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Experimental Analysis of Unsteady Aerodynamic Behaviour for a Small Rotor in an Open Jet Wind Tunnel

Gregor E. van Baars
Philips Applied Technologies

April 28th, 2010

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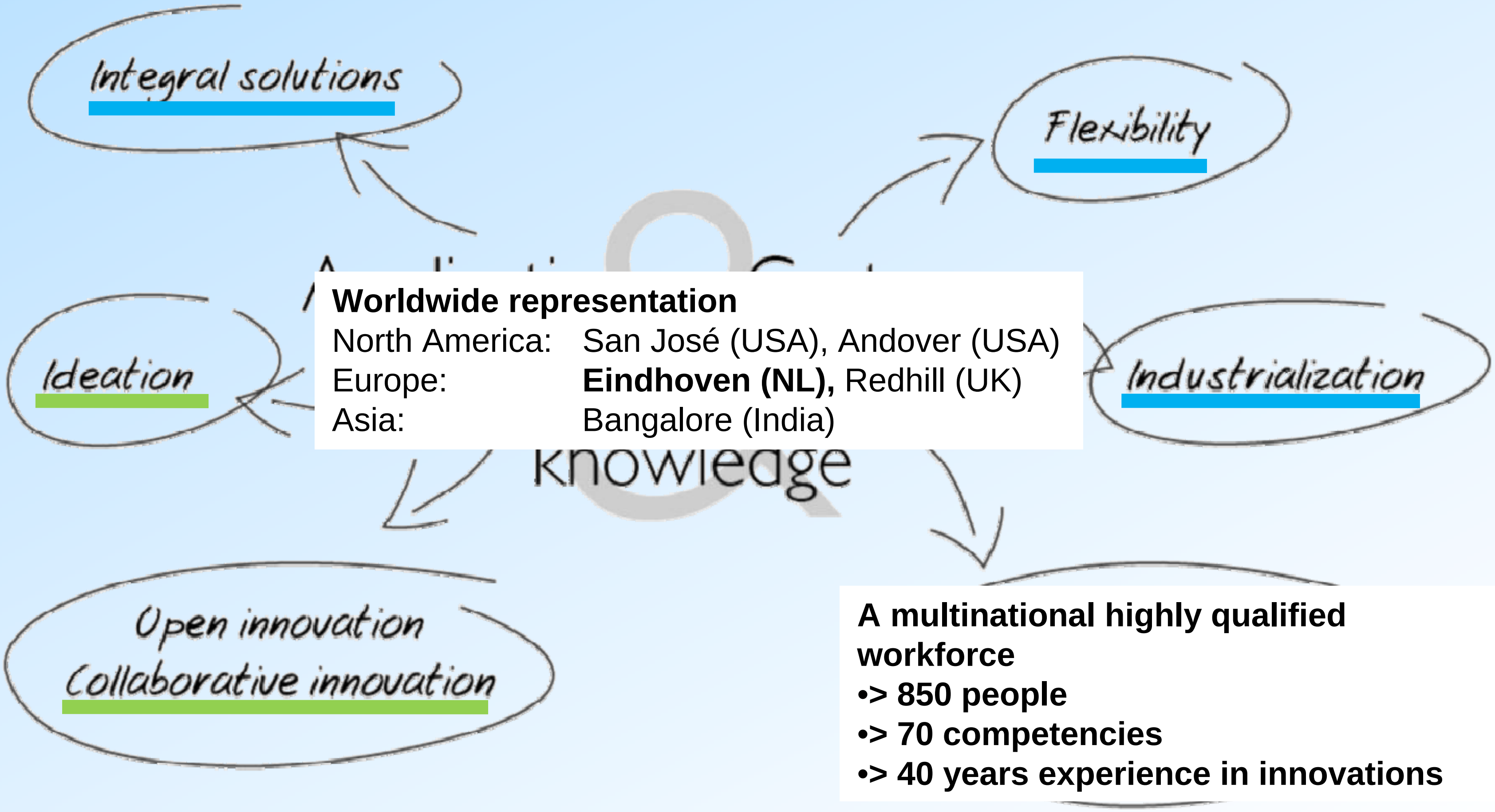

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Concept

Design

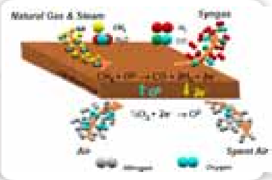
Engineering

Industrialization

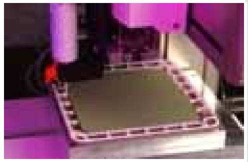
Ramp-up/ manufacturing

Energy Generation Scope at Apptech

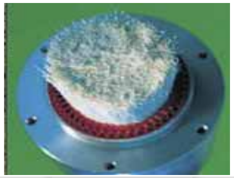
Direct Methanol
Fuel Cell



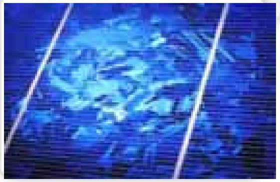
Solid Oxide
fuel cells



Gas separation
membranes



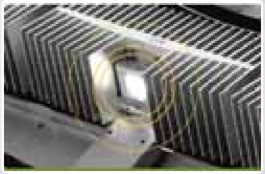
Production
Equipment



Silicon based
photo voltaic

Thin film Photo Voltaic

Concentrated
Solar power



Concentrated
photo voltaics

Small Wind

Inverters

Materials
Multi physics
Coating
Industrialization
Manufacturing
processes
Mechatronics

Competence base

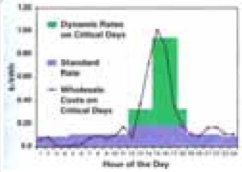
System
architecture
Power
electronics
Sensors
Thin film
Thermal mgt.

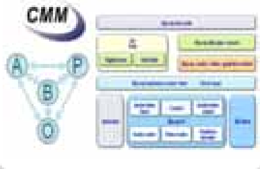
Wind Energy Scope at Apptech

Robotics for remote inspection and maintenance

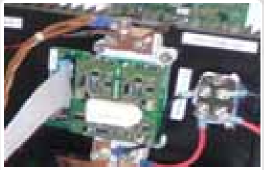
Monitoring & control

Demand side management



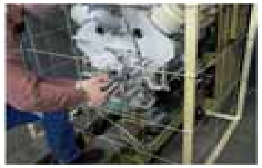


System Engineering



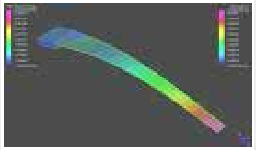
Power Electronics

Sensor Systems

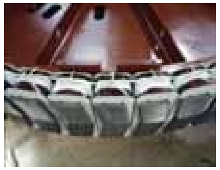


Acoustics

Wind turbine modeling



Design optimization



Reliability Engineering

Digital Signal Processing

Materials

Multi physics

Electronic Design

Industrialization

Manufacturing processes

Mechatronics

Competence base

System architecture

Power electronics

Software Engineering

Sensor Technology

Standardization

Outline

- Introduction
- Small rotor aerodynamics challenges
- Unsteady aerodynamics modeling
- Validation approach
- Experimental rotor set-up & Open Jet wind tunnel Facility
- Measurement campaign
- Initial data analysis and results
- Conclusions
- Next steps

Introduction

- Philips Applied Technologies is interested in challenges and innovations associated with small wind applications
- Significant growth in small wind turbines for residential and commercial applications is expected
- Small wind systems will be in closer vicinity to domestic environments and addresses a consumer market
- Small wind system designs should be affordable, reliable and safe
- Combining low cost components and desired lifetime into a feasible design calls for thorough understanding of the load cases and behaviour of the system
- This sets high requirements on the system design tools, such as simulation models for evaluation of loads and aerodynamic behaviour

