM-Panel coupling in a fluid-structure interaction workflow requires two levels of coupling and hence two levels of communication. First of all, the structural solver needs to communicate with the fluid solver in order to exchange loading and displacement data. Secondly, on the fluid side, the BEM solver needs to receive the lift and drag coefficients from the 2D panel method solver at each iteration in order to update the relative velocity at each blade section.

During the explicit coupling iteration these steps are performed for each iteration in the following order:

(i) The BEM solver receives the lift and drag coefficient and calculates the induced velocities for all radial blade sections.

(ii) The panel solver solves the fluid problem. The resulting forces are then sent to the structural solver.

(iii) The structural solver calculates the displacements and sends them to the BEM solver, the 2D panel solver and the 3D panel solver.

The above-mentioned steps are taken for each iteration until convergence is reached. For the iterative solution of the BEM solver a relative tolerance of $10^{-6}$ for the convergence of the axial and tangential induction factors is used. The same tolerance is also used for the convergence
of the coupling iterations between the fluid solver and the structural solver. The schematic representation of a single coupling iteration is shown in Fig. 2. For the sake of brevity more details on the implemented panel solvers and structural modeling of the membrane blade is referred to [5] and [6].

![Diagram of FSI coupling](image)

**Figure 2:** Realization of FSI coupling: sequence of data transfer between the solvers.

The overall algorithm for performing the steady-state FSI analysis of the membrane blade via Panel-BEM coupling is presented in algorithm 1. The color coding in the algorithm follows that of Fig. 2. The proposed workflow is verified by testing it for the NASA-Ames Phase VI wind turbine, which is used as the baseline rigid blade. The obtained pressure distribution at the radial position of \( \frac{r}{R} = 0.8 \) for a wing velocity of \( U = 7 \, \text{m/s} \) and a pitch angle of \( \theta_p = 3^\circ \) is presented in Fig. 3. The comparison is made with the numerical data and experimental results reported in [7].

![Graph comparing pressure distribution](image)

**Figure 3:** Comparison of the pressure distribution obtained using the proposed work flow with numerical and experimental data.
while convergence = false do
  for each coupling iteration do
    update the fluid mesh;
    for each radial element do
      initialize $a$ and $a'$;
      while BEMconvergence = false do
        calculate the relative flow angle;
        calculate angle of attack;
        // 2D Panel method
        2D profile discretization;
        calculate panel properties;
        calculate the influence coefficients;
        calculate the RHS;
        solve for vortex strength;
        calculate pressure;
        calculate $C_l$ and $C_d$;
        calculate $C_n$ and $C_t$;
        check BEMconvergence;
      end
    end
  end
  write BEM output;
  calculate panel properties; // 3D panels
  update the local velocity;
  calculate 3D influence coefficients;
  calculate the RHS;
  solve for vortex strength;
  calculate pressure;
  send force;
  write output;
  receive force;
  calculate displacement;
  send displacement;
end
check convergence;
end

Algorithm 1: The iterative BEM solution for the membrane blade.

Structural analysis of membrane structures consists of two steps: form finding and static or dynamic analysis.

The goal of form finding analysis is to find the equilibrium shape of the membrane for a prescribed pre-stress distribution and confined to a predefined boundary condition (supporting frame, i.e. the ribs, trailing edge cable and the rigid leading edge in the case of the membrane blade). For structural modeling of the blade in FEM, 3 element types have been used. The trailing edge cable is modeled as truss elements, the ribs are modeled as beams and membrane elements (with no bending stiffness) are used to model the pre-stressed membranes. The leading edge is assumed to be rigid in the analysis.

Non-linear static analysis of the membrane blade in FSI analysis is performed using load-control approach [8]. The analysis starts with the equilibrium shape which is the outcome of the form finding analysis (shown in Fig. 4) and consequently updates the shape of the blade by
calculating its deformation under the applied aerodynamic load.

3. Results
FSI analysis of a membrane blade via Panel-BEM coupling is presented in this section for a specific membrane blade based on the NASA-Ames Phase VI turbine. The finite element model of the blade is shown in Fig. 4.

Figure 4: The finite element model of the membrane blade.

Comparison of the Deformed Shapes
The cross section of the membrane blade at the middle of the third segment is shown in Fig. 5. Both deformed and undeformed cross sections are presented. For lower wind velocities there are suction regions on both sides of the blade and parts of the lower membrane move downward, causing the profile thickness to increase. But as the wind speed increases, above 8 m/s in this case, only positive pressure is observed at the side of the blade which faces the wind. With the upward movement of the lower membrane, the profile thickness decreases and at the same time the camber increases.

Comparison of the Angle of Attack
In this section, the local angle of attack along the blade for the flexible membrane blade is compared with the baseline rigid blade. The variation of the angle of attack (and chord length) with the deflection of the trailing edge (Fig. 6) is taken into account in calculating the effective angle of attack and chord length for the membrane blade.

