Finite element analysis of a kite for power generation

Computational modelling of flight dynamics of a tethered wing including non-linear fluid-structure interaction.

Allert Bosch - 26 April 2012
We use 16TW of power

= 8,000,000,000
The energy consumption will grow with *53%* between 2008-2035.
The power of the wind at 100m is 1700TW.
only 0.02 TW installed capacity in 2000
0.2TW
installed capacity in 2011
0.2TW
installed capacity in 2011

a very small fraction
Two problems with wind turbines

Intermittent technology
Two problems with wind turbines

Intermittent technology

High construction costs
Airborn wind energy devices are lightweight and have access to higher altitudes.
There is more wind-energy at high altitudes.
Kites can be used to generate electric power.

TU Delft:
Kites can be used to generate electric power.
Content

1. Kite powered energy
2. Thesis goal
Content

1. Kite powered energy
2. Thesis goal
3. Approach
4. Kite model
5. Aerodynamic model
6. Cable model
7. System integration

what?

how?
Content

1. Kite powered energy  
2. Thesis goal  
3. Approach  
4. Kite model  
5. Aerodynamic model  
6. Cable model  
7. System integration  
8. Results  
9. Conclusions
Kite powered energy
How does it work?

generation phase
How does it work?

**generation phase**

**retraction phase**
Crosswind figure eight
System overview

- kite
- bridles
- power lines
- steering lines
- control pod
- tether
- ground station
System overview

- kite
- bridles
- power lines
- steering lines
- control pod
- tether
- ground station

wind direction

power lines
steering lines

powered
depowered

pitch angle
System overview

- Kite
- Bridles
- Power lines
- Steering lines
- Control pod
- Tether
- Ground station
- Struts
- Canopy
- Leading edge
- Bridles
- Trailing edge
- Steering lines
- Power lines
- Control pod
Kite modelling

1. Controller design
2. Optimization studies
3. Develop new kites

Difficulty: extreme flexibility
Kite modelling

1. Controller design
2. Optimization studies
3. Develop new kites

Difficulty: extreme flexibility

Existing kite models
- Too simple
- Too artificial
- Too complex
Thesis Goal
The goal of this thesis is to show a new **realistic** and **reduced** approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.
The goal of this thesis is to show a new **realistic** and **reduced** approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.

**Realistic**
- Global flexible behaviour
- Real steering
- Physical principles
The goal of this thesis is to show a new **realistic** and **reduced** approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.

### Realistic
- Global flexible behaviour
- Real steering
- Physical principles

### Reduced
- Fast
- Simplified
Approach
Components
Components

Finite element kite model
- neglect inertia: quasi-static
- simplified
Components

Breukels aerodynamic model
- includes kite deformation
- distributed load

Finite element kite model
- neglect inertia: quasi-static
- simplified
Components

Breukels aerodynamic model
- includes kite deformation
- distributed load

Finite element kite model
- neglect inertia: quasi-static
- simplified

Dynamic cable model
- simplified
Integration

Finite element kite model

Aerodynamic model

Quasi static fluid structure interaction problem

Displacements

Forces

Kite power - **Approach** - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Integration
Integration

Dynamic simulation
- Dynamic tether and bridles model
- Finite element kite model
- Aerodynamic model
  - Quasi static fluid structure interaction problem

forces
- floating kite frame
- displacements

forces
- displacements

Kite power - Goal - **Approach** - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Finite element kite model
Finite element method

Discretized structure in small elements
Finite element method

Discretized structure in small elements

displacements $q$  
internal forces $f$  
external forces $g$

Non-linear equations

$$M\ddot{q} + f(q) = g(q, X)$$
Finite element method

Discretized structure in small elements

Displacements $q$, internal forces $f$, external forces $g$

Non-linear equations

$\mathbf{K} \mathbf{q} + \mathbf{f}(q) = \mathbf{g}(q, X)$
Finite element method

Discretized structure
in small elements

\[
\begin{align*}
\text{displacements } q & \quad \text{internal forces } f & \quad \text{external forces } g \\
\text{Non-linear} & \quad \begin{cases} f(q) = g(q, X) \\
q_0, q_b, X \text{ prescribed} \end{cases} & \quad \text{initial conditions} \\
\text{equations} & & \text{boundary conditions} \\
\end{align*}
\]
North Rhino 16m²
Modelling - mesh