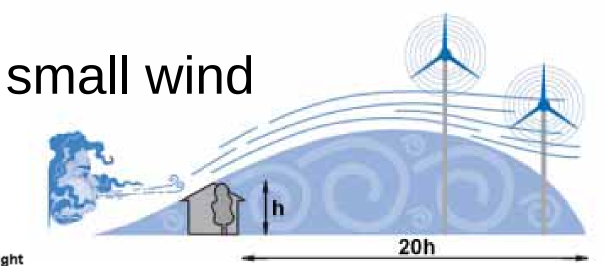
Small rotor aerodynamics challenges

- Very destructive threats to the rotor system are aerodynamic instabilities such as stall hysteresis and flutter
- By design, rotor instabilities should be prevented in small wind systems
- Proper aerodynamic + rotor dynamics models are key to predict such dangerous limit-cycle behaviour

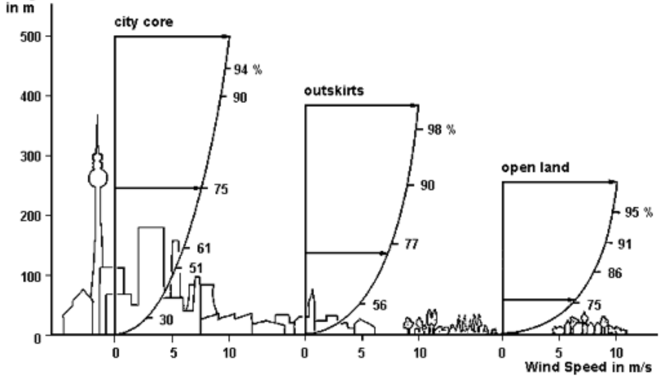
- Small wind systems the will experience many wind inflow variations
- Reliability of the unsteady aerodynamics models is therefore crucial
- Validation of models is built through
  - representative experimental set-ups,
  - under realistic operational conditions,
  - a lot of informative experiments,
  - and effective identification techniques

Small rotor aerodynamics challenges

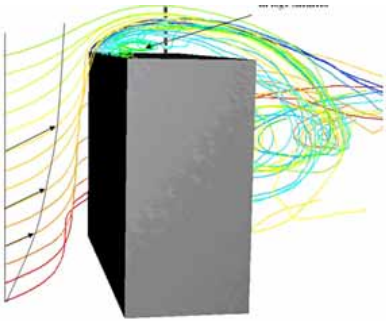
- Unsteady aerodynamics are more prominent for small wind systems in residential environments



- Wind induced :
  - Wind speed (gusts)
  - Wind profile (gradient/ shear)
  - Wind direction (yawed flow)

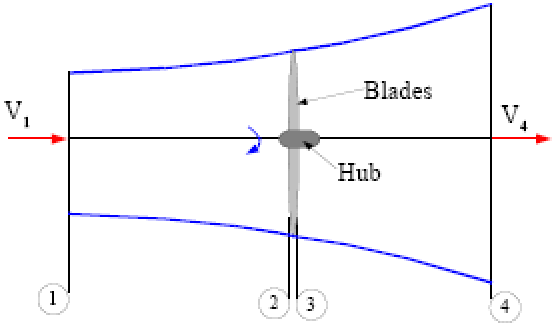


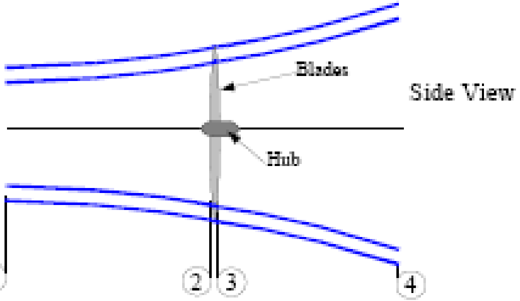
- Rotor induced:
  - Relatively high rotational speed
  - Blade motion (flexibilities in bending, torsion, lead lag)
  - Tower bending, nacelle yawing (rotor displacements)



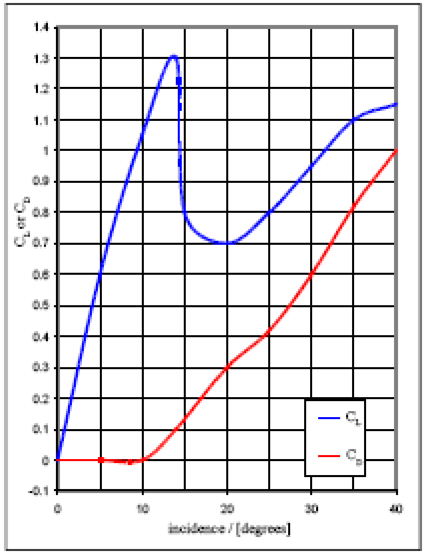
Unsteady aerodynamics modeling

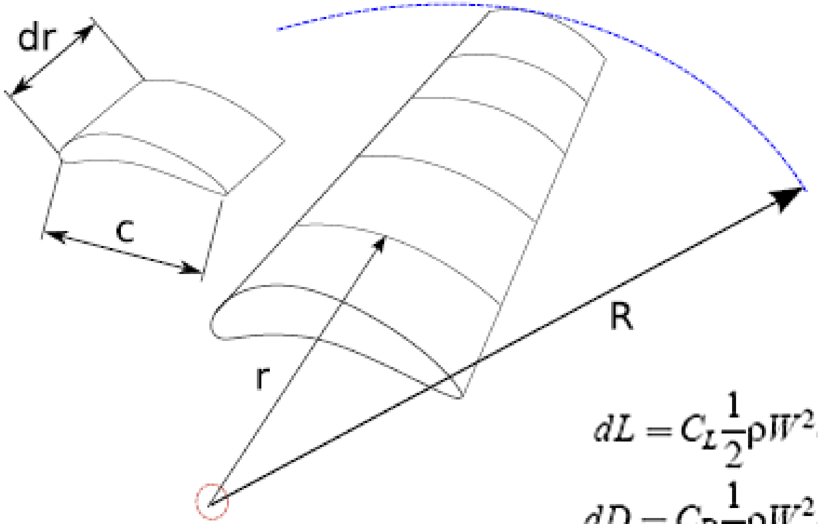
Starting point: Blade Element theory for wind turbine rotors





2D stationary profile characteristics

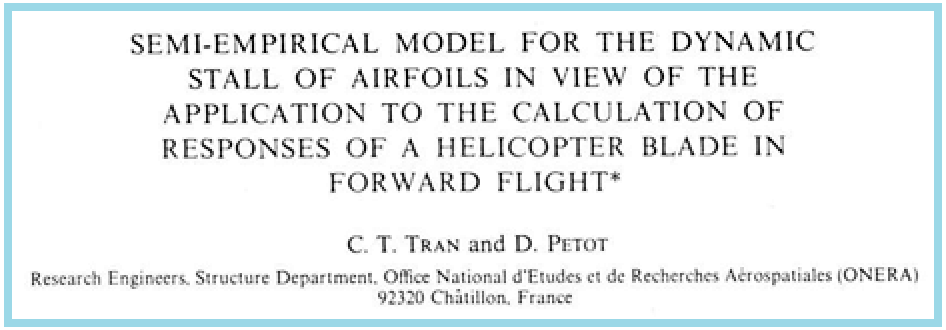




$$dL = C_L \frac{1}{2} \rho W^2 c dr \qquad dF_\theta = dL \cos\beta - dD \sin\beta$$

$$dD = C_D \frac{1}{2} \rho W^2 c dr \qquad dF_x = dL \sin\beta + dD \cos\beta$$

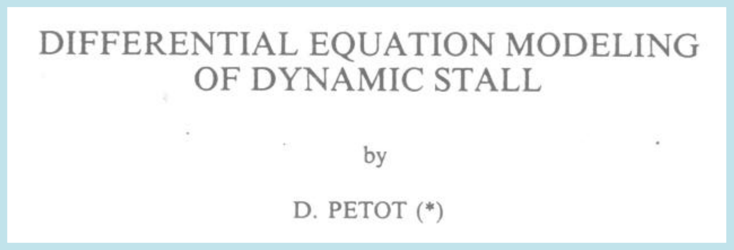
A long history of unsteady aerodynamics studies