The comparison is depicted in Fig. 7 for the wind speed of $U = 8\text{ m/s}$ at the pitch angle of $\theta_p = 5^\circ$. The vertical lines show the position of the ribs. The maximum local angle of attack along the blade is about 10.2°. Apart from a portion of the first segment, for the other segments of the membrane blade the local angle of attack for the membrane blade is smaller than the stall angle of attack for the S809 airfoil. Therefore, for this operating condition of the turbine the results from panel method are valid.

Apart from the first segment, for the other segments the membrane blade has a smaller local angle of attack compared to the rigid blade. Despite lower local angle of attack along most parts of the blade for the membrane blade compared with the rigid blade, the generated power by
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U = 5 m/s
U = 6 m/s
U = 7 m/s
U = 8 m/s
U = 9 m/s
U = 10 m/s

Figure 5: Profile comparison at the middle of the third segment. The arrows and the legends correspond to the displacement (m).

|AB| = undeformed chord length

|AC| = deformed chord length

Figure 6: Change of the angle of attack and chord length as a result of trailing edge’s deflection.

Figure 7: Comparison of the local angle of attack between the membrane blade and the baseline rigid blade. ($U = 8 \text{ m/s}, \theta_p = 5^\circ$)

the membrane blade is higher. This should be attributed to the change in blade’s cross section and the increase of camber in the membrane blade. This is also reflected in the distribution of the lift coefficient along the blade which is shown in Fig. 8. Since for each blade segment the maximum deflection of the membrane occurs at the middle of the segment, the camber of the blade’s profile has a local maximum in the middle of each segment. Consequently there exists a local maximum for the lift coefficient at the middle of each segment as well. At the first segment the lift coefficient is smaller for the membrane blade, but at the other three segments, the membrane blade has higher lift coefficient. Based on the Betz theory, for an ideal rotor and with neglecting the drag force and wake rotation the optimum energy extraction from the wind occurs at an axial induction factor of $\frac{1}{3}$. For the three outer segments of the blade, the axial
induction factor of the membrane blade is higher than the rigid baseline blade (Fig. 9). Overall, the axial induction factor along the blade is nearer to the optimum axial induction factor for the studied membrane blade.

Figure 8: Comparison of the 2D lift

Figure 9: Comparison of the axial induction factor.

4. High Fidelity Analysis

To overcome the shortcoming of the proposed approach (neglecting the viscous effects), it is necessary to analyze the final design of the membrane blade using high fidelity models utilizing CFD for flow modeling. This section discusses the performance of the membrane blade in rotating configuration via high fidelity steady-state FSI analysis. Multiple Reference Frame (MRF) approach in OpenFOAM is used for modeling of the rotating blade. In the coming sections, first the model setup in OpenFOAM is presented and verified for the case of the rigid blade. The verified setup is then used for the FSI analysis of the membrane blade. Finally, comparison of the performance of the membrane blade with the baseline rigid blade is discussed.

4.1. Simulation setup

Schematic representation of the computational domain used in the analysis is presented in Fig. 10. The NASA-Ames Phase VI wind turbine is a two-bladed turbine. Only one blade is modeled using periodic boundary condition for the boundaries cyclicAMI1 and cyclicAMI2. The utilized boundary conditions are summarized in Table 1.

Figure 10: Computational domain and its dimensions. R is rotor’s radius.

Figure 11: Vortex structures in the wake of the rotor.
Table 1: Boundary conditions for CFD simulations.

| boundary         | \( U \)   | \( p \)     | \( nut \)  | \( nuFields \) |
|------------------|-----------|-------------|------------|---------------|
| inlet            | fixedValue| zeroGradient| fixedValue | fixedValue    |
|                  | uniform \((u, v, w)\) |             | uniform 1.03\(e^{-5}\) | uniform 6\(e^{-5}\) |
| outlet           | zeroGradient| fixedValue  | zeroGradient| zeroGradient  |
| farFieldWall     | slip      | slip        | slip       | slip          |
| blade            | fixedValue| zeroGradient| nutkWallFunction| fixedValue    |
|                  | uniform \((0, 0, 0)\) |             | uniform 0 | uniform 0     |
| cyclicAMI1&2     | cyclicAMI | cyclicAMI   | cyclicAMI  | cyclicAMI     |

4.2. CFD analysis of the baseline rigid blade

Steady-state analysis of the rotating blade problem is performed using the simpleFoam solver. Rotation of the blade is taken into account via Multi Reference Frame (MRF) in OpenFOAM. The SpalartAllmaras model is used for turbulence modeling. The blade is discretized into 75 elements in the spanwise direction and into 240 elements in the chordwise direction, resulting in a 3D volume mesh consisting of about 9.3 million elements. The structure of the vortices in the wake of the rotor and the induced rotation in the flow is graphically presented in Fig. 11 \( (U = 7 \text{ m/s}, \theta_p = 5^\circ) \).

