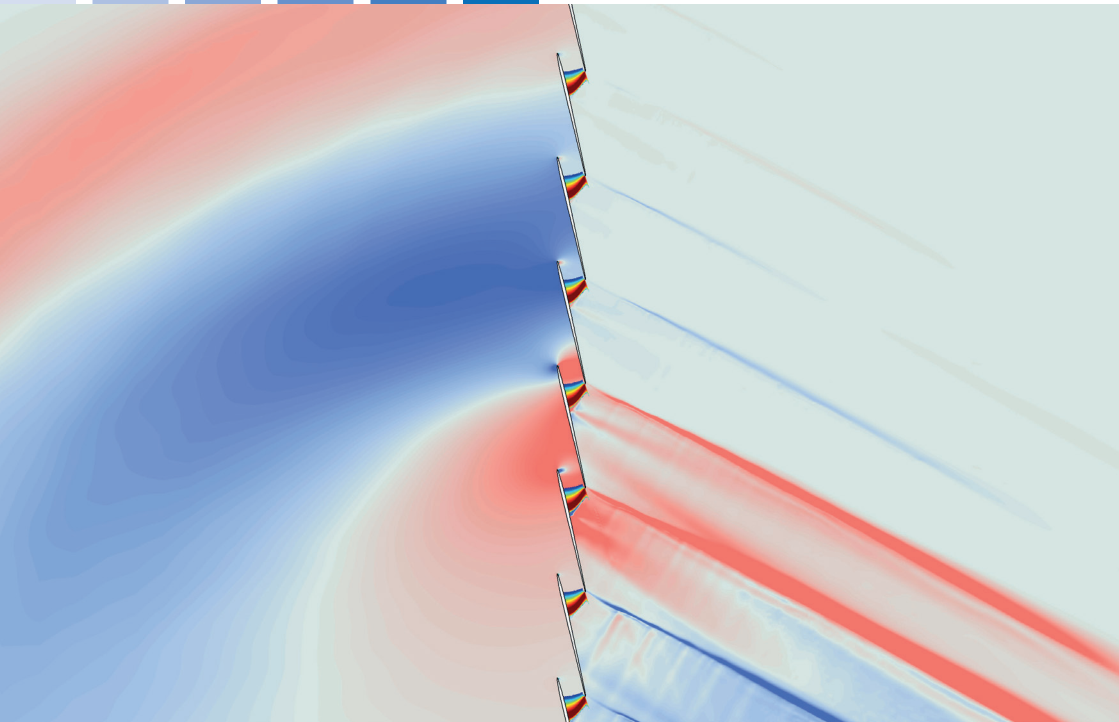
# Numerical Investigation on Spontaneous Condensation in Low-Pressure Steam Turbine Aeroelasticity

Christopher Fuhrer



# Numerical Investigation on Spontaneous Condensation in Low-Pressure Steam Turbine Aeroelasticity

Von der Fakultät Energie-, Verfahrens- und Biotechnik
der Universität Stuttgart zur Erlangung der Würde eines Doktors
der Ingenieurwissenschaften (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

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aus Herrenberg

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Institut für Thermische Strömungsmaschinen und
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Berichte aus der Strömungstechnik

**Christopher Fuhrer**

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# Contents

# Nomenclature

## Acronyms

| | |
|---|---|
| CFD | computational fluid dynamics |
| EQS | equilibrium steam |
| FE | finite element |
| HLRS | High-Performance Computing Center Stuttgart |
| IBPA | interblade phase angle |
| IC | influence coefficients |
| ITSM | Institute of Thermal Turbomachinery and Machinery Laboratory |
| LE | leading edge |
| LP | low-pressure |
| MAC | modal assurance criterion |
| NES | non-equilibrium steam |
| PS | pressure side |
| RANS | Reynolds averaged Navier-Stokes |
| SS | suction side |
| SST | shear stress transport |
| STAC | Steam turbine Test case for Aeromechanics and Condensation |
| STCF | standard configuration |
| TE | trailing edge |
| TWM | traveling wave mode |