SEMI-EMPIRICAL MODEL FOR THE DYNAMIC STALL OF AIRFOILS IN VIEW OF THE APPLICATION TO THE CALCULATION OF RESPONSES OF A HELICOPTER BLADE IN FORWARD FLIGHT*

C. T. TRAN and D. PETOT

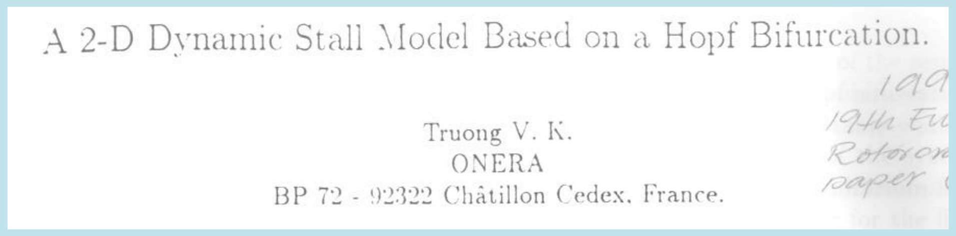
Research Engineers, Structure Department, Office National d'Etudes et de Recherches Aérospatiales (ONERA)
92320 Châtillon, France



DIFFERENTIAL EQUATION MODELING OF DYNAMIC STALL

by

D. PETOT (*)



A 2-D Dynamic Stall Model Based on a Hopf Bifurcation.

Truong V. K.
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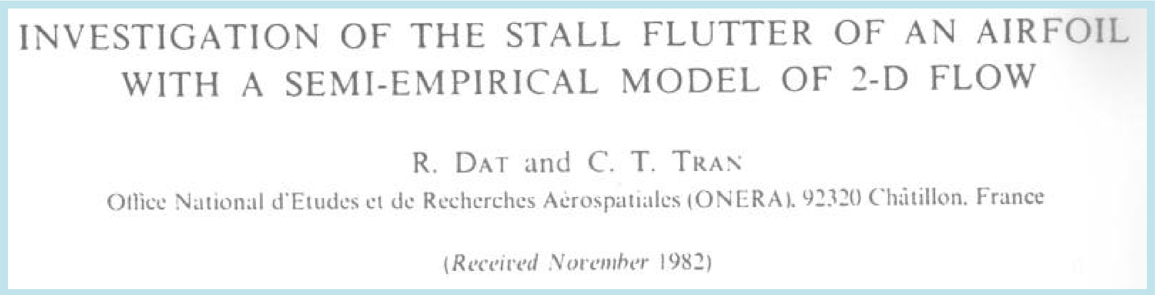
199
19th Eu
Rotorcr
paper



INVESTIGATION OF THE STALL FLUTTER OF AN AIRFOIL WITH A SEMI-EMPIRICAL MODEL OF 2-D FLOW

R. DAT and C. T. TRAN

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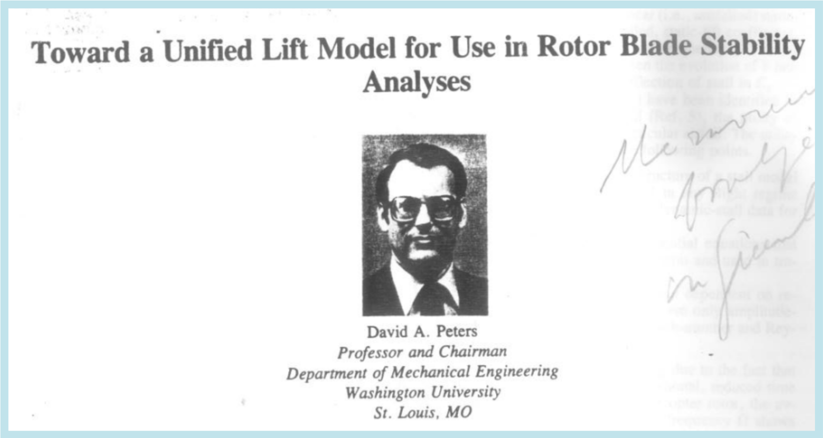
(Received November 1982)



Toward a Unified Lift Model for Use in Rotor Blade Stability Analyses

David A. Peters
Professor and Chairman
Department of Mechanical Engineering
Washington University
St. Louis, MO

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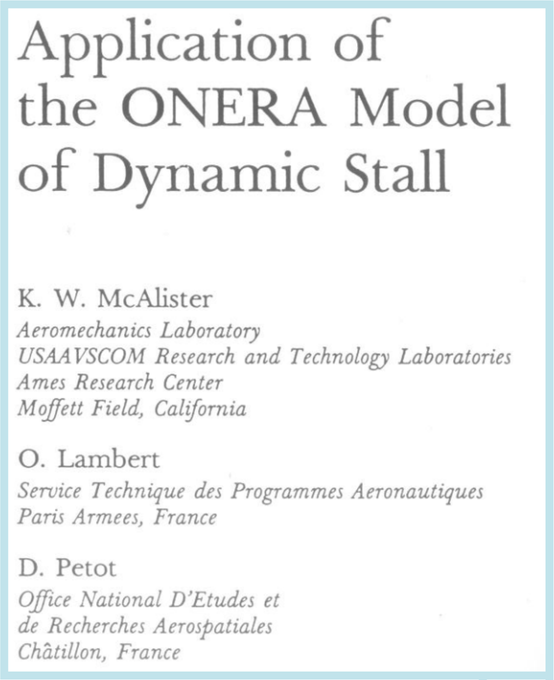

Application of the ONERA Model of Dynamic Stall

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USAAVSCOM Research and Technology Laboratories
Ames Research Center
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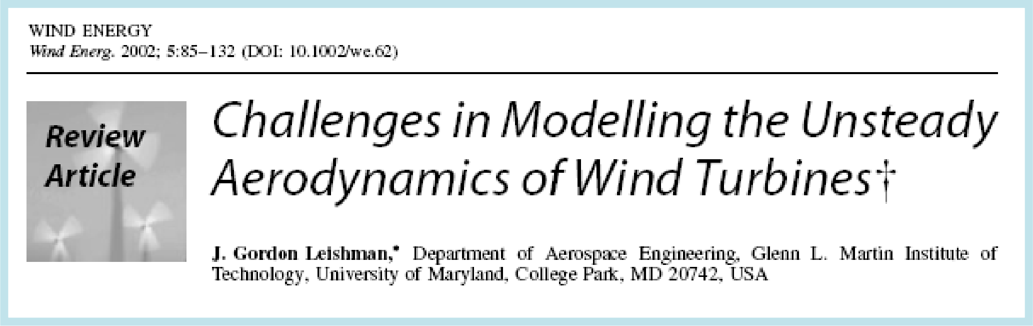
Service Technique des Programmes Aeronautiques
Paris Armees, France

D. Petot
Office National D'Etudes et
de Recherches Aerospatiales
Châtillon, France

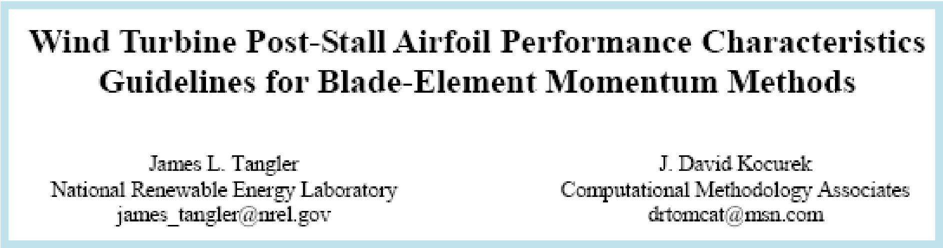
A long history of unsteady aerodynamics studies


WIND ENERGY
Wind Energ. 2002; 5:85–132 (DOI: 10.1002/we.62)