To verify the simulation setup the obtained results have been compared with the available experimental and numerical results. Comparison of the distribution of the pressure coefficient over the blade with experimental and numerical data reported in [7] is shown in Fig. 12 at \( r/R = 0.3 \) section and in Fig. 13 at \( r/R = 0.8 \) section of the blade. Both figures correspond to \( U = 7 \text{ m/s} \) and \( \theta_p = 3^\circ \). There is a good agreement between the OpenFOAM results and the reference results.

![Figure 12: comparison of the pressure coefficient at \( r/R = 0.3 \)](image1)

![Figure 13: comparison of the pressure coefficient at \( r/R = 0.8 \)](image2)

Next, comparison of the predicted power generation is made in Fig. 14 for the pitch angle of \( \theta_p = 5^\circ \) and for wind speeds of 5, 7 and 9 m/s. Again, the calculated results match very well the reference results, with their relative difference being less than 5%. The verified fluid setup is used in the next section for FSI analysis of the membrane blade.

4.3. FSI analysis of the rotating membrane blade

This section discusses the steady-state FSI analysis of the membrane blade in rotating, uniform flow condition. The analysis is done for the pitch angle of \( \theta_p = 5^\circ \) and for three different wind speeds: 5, 7 and 9 m/s.
Comparison of the calculated power ($\theta_p = 5^\circ$).

Camber line comparison
Comparison of the camber line between the membrane blade and the baseline rigid blade is presented in Fig. 15. The camber line in the middle of segment 1 and 4 is depicted in the figure. For $U = 5\ m/s$ the rigid blade has a higher camber. Furthermore, the point of maximum camber is shifted toward the leading edge for the membrane blade. With the increase of membrane’s deflection with the increase of wind speed, for $U = 7\ m/s$ and $U = 9\ m/s$ the camber for the membrane blade is higher than the baseline rigid blade.

Power comparison
Fig. 16 compares the generated power between the membrane blade and the baseline rigid blade. The same trend as in panel-BEM coupling results is observed in the high-fidelity analysis of the membrane blade. The initial shape of the membrane blade is not an aerodynamically optimal shape. In the initial shape, the cross section of the membrane blade at different spanwise locations looks like shrunk airfoils. It is the deflection of the membranes which changes the cross section profile of the blade and converts the initial shape to a more airfoil-like shape. At the wind speed of $U = 5\ m/s$ the deflection of the membranes is apparently smaller than 7 and 9 $m/s$ and the power generated by the membrane blade is slightly lower than that of the baseline rigid blade. But with the increase of wind speed and respectively the increase of membrane’s
deflection and profile’s camber, the studied membrane blade surpasses the baseline blade in generating power. For $U = 5 \text{ m/s}$ the membrane blade generates about 1.5% less power, but for $U = 7 \text{ m/s}$ and $U = 9 \text{ m/s}$ the membrane blade produces respectively 9.2% and 7% more which should be mainly due to increase of profile’s camber compared with the rigid blade.

![Figure 16: Comparison of the generated power.](image)

**Pressure distribution comparison**
Finally, the pressure distribution over the two blades is compared. The comparison is made in Fig. 17 for the wind velocity of $U = 7 \text{ m/s}$. The enclosed area within the pressure coefficient curve shows the pressure difference between the suction and the pressure side of the blade which is the main contributor to the lift force. The membrane blade produces more power at $U = 7 \text{ m/s}$, so it should have generated more lift. This is approved by the comparison of the pressure distribution over the blade. Compared with the rigid blade the enclosed area within the pressure coefficient curve of the membrane blade is larger. For the first segment, the difference is less significant, but the relative difference increases toward the tip of the blade.

![Figure 17: Comparison of pressure coefficient distribution at the middle of blade segments ($U = 7 \text{ m/s}$). Left: segment 1, right: segment 4.](image)

5. **Conclusion**
A methodology for FSI analysis of a membrane blade concept via panel-BEM coupling was introduced. The analysis work flow is based on coupling between a structural solver and a fluid
solver block including a 2D and 3D panel solver for calculating the loading and a BEM part for evaluating the performance of the blade. The proposed approach is, despite its drawback in neglecting viscous effects, a very fast and robust tool for analysis of the membrane blade and performing an extensive exploration of the design envelope in the early stages. Furthermore, the high fidelity analysis of the blade is presented. The result obtained from the two modeling levels predict the same trend: for smaller wind speed the rigid blade is more efficient than the studied membrane blade, but with the increase of wind speed and membrane’s deflection the studied membrane blade becomes more efficient and operates at an axial induction factor which is nearer to the Betz optimal value of 1/3.

Even though the obtained results for the membrane blade in the studied example are promising, future studies regarding the transient response of such a blade including viscous effects, fatigue life-time analysis of the membranes, response of the blade to wind gusts, etc. need to be performed. Performance of the studied membrane blade concept in the case of larger rotors needs to be done in future steps as well.

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