North Rhino 16m2

Simplified mesh:
- inflatable beams as regular beams
- coarse mesh
- simplifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam elements</td>
<td>107</td>
</tr>
<tr>
<td>Shell element</td>
<td>360</td>
</tr>
<tr>
<td>Nodes</td>
<td>222</td>
</tr>
<tr>
<td>DOF</td>
<td>1332</td>
</tr>
</tbody>
</table>

= NL shell element
= NL beam element
Non-linearities

Geometric non-linearities: stiffness changes with geometry $K(q)$
Geometric non-linearities: stiffness changes with geometry $K(q)$
Non-linearities

Geometric non-linearities: stiffness changes with geometry \( K(q) \)
Geometric non-linearities: stiffness changes with geometry $K(q)$
Non-linearities

Geometric non-linearities: stiffness changes with geometry $K(q)$

Diagram:
- $F_{aero}$ and $F_{canopy}$
- Linear and Non-linear behavior

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Non-linearities

1. Material non-linearities in the inflatable parts
2. Force non-linearities from the aerodynamic forces beams
3. Other non-linear effects as buckling
Aerodynamic model
Breukels model

Assumption: wing sections
Assumption: wing sections

Wing section parameters $\kappa, t, \alpha$

camber $\kappa = h/c$

thickness $t = D/L$

chord $c$

angle of attack $\alpha$
Breukels model

Assumption: wing sections
Wing section parameters $\kappa, t, \alpha$
Aerodynamic coefficients $C_L, C_D, C_M$

2D CFD simulations

Aerodynamic coefficient curves

$\kappa, t, \alpha \rightarrow C_L, C_D, C_M$
Breukels model

Assumption: wing sections

Wing section parameters $\kappa, t, \alpha$

Aerodynamic coefficients $C_L, C_D, C_M$

Forces $F_L, F_D, M$

Forces:

\[
F_L = \frac{1}{2} C_L S \rho_{\text{air}} V_{w,a}^2
\]

\[
F_D = \frac{1}{2} C_D S \rho_{\text{air}} V_{w,a}^2
\]

\[
M = \frac{1}{2} C_M S c \rho_{\text{air}} V_{w,a}^2
\]
Breukels model

Assumption: wing sections

Wing section parameters $\kappa, t, \alpha$

Aerodynamic coefficients $C_L, C_D, C_M$

Forces $F_L, F_D, M$

Distribute the forces

Nodes

Constant weight factors $w_i$

Varying weight factors $u_ia$

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Assumption: wing sections

Wing section parameters $\kappa, t, \alpha$

Aerodynamic coefficients $C_L, C_D, C_M$

Forces $F_L, F_D, M$

Distribute the forces

3D correction
Breukels model

Assumption: wing sections

Wing section parameters $\kappa, t, \alpha$

Aerodynamic coefficients $C_L, C_D, C_M$

Forces $F_L, F_D, M$

Distribute the forces

Combine with FE-model
Results aerodynamics
Dynamic modelling

- Bridles as springs
- Tether fixed distance
- Masses at bridle attachment points
- 12 degrees of freedom
- Forces

\[ f = f_{\text{kite}} + f_{\text{bridle}} + f_{\text{cable,drag}} + f_{\text{damp}} + f_{\text{g}} \]