## Latin Symbols

| | | |
|---|---|---|
| $a$ | $\mathrm{m\,s^{-1}}$ | speed of sound |
| $A$ | $\mathrm{m^2}$ | area |
| $b$ | m | blade height |
| $c$ | m | chord length |
| $c_p$ | $\mathrm{J\,kg^{-1}\,K^{-1}}$ | specific heat capacity at constant pressure |
| $C_p$ | – | normalized unsteady pressure coefficient |

| | | |
|---|---|---|
| $\mathbf{D}$ | – | damping matrix |
| $f$ | Hz | frequency |
| $\mathbf{f}$ | – | force vector |
| $F$ | N | force |
| $h$ | m | translational amplitude |
| $\mathbf{h}$ | – | vector of local displacement |
| $h_{\mathrm{fg}}$ | $\mathrm{J\,kg^{-1}}$ | specific enthalpy of evaporation |
| $h_{\mathrm{t}}$ | $\mathrm{J\,kg^{-1}}$ | specific total enthalpy |
| i | – | imaginary unit, $\mathrm{i}=\sqrt{-1}$ |
| $J$ | $\mathrm{s^{-1}\,m^{-3}}$ | nucleation rate |
| $k$ | – | reduced frequency |
| K | – | Boltzmann's constant |
| $\mathbf{K}$ | – | stiffness matrix |
| Kn | – | Knudsen number |
| $K^2$ | – | complex wave vector |
| $l$ | – | nodal diameter |
| $L$ | $\mathrm{J\,kg^{-1}}$ | specific latent heat |
| $m$ | kg | mass |
| $m^*$ | kg | mass of critical droplet |
| $M$ | N m | torsional moment |
| $\mathbf{M}$ | – | mass matrix |
| Ma | – | Mach Number |
| $n$ | – | blade normal vector |
| $N$ | – | number of blades |
| $N_{\mathrm{d}}$ | – | number of dispersed phases |
| $N_{\mathrm{l}}$ | – | droplet number |
| $N_{\mathrm{p}}$ | – | number of phases |
| $p$ | Pa | pressure |
| Pr | – | Prandtl number |
| $q$ | – | local blade number |
| $q_{\mathrm{c}}$ | – | condensation coefficient |
| $r$ | m | radius |
| $r^*$ | m | critical droplet radius |

| | | |
|---|---|---|
| R | $J\,kg^{-1}\,K^{-1}$ | specific gas constant |
| $S_C$ | $kg\,m^{-3}\,s^{-1}$ | mass source term |
| $S_H$ | $W\,m^{-3}$ | energy source term |
| $t$ | s | time |
| $T$ | s | time period |
| $T$ | K | temperature |
| $T_c$ | K | critical temperature |
| $u$ | $m\,s^{-1}$ | flow velocity |
| $V$ | $m\,s^{-1}$ | blade velocity vector |
| $w$ | – | local stability coefficient |
| $W$ | J | work |
| $x$ | m | Cartesian coordinate x |
| $x$ | – | wetness fraction |
| $\mathbf{x}$ | – | mass matrix |
| $y$ | m | Cartesian coordinate y |
| $y+$ | – | non-dimensional wall distance |
| $z$ | m | Cartesian coordinate z |

## Greek Symbols

| | | |
|---|---|---|
| $\alpha$ | – | constant in Young's growth model |
| $\alpha$ | rad | rotational amplitude |
| $\beta$ | – | constant in Young's growth model |
| $\gamma$ | rad | stagger angle |
| $\gamma$ | – | isentropic index |
| $\Gamma$ | $W\,kg\,m^{-1}\,K^{-1}$ | thermal diffusion coefficient |
| $\Gamma_{disp}$ | – | mesh stiffness |
| $\delta$ | m | mesh displacement |
| $\varepsilon$ | – | non-isothermal correction of Kantrowitz |
| $\zeta$ | rad | rotational coordinate |
| $\eta$ | m | coordinate normal to chord |
| $\theta$ | rad | angular coordinate in cylindrical system |
| $\lambda$ | $W\,m^{-1}\,K^{-1}$ | thermal conductivity |

| | | |
|---|---|---|
| $\mu$ | $\mathrm{kg\,m^{-1}\,s^{-1}}$ | dynamic viscosity |
| $\nu$ | – | function in Young's growth model |
| $\xi$ | m | coordinate along chord |
| $\Xi$ | – | normalized stability parameter |
| $\rho$ | $\mathrm{kg\,m^{-3}}$ | density |
| $\sigma$ | ° | interblade phase angle |
| $\sigma$ | $\mathrm{N\,m^{-1}}$ | surface tension |
| $\tau$ | m | blade pitch |
| $\tau_{\mathrm{I}}$ | s | inertial relaxation time |
| $\tau_{\mathrm{T}}$ | s | thermal relaxation time |
| $\varphi$ | rad | phase of complex pressure |
| $\phi$ | – | volume fraction |
| $\omega$ | $\mathrm{rad\,s^{-1}}$ | angular frequency |