Review Article

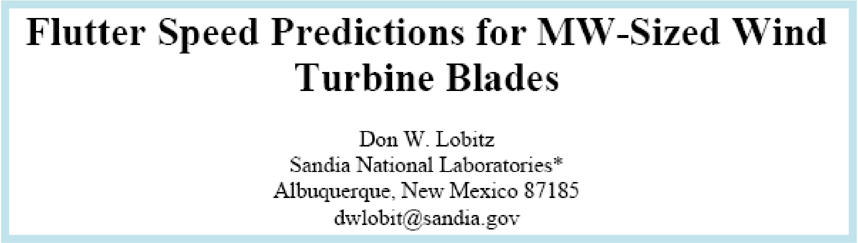
Challenges in Modelling the Unsteady Aerodynamics of Wind Turbines†

J. Gordon Leishman,* Department of Aerospace Engineering, Glenn L. Martin Institute of Technology, University of Maryland, College Park, MD 20742, USA

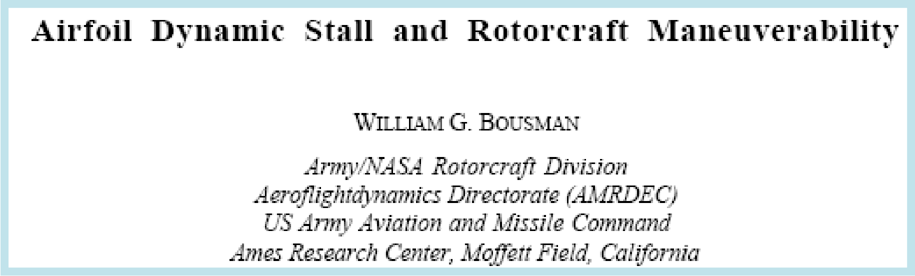

Wind Turbine Post-Stall Airfoil Performance Characteristics Guidelines for Blade-Element Momentum Methods

James L. Tangler
National Renewable Energy Laboratory
james_tangler@nrel.gov

J. David Kocurek
Computational Methodology Associates
drtomcat@msn.com


Flutter Speed Predictions for MW-Sized Wind Turbine Blades

Don W. Lobitz
Sandia National Laboratories*
Albuquerque, New Mexico 87185
dwlobit@sandia.gov


Airfoil Dynamic Stall and Rotorcraft Maneuverability

WILLIAM G. BOUSMAN

Army/NASA Rotorcraft Division
Aeroflightdynamics Directorate (AMRDEC)
US Army Aviation and Missile Command
Ames Research Center, Moffett Field, California

And many more…


Review of state of the art in smart rotor control research for wind turbines

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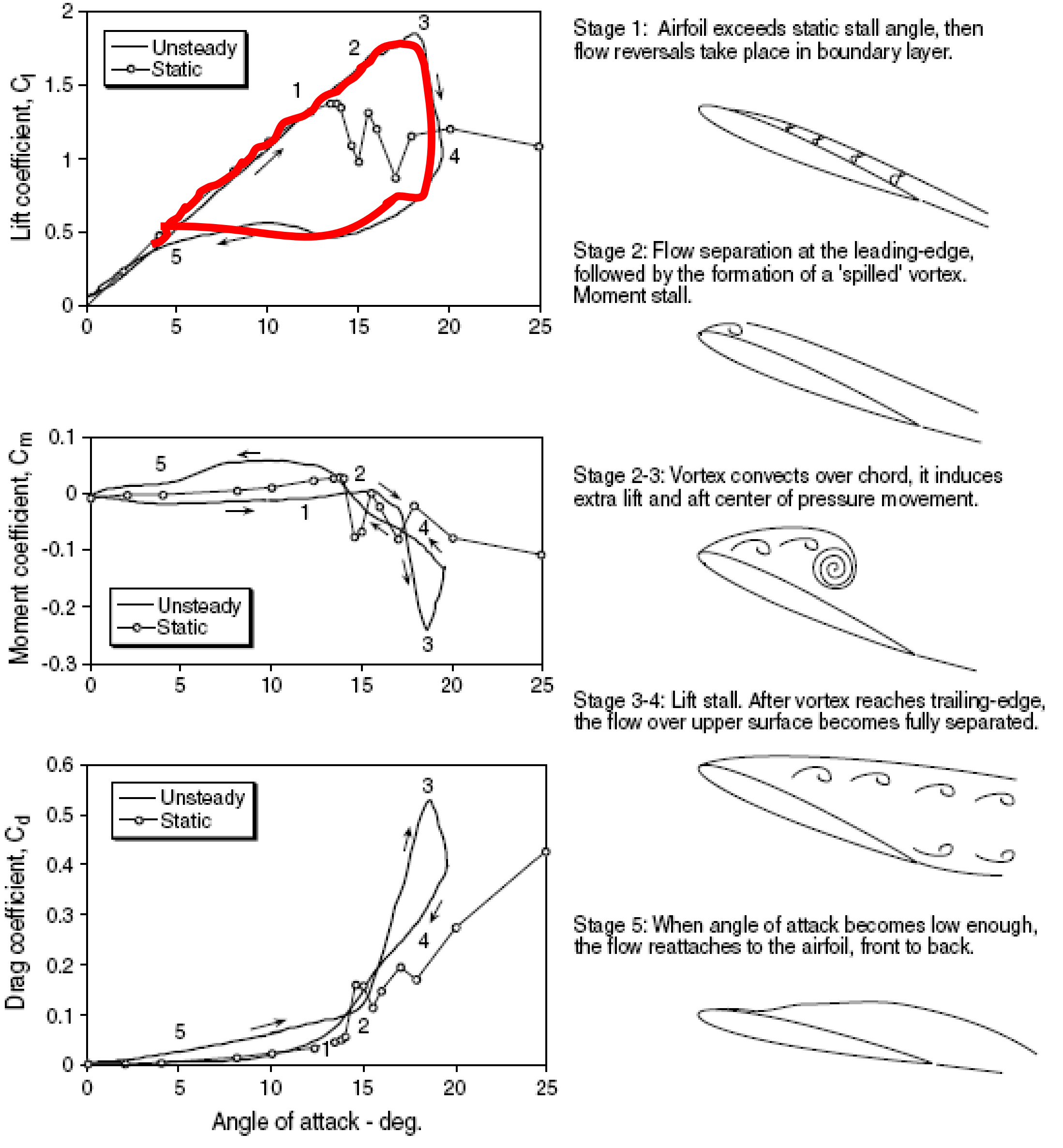
Delft University Wind Energy Research Institute (DUWIND), Wind Energy Group, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS Delft, The Netherlands

Unsteady aerodynamics: dynamic stall



Stage 1: Airfoil exceeds static stall angle, then flow reversals take place in boundary layer.

Stage 2: Flow separation at the leading-edge, followed by the formation of a 'spilled' vortex. Moment stall.

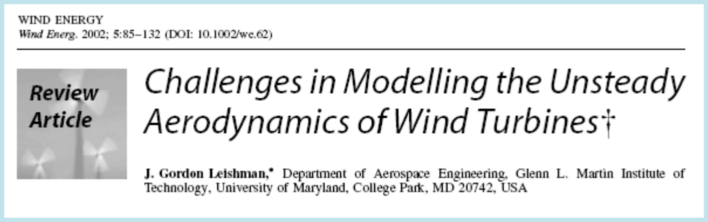
Stage 2-3: Vortex convects over chord, it induces extra lift and aft center of pressure movement.

Stage 3-4: Lift stall. After vortex reaches trailing-edge, the flow over upper surface becomes fully separated.

Stage 5: When angle of attack becomes low enough, the flow reattaches to the airfoil, front to back.