- Equations of motion

\[ \ddot{M} \ddot{y} = \dot{f} \]
System integration

Algorithm 3 Newton-Raphson with aero-elasticity and load control

\[
\text{Initialize boundary conditions } q_1^0, q_2^0 \text{ and state vector } X^1, X^0, \text{ initial configuration } \tilde{q}^s = q^s, \text{ pseudo time-step } s = 1, \text{ pseudo time } \lambda_s = \Delta \lambda_s \\
\text{while } \lambda_s < 1 \text{ and } n_{\lambda_s}^s \neq 1 \text{ do} \\
\text{Initialize iteration counters } l = 0, m = 0 \\
\text{Calculate external forces and aero-dynamic convergence criteria} \\
X_s = X^0 + \lambda_s (X^1 - X^0) \\
q_{h,s} = q_{h}^s + \lambda_s (q_{h}^{s+1} - q_{h}^s) \\
f^s = f(q_s, X_s) \\
c_{a,s}^m = c_{a,s}^m \\
\alpha = \alpha_{\text{init}} \\
\text{while } c_{a,s}^m > \varepsilon_1 \text{ and } c_{a,s}^m > \varepsilon_2 \text{ do} \\
\text{Predictor } \tilde{q}^s = \tilde{q}^s \\
\text{Calculate the internal forces and residual} \\
f(q_s) = f(q_s) - g^m \\
r(q_s) = r(q_s) \\
q_s^{m+1} = q_s^m + \Delta q^m \\
\text{Recalculate internal forces and residual} \\
f(q_s^{m+1}) = f(q_s^{m+1}) - g^m \\
k = k + 1, l = l + 1 \\
\text{end while} \\
\tilde{q}_s^{m+1} = q_s^{m+1} \\
\text{Recalculate external forces and aero-dynamic convergence criteria} \\
g(q_s^{m+1}, X_s) \\
c_{a,s}^m = g(q_s^{m+1}, X_s) - g(q_s^m, X_s) \\
c_{a,s}^m = g(q_s^{m+1}, X_s) - g(q_s^m, X_s) \\
\text{if } c_{a,s}^m \geq \varepsilon_1 \text{ OR } c_{a,s}^m \geq \varepsilon_2 \text{ then} \\
\alpha = \text{decrease } \alpha \\
g_s^{m+1} = g_s^m + \alpha (g(q_s^{m+1}) - g(q_s^m)) \\
q_s^{m+1} = q_s^m \\
\text{else} \\
\alpha = \text{increase } \alpha \\
g_s^{m+1} = g_s^m + \alpha (g(q_s^{m+1}) - g(q_s^m)) \\
\text{end if} \\
m = m + 1, l = l + 1 \\
\text{end while} \\
q_s^{m+1} = q_s^m \\
\text{Update pseudo time } \lambda_s \text{ according to Algorithm 4} \\
s = s + 1 \\
\text{end while} \\
F_5 = f_b
Full time-integration system

Initialization

Update full system state $X$

FSI problem

Controller

Bridle forces

Line lengths

Time integration $f(y, \dot{y}, X, t)$

End time? NO → New timestep

YES → Stop simulation

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Full time-integration system

Assumption: forces from FSI constant during time-step.

Solve FSI problem once per time-step.
Assumption: kite forces constant during time-step.

Solve FSI problem once per time-step.
FSI problem - structural

Quasi-static equation to solve:

\[
\begin{align*}
    f(q) &= g(q, X) \\
    q_0, q_b, X &\quad \text{prescribed}
\end{align*}
\]

Iterative solver:
Newton-Raphson

Stiffness matrix recalculated in every iteration

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Recalculating aerodynamic forces every iteration results in a slow or unstable system.
Recalculating aerodynamic forces every iteration results in a slow or unstable system.

Split in two loops. Keep aerodynamic forces constant during Newton-Raphson iteration.

\[ f(q) = g(q, X) \]
FSI problem - load control

Problem

Stability
Convergence speed
FSI problem - load control

Problem

Stability
Convergence speed

Solution

Load control with pseudo time

\( \lambda_s \)

Gradually increase inputs \( g(q, X) \)

\[ X_s = X^0 + \lambda_s(X^1 - X^0) \]

\[ q_{b,s} = q_b^0 + \lambda_s(q_b^1 - q_b^0) \]
Problem

Stability
Convergence speed

Solution

Load control with pseudo time \( \lambda_s \)

Graduatly increase inputs \( g(q, X) \)

\[
X_s = X^0 + \lambda_s (X^1 - X^0) \\
q_{b,s} = q_b^0 + \lambda_s (q_b^1 - q_b^0)
\]
Controller

Steering controller

Proportional
Controls steering lines
Controller

Steering controller

Proportional
Controls steering lines

Power controller

Proportional
Controls the power in the kite with the steering lines

\[ r_{power} = \frac{F_{steering\ lines}}{F_{power\ lines}} \]
Results & Discussion

Angle of attack of every aerodynamic subsection
Test set-up

- Verification is difficult
- Full verification out of the scope
- Use existing knowledge for validation
Test set-up

- Verification is difficult
- Full verification out of the scope
- Use existing knowledge for validation
Test set-up
Movie
Breukels: steering due to an offset in the lift forces at the tips
Steering behaviour

- Breukels: steering due to an offset in the lift forces at the tips
- Expected
  - asymmetric deformation
  - increased lift, drag force and aoa of the tip
  - yawing motion as a result from the steering input
Steering behaviour

Right turn

Left turn
Steering behaviour

Increase/decrease AOA at the tips

Angle of attack at the tips while cornering

- AOA left tip
- AOA right tip
- AOA middle

Results - Conclusions
Steering behaviour

Real steering inputs
Proportional relation between yaw rate and steering input

The steering controller input and the yaw rate

Steering controller input, steering line difference (m)

Steering input
Yaw rate

Time (s)

0 5 10 15 20

0 0.1 0.2 0.3

0 0.3

0.3

P0 P1 P2 P3 P4

P1 P2 P3 P4

Results
Conclusions
Structural deformation

Displacements of the bridle attachment points in FE

Typical jellyfish motion
High L/D ratio results in high speeds and forces.
Aerodynamics / time integration

High L/D ratio results in high speeds and forces.