Figure 17. Schematic diagram showing unsteady airloads and flow physics for a two-dimensional aerofoil undergoing dynamic stall

Ref:



WIND ENERGY
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Review Article

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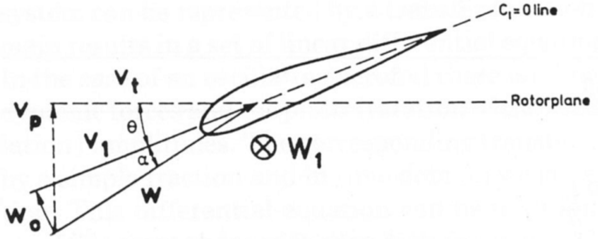
J. Gordon Leishman,* Department of Aerospace Engineering, Glenn L. Martin Institute of Technology, University of Maryland, College Park, MD 20742, USA

ONERA model for dynamic stall [ref: Tran&Petot]

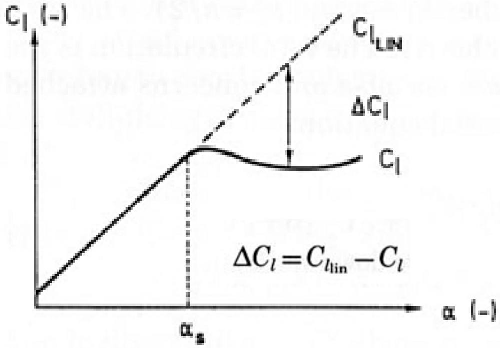
$$\mathrm{d}L_x = -\tfrac{1}{2}\rho\, c\, \mathrm{d}r \left(S_L \frac{c}{2}\, \dot{W}_0 \sin\Theta + k_L \frac{c}{2}\, \dot{W}_1 \sin\Theta + V_\mathrm{p}(\Gamma_1 + \Gamma_2) \right),$$

$$\mathrm{d}L_y = \tfrac{1}{2}\rho\, c\, \mathrm{d}r \left(S_L \frac{c}{2}\, \dot{W}_0 \cos\Theta + k_L \frac{c}{2}\, \dot{W}_1 \cos\Theta + V_\mathrm{t}(\Gamma_1 + \Gamma_2) \right),$$



$$\dot{\Gamma}_1 + \lambda_L \frac{1}{\tau} \Gamma_1 = \lambda_L \frac{1}{\tau} C_{l\alpha} (W_0 - V_1 \alpha_0) + \lambda_L \frac{1}{\tau} \sigma_L W_1 + (\alpha_L C_{l\alpha} + d_L) \dot{W}_0 + \alpha_L \sigma_L \dot{W}_1,$$

$$\ddot{\Gamma}_2 + \alpha_L \frac{1}{\tau} \dot{\Gamma}_2 + r_L \frac{1}{\tau^2} \Gamma_2 = -r_L \frac{1}{\tau^2} V_1\, \Delta C_l - E_L \frac{1}{\tau} \dot{W}_0$$



$$a_L = a_0 + a_2 (\Delta C_l)^2, \quad \sqrt{r_L} = r_0 + r_2 (\Delta C_l)^2,$$
$$E_L = E_2 (\Delta C_l)^2, \quad d_L = \sigma_1 \,|\Delta C_l|.$$

$$\tau_1 = \frac{\tau}{\lambda_L} = \frac{\tfrac{1}{2}c}{V_1 \lambda_L}, \qquad \omega_n = \frac{\sqrt{r_L}}{\tau}, \qquad \zeta = \frac{\alpha_L/\tau}{2\,\omega_n} = \frac{a_L}{2\sqrt{r_L}}\,.$$

ONERA coefficients

NACA 0012
$\Delta\tau_d = 10$
$\sigma_1 = -2.29$
$r_0 = 0.2,\ r_2 = 0.1$
$a_0 = 0.25,\ a_2 = 0.1$
$E_2 = -4.01$

ONERA model for dynamic stall

Identification procedure of rotor specific coefficients

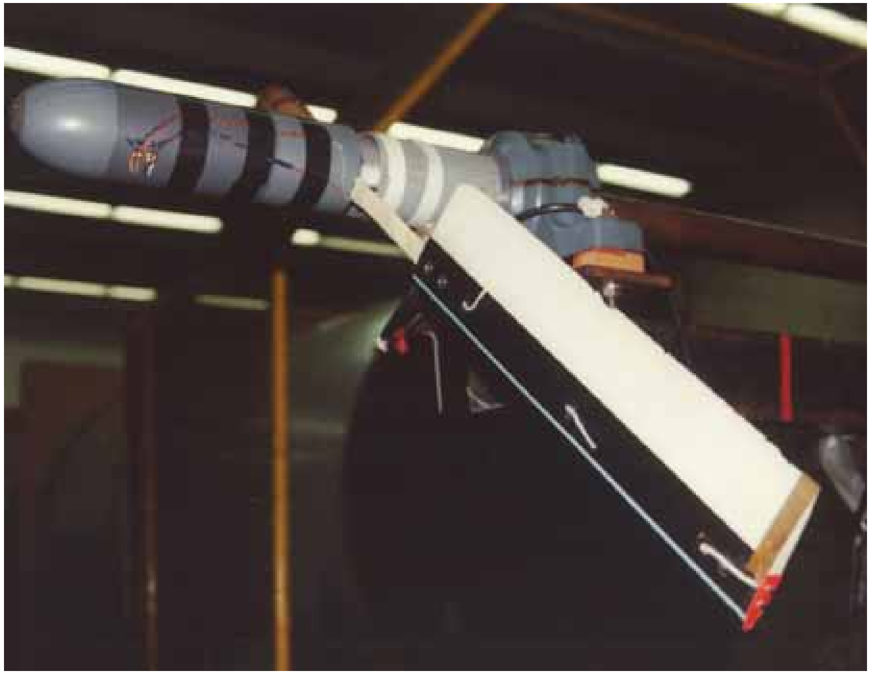
- State-of-the-art described in literature

- Applied to both 2D wind tunnel tests (forced pitch and plunge oscillations) and 3D helicopter data (forward flight test data)

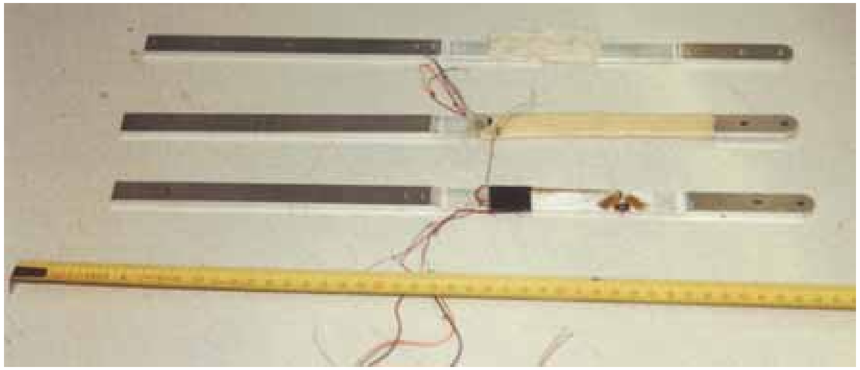
- Identification experiments
  - Small amplitude pitch oscillations
  - Large amplitude pitch oscillations
  - Defined experimental conditions and some known parameters

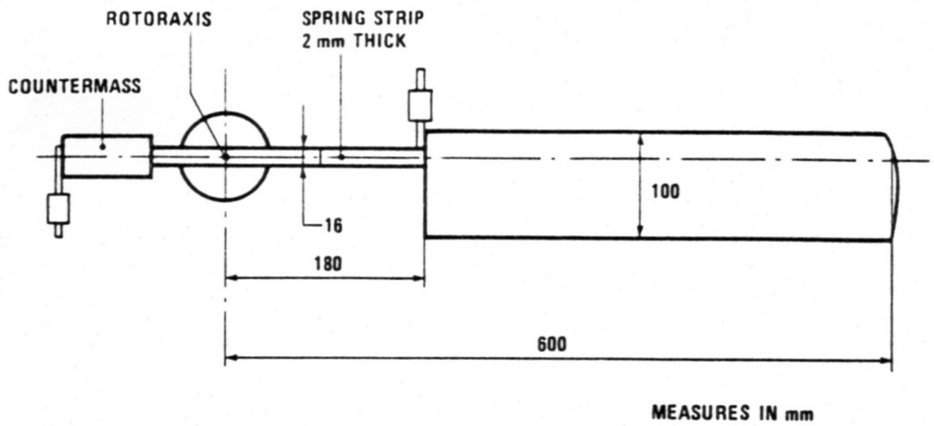
- Application to 3D rotating wind turbine situation relatively unexplored
  - Lack of informative data
  - Too much loading on system
  - Input cannot be controlled according to experimental plans (wind input)