Average time step: 4.5ms
25-30 slower than real-time
Conclusions

Thesis goal

Show a new **realistic** and **reduced** approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.
Conclusions

Thesis goal

Show a new **realistic** and **reduced** approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.

**Realistic**

- Based on physical principles
- Captures the non-linear global dynamics realistically
- Real steering inputs
- Aerodynamic model is the limiting factor
Conclusions

Thesis goal

Show a new realistic and reduced approach in the modelling of flying flexible inflatable tube kites used in airborne wind energy systems.

Reduced

• Reduction assumptions without losing the essential dynamics.
• Low calculation times: 25-30 slower than real-time.
• Candidate for further model reduction techniques.
• Flexible in its use.
Conclusions

The new approach is

1. successful.
2. an improvement to existing models.

Recommendations

1. Develop better aerodynamic models.
2. Do an extensive model validation.
“First, there is the power of the Wind, constantly exerted over the globe.... Here is an almost incalculable power at our disposal, yet how trifling the use we make of it! It only serves to turn a few mills, blow a few vessels across the ocean, and a few trivial ends besides. What a poor compliment do we pay to our indefatigable and energetic servant!”

Henry Thoreau - 1866
I would like to invite you for the presentation of my Master Thesis:

Finite element analysis of a kite for power generation
Computational modelling of flight dynamics of a tethered wing including non-linear fluid-structure interaction.

Presentation: Thursday April 26\textsuperscript{nd} - 12.45u
TU Delft - Faculty of 3mE - room E, Mekelweg 2

Party: Friday April 27\textsuperscript{th} - 21.00u
Confide - Oude Delft 9 - Delft

Allert Bosch - 0642924608

Photo by Max Dereta
Extra results

Line forces in the bridles

Angle of attack of every aerodynamic subsection
Extra results

Rotational kite speed in the kite frame $\Psi_k$

Kite speed in the kite frame $\Psi_k$
System overview
Current research

Degrees of freedom

Calculation time

- point mass
- rigid body
- multi plate
- lumped mass
- multi body
- finite element
- new model
- black box
Current research
Current research

Degrees of freedom

Calculation time

black box

point mass

rigid body

multi plate

lumped mass

multi body

new model

finite element

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Current research

Calculation time vs. Degrees of freedom

- Point mass
- Rigid body
- Multi plate
- Lumped mass
- Multi body
- Finite element
- New mode
- Black box

Degrees of freedom
Current research

Need for better models

Calculation time

Degrees of freedom
Reduced & Realistic

Realistic
1. Based on physical properties & includes full flexibility

Reduced
1. Quasi-static: time integration only for small number of dofs
2. Solve FSI-problem only once per time-step
3. Smart finite element model

Furthermore
1. Modular
2. Implementation in Matlab
Results aerodynamics

- Deformation of the kite completely depends on the aerodynamic forces

Shortcomings:
- Model doesn’t use information efficiently
- Cannot provide aerodynamic damping
- Unrealistic pressure distributions for some angles of attack
Modelling - inflatable beams

\[ EI(p, v, r) = \frac{F_{\text{tip}}(p, r, v)L^3}{3v} \]
Steering behaviour

Increase/decrease AOA at the tips

Increase/decrease forces at the tips

Kite power - Goal - Approach - Kite - Aerodynamics - Cable - System integration - Results - Conclusions
Steering behaviour

Length of the steering lines

Real steering inputs

Proportional relation between yaw rate and steering input

The steering controller input and the yaw rate
Modelling - canopy

- Ripstop material, 0.08mm thick
- Non-linear three node flat shell element
- Membrane (9 dof) + Bending (9dof)

Non-linear contribution from the kinematic equations

\[
\begin{align*}
\varepsilon_x &= \frac{1}{A} \int_A [u_{,x} + \frac{1}{2}(v_{,x}^2 + w_{,x}^2)]dA \\
\varepsilon_y &= \frac{1}{A} \int_A [v_{,y} + \frac{1}{2}(u_{,y}^2 + w_{,y}^2)]dA \\
\varepsilon_{xy} &= \frac{1}{A} \int_A [\frac{1}{2}(u_{,y} + v_{,x}) + \frac{1}{2}(w_{,x}w_{,y})]dA \\
\chi_{xx} &= \frac{1}{A} \int_A w_{,xx}dA \\
\chi_{yy} &= \frac{1}{A} \int_A w_{,yy}dA \\
\chi_{xy} &= \frac{1}{A} \int_A w_{,xy}dA
\end{align*}
\]
Modelling - inflatable beams

- Geometric non-linear three dimensional beam element
- Based on the classic Bernoulli beam theory
- Material properties from Breukels experiments

• Kinematic equations
  \[ \varepsilon_{11} = \left( \frac{du}{dx} \right) + \frac{1}{2} \left( \frac{dv}{dx} \right)^2 + \frac{1}{2} \left( \frac{dw}{dx} \right)^2 \]
  \[ \gamma = \rho \frac{d\phi}{dx} = \rho \kappa_x \]
Controller

Steering controller
Proportional
Controls steering lines

Power controller
Proportional
Controls the power in the kite with the steering lines

\[ r_{\text{power}} = \frac{F_{\text{steering lines}}}{F_{\text{power lines}}} \]
Damping

Sequence of static solutions of the deformed kite.

Problem

• Quasi-static: no local velocities
• Aerodynamic damping: unstable with local velocities

Solution

Simulate aerodynamic damping
Solving the dynamic equations

**Dynamic differential equations to solve:**

\[ \ddot{y} = f(y, \dot{y}, X, t) \]

**Assumption:**
kite forces constant during time-step.

Solve FSI problem once per time-step.

Explicit Runge-Kutta45
FSI problem - structural

Quasi-static equation to solve:

\[
\begin{cases}
  f(q) = g(q, X) \\
  q_0, q_b, X \quad \text{prescribed}
\end{cases}
\]

Iterative solver: Newton-Raphson

Stiffness matrix recalculated in every iteration
Finite element method

Displacements $q$ → strains $\varepsilon$ → stresses $\sigma$ → internal forces $f(q)$

Linear

$$M\ddot{q} + Kq = g(t)$$

Non-linear

$$M\ddot{q} + f(q) = g(t)$$

Quasi-static

$$\begin{cases} f(q) = g(q, X) \\ q_0, q_b, X \text{ prescribed} \end{cases}$$

External forces $g(t)$
System overview
Finite element method

displacements $q \rightarrow$ strains $\varepsilon \rightarrow$ stresses $\sigma \rightarrow$ internal forces $f(q)$

Non-linear

$M \ddot{q} + f(q) = g(t)$

quasi-static

external forces $g(t)$

\begin{align*}
\begin{cases}
  f(q) = g(q, X) \\
  q_0, q_b, X \quad \text{prescribed}
\end{cases}
\end{align*}

initial conditions $q_0$
boundary conditions $q_b$
system state $X$
Finite element method

Discretized field in small elements
Solving the dynamic equations

Dynamic differential equations to solve:

\[ \ddot{y} = f(y, \dot{y}, X, t) \]
Solving the dynamic equations

Dynamic differential equations to solve:

\[ \ddot{y} = f(y, \dot{y}, X, t) \]

Solve FSI problem multiple times per time-step
Solving the dynamic equations

Dynamic differential equations to solve:

\[ \ddot{y} = f(y, \dot{y}, X, t) \]

Solve FSI problem multiple times per time-step
Solving the dynamic equations

Dynamic differential equations to solve:

\[ \ddot{y} = f(y, \dot{y}, X, t) \]

Assumption:
kite forces constant during time-step.

Solve FSI problem once per time-step.
Solving the FSI problem

Dynamic differential equations to solve:

\[ \ddot{y} = f(y, \dot{y}, X, t) \]

Assumption: kite forces constant during time-step.

Solve FSI problem once per time-step.
Modelling - canopy

Canopy
• NL three node flat shell element
• Membrane + Bending (18dof)
• 0.08mm ripstop

Inflatable beams
• NL 3D beam element
• Bernoulli beam theory
• Experimental material properties