Experimental rotor set-up

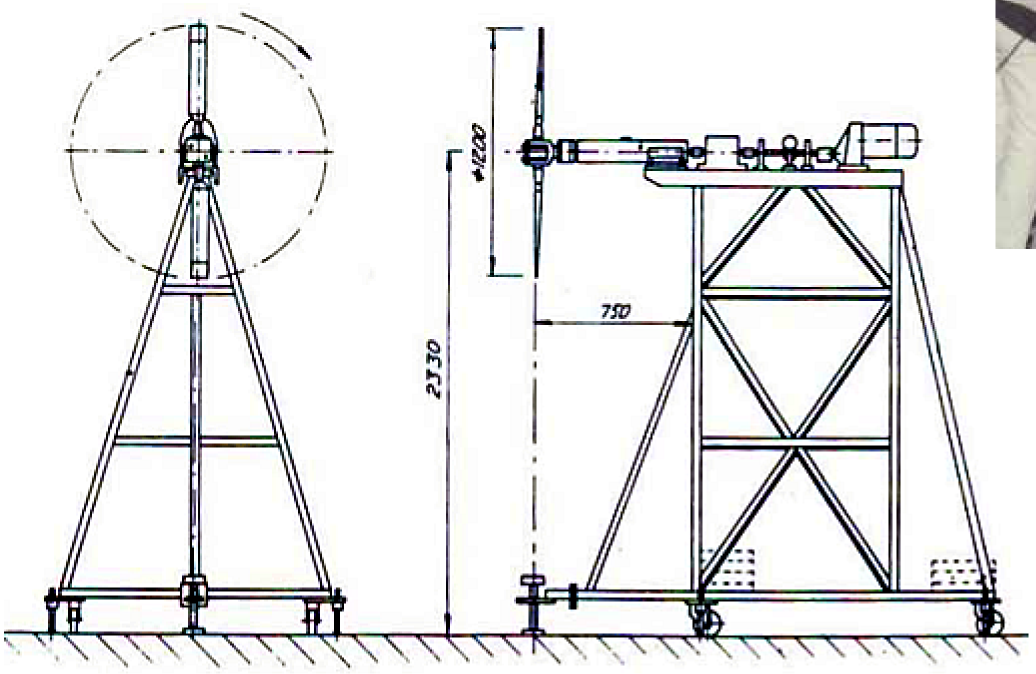


- NACA0012 profile
- Straight blade (constant chord)
- Flexible element mounting
    - 1,5 / 2,0 / 3,0 mm thick strip
- Counter mass for rotational balance
- Tufts, trip wires, tape





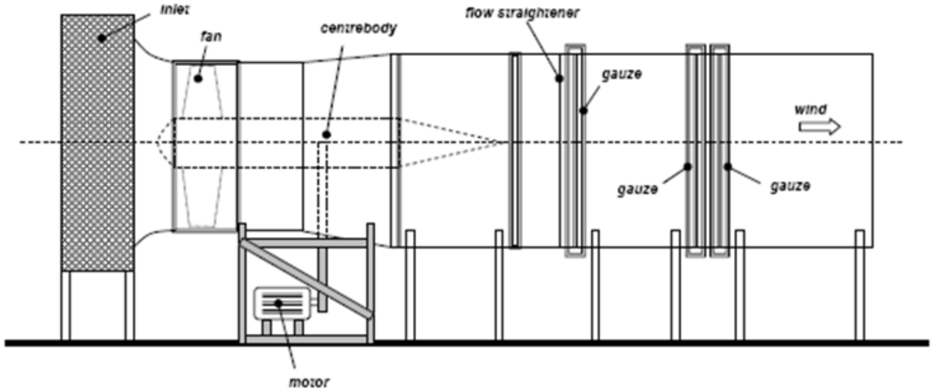
Experimental rotor set-up



- Forced rotor speed (driven)
- Flexible coupling between drive unit and rotor
- Wireless data transfer of torsion and bending strain gauges
- Axis at center heigth of wind tunnel outflow
- Rotor plane 1 m downstream of wind tunnel outlet

Measured signals:
- Wind speed
- Rotor shaft speed
- Bending and torsion at flexible element (wireless)

Open jet wind tunnel facility @ Delft University



- Max wind speed = 14,5 m/s
- Circular cross section = 2,2 m
- Central axis height = 2,3 m
- 45 kW DC motor to drive fan
- Flow straighteners & gauzes
- Turbulence levels 1,2 +/- 0,2%
- Building hall = 35 x 20 x 5,5 m (LxWxH)
- Clearance to back wall = 11 m

Proposed Identification and Validation approach

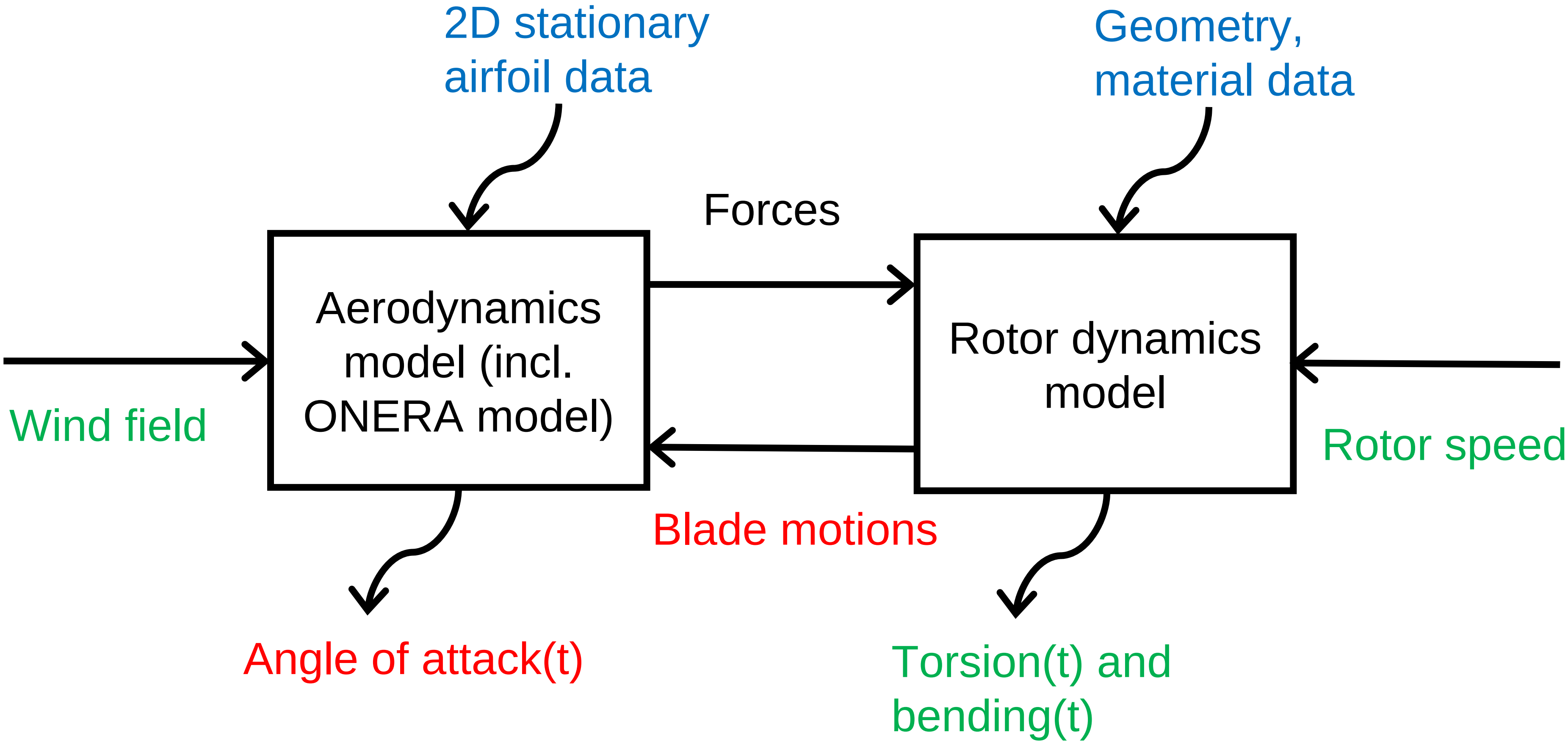
Combination of:

- Defined, steady, uniform wind input (defined by wind tunnel)
- Defined, constant rotational speed (driven rotor shaft rotation by motor)
- Measured torsion and bending of flexible element
- Assuming the blade deformations are significantly small
- Realistic rotor dynamics model

Procedure:

- Calculate blade motion from rotational speed and element torsion and bending
- Calculate angle of attack from blade motion and wind field velocity
- Combine set of experiments over a range of frequencies and wind speeds into a data set for identification of the ONERA coefficients (similar as needed for 2D wind tunnel experiments with forced oscillations)
- Apply identified ONERA coefficients into rotor aerodynamics model (e.g. BEM based) and validate against fresh data (not used for identification)
- Compare simulated behavior with measured torsion and bending data

Identification and Validation approach



2D stationary airfoil data

Geometry, material data

Forces

Aerodynamics model (incl. ONERA model)

Rotor dynamics model

Wind field

Rotor speed

Blade motions

Angle of attack(t)

Torsion(t) and bending(t)

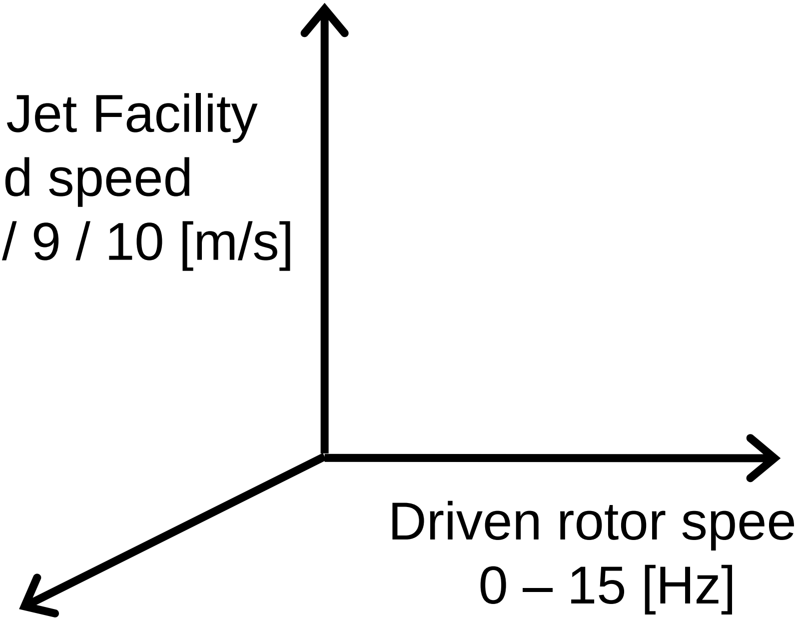
Measurement campaign

- Wind tunnel qualification experiments
- Non-rotating experiments without wind
  - Elementary vibration tests (structural qualification)
  - Noise excitation
- Rotating experiments without wind
  - Reference behavior without dominant aerodynamics
- Transient experiments
  - Rotor gearing up or spinning down
  - Wind flow speed change
  - Shutting of wind fan
- Perpendicular flow experiments
  - See overview on next slide
- Yawed flow experiments
  - See overview on next slide

Over 200 data sets

Measurement campaign

Experimental conditions variations



Open Jet Facility
Wind speed
0 / 3 / 6 / 9 / 10 [m/s]

Driven rotor speed
0 – 15 [Hz]

Yaw angle
-30 / -15 / 0 / +15 / +30 [deg]

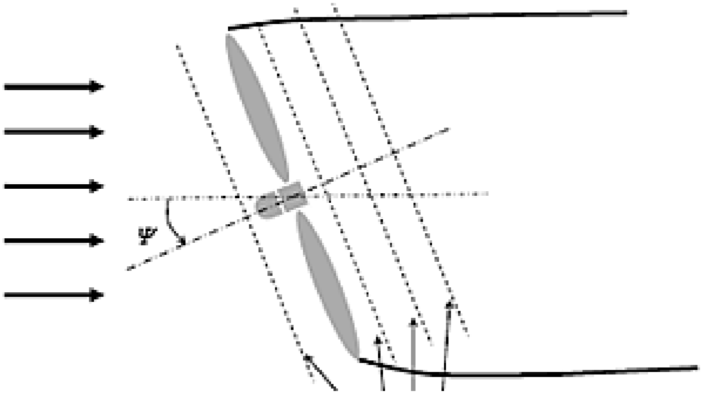
Rotor set-up variations:

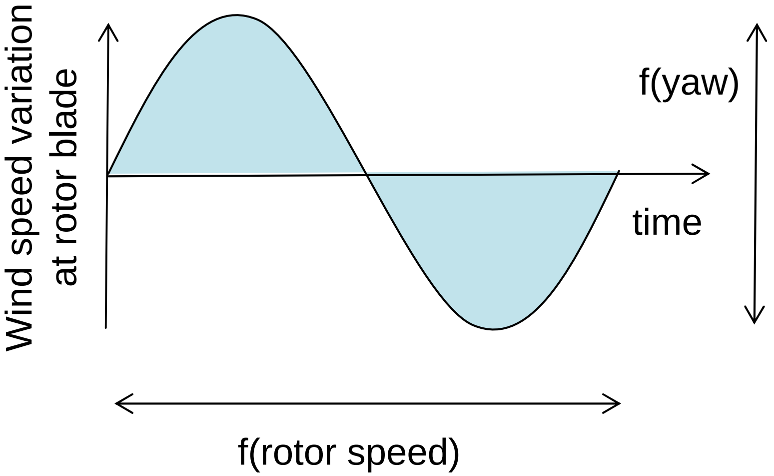
- Blade root flexible element thickness
  - 1,5 mm
  - 2,0 mm
- Prony brakes yes / no
- Trip wires yes/no
- …

Yawed rotor experiments

- Through yawed positioning of rotor relative to wind inflow, cyclic wind variations are enforced on the rotor

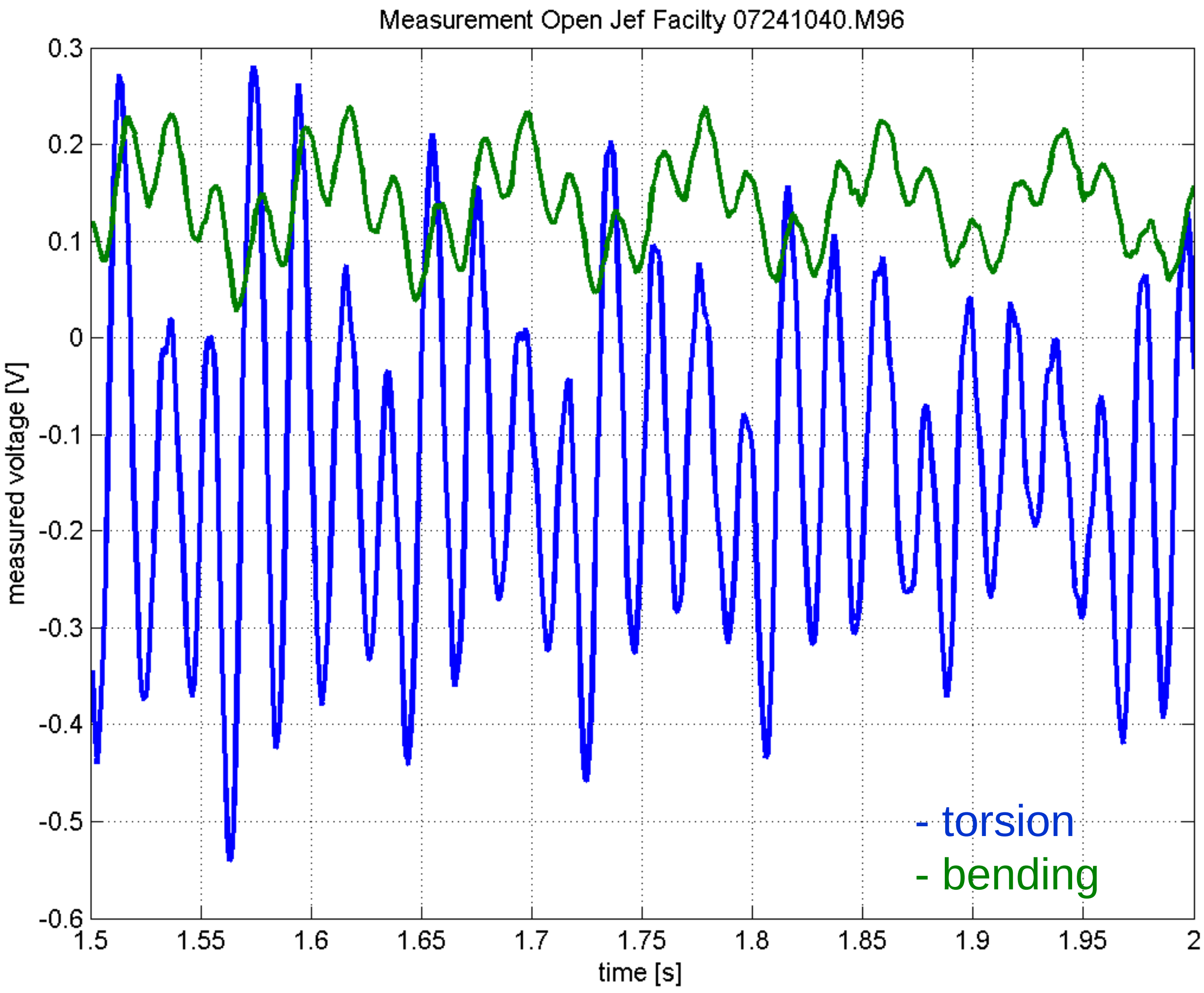
- Defined unsteady aerodynamic situation is created
  - The amplitude is a function of the yaw angle
  - The frequency is a function of the rotor speed





Initial data analysis and results

Rotor speed = 12 Hz
Wind speed = 9.5 m/s
Yaw = +15 deg
Element = 1,5 mm



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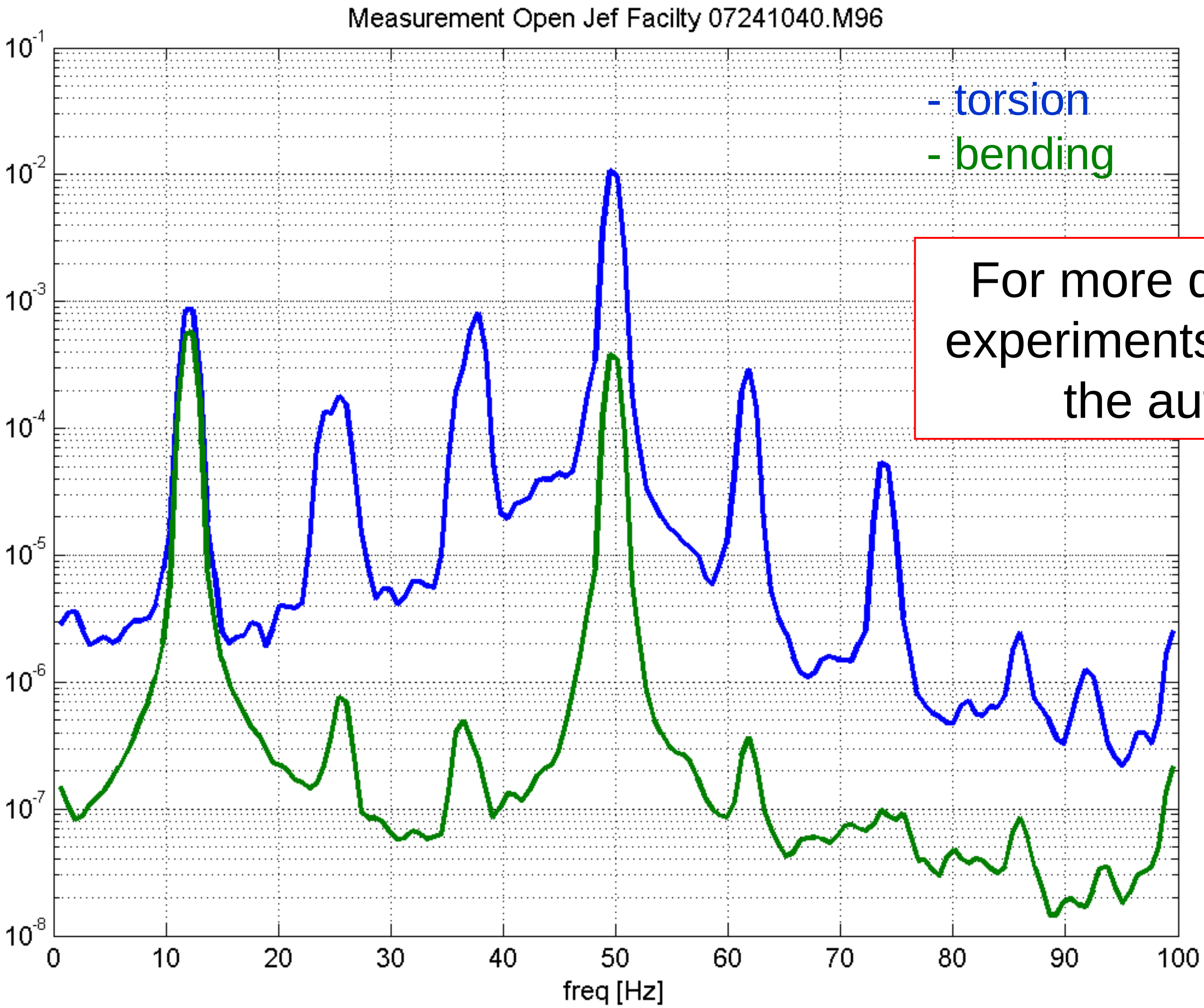

For more data and experiments, contact the author

Conclusions

- Small wind turbine systems should be reliable and affordable despite the expectation that aerodynamic and rotor dynamic variations are more prominent than for traditional large scale wind turbine systems
- Aerodynamic modeling, especially unsteady aerodynamics, combined with flexible rotor concepts deserves renewed attention to guarantee reliable designs based on accurate predictions of wind turbine behavior
- A open jet wind tunnel facility has been used to experiment with a instrumented small rotor setup with a flexible rotor mounting element and controllable rotor speed (motor driven)
- An extensive set of experiments has been recorded, bringing the rotor in dynamic stall conditions, inducing stall-flutter
- An approach has been introduced to identify the rotor airfoil coefficients that are incorporated in the ONERA model for dynamic stall
- Preliminary data analysis show the potential of this experimental data base to identify these coefficients from the available experiments

Next steps

- Further elaborate experimental data
- Combine measurements into identification of ONERA coefficients
- Validate dynamic stall model with identified coefficients against unused experiments over a range of aerodynamic conditions
  - Qualitatively : do we see correspondence in the kind of behavior?
  - Quantitatively: does also match in absolute sense?

- Repeat some of the experiments with the new Open Jet Facility at Defft University of Technology

New Open Jet wind tunnel Facility at Delft University of Technology

- Located at Aerospace department
- Opened january 2009
- Opening 2,85 x 2,85 m
- Wind speed up to 35 m/s
- ‘Open' layout

- 2 bladed rotor
- Current research on dynamic stabilization exploiting smart structure rotor concepts
- Piezo driven blade flaps to reduce fatigue loading
- Extensive instrumentation

Thank you! Questions?

Visit us at www.apptech.philips.com
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