## Subscripts / Superscripts

| | |
|---|---|
| crit | critical |
| cycle | oscillation cycle |
| damp | damping |
| disturb | disturbance |
| dyn | dynamic |
| D | Doppler |
| e | equilibrium |
| EQ | equilibrium |
| f | frozen |
| g | vapor phase |
| i | tensor notation |
| j | tensor notation |
| l | liquid phase |
| NE | non-equilibrium |
| $o$ | phase index |
| ref | reference |
| s | saturation condition |

# Abstract

In steam turbines, condensation of water vapor usually occurs in the last stages leading to the formation of droplets. This changes the course of the expansion and the thermodynamics of the flow. The aim of this study is to numerically investigate the influence of wet steam effects on the flutter behavior of turbine blades.

Extensively validated numerical models are used to describe the two-phase flow. The droplet formation under thermodynamic non-equilibrium conditions is described with a classical homogeneous nucleation model. For the determination of the aerodynamic damping, the energy method with influence coefficients is used as today's state of the art.

Different wetness conditions are defined at the inlet of a tip section of a rotor blade. At first, different droplet sizes and wetness contents hardly show any influence on the stationary blade loading. However, the condensation that occurs leads to a reduction of the speed of sound. In cases with dry inlet conditions, strong spontaneous condensation occurs at different positions in the blade passage and leads to a considerable local pressure increase, which also influences the shock structure. Such changes are not represented by the single-phase fluid models.

The determination of the aerodynamic damping provides new insights, whereby the torsion mode has a clearer influence on the least stable point due to wetness effects than a translational movement, i.e. bending mode. In general, condensation on a large area on the blade surface has a stabilizing character in contrast to very strong, spatially limited nucleation. In addition, the aerodynamic damping increases linearly with wetness in the case of the bending mode and decreases for torsional motion. An analysis of the acoustic resonances confirms the dependence of the speed of sound not only on the thermodynamics but also on the oscillation frequency of the disturbance, which previously has been discussed in literature.

# Kurzfassung

In Dampfturbinen setzt die Kondensation des Wasserdampfes üblicherweise in den letzten Stufen ein. Diese Tatsache und die entstehenden Tropfen haben einen Einfluss auf den Expansionsverlauf und die Thermodynamik der Strömung. Ziel dieser Arbeit ist den Einfluss der Nassdampfeffekte auf das Flatterverhalten von Turbinenschaufeln numerisch zu untersuchen.

Es werden ausführlich validierte, numerische Modelle zur Beschreibung der Zweiphasenströmung verwendet. Dabei wird die Tropfenentstehung unter thermodynamischen Ungleichgewichtsbedingungen mit einem klassischen homogenen Keimbildungsmodell beschrieben. Zur Bestimmung der aerodynamischen Dämpfung wird die Energiemethode mit Einflusskoeffizienten als heutiger Stand der Technik verwendet.

Verschiedene Nässezustände werden am Eintritt eines Spitzenschnitts einer Rotorschaufel definiert. Zunächst zeigen verschiedene Tropfengrößen und Nässeanteile kaum einen Einfluss auf die stationäre Schaufelbelastung. Jedoch führt die auftretende Kondensation zu einer Verringerung der Schallgeschwindigkeit. Bei Fällen mit trockenen Eintrittsbedingungen tritt starke spontane Kondensation an verschiedenen Positionen in der Schaufelpassage auf und führt zu einem erheblichen lokalen Druckanstieg, dabei wird auch die Stoßstruktur beeinflusst. Derartige Veränderungen werden von den einphasigen Fluidmodellen nicht abgebildet.

Neue Erkenntnisse liefert die Bestimmung der aerodynamischen Dämpfung, dabei weist die Torsionmode eine deutlichere Beeinflussung des instabilsten Punktes durch Nässeffekte als eine translatorische Bewegung, wie beispielsweise bei einer Biegemode, auf. Allgemein hat die Kondensation auf einem großen Gebiet auf der Schaufeloberfläche einen stabilisierenden Charakter im Gegensatz zur sehr starken, räumlich begrenzten Nukleation. Zusätzlich steigt die aerodynamische Dämpfung mit der auftretenden Nässe im Fall der Biegemode linear an und sinkt für die Torsionsbewegung. Eine Auswertung der auftretenden akustischen Resonanzen bestätigt die in der Literatur diskutierte Abhängigkeit der Schallgeschwindigkeit nicht nur von der Thermodynamik, sondern auch von der Schwingfrequenz der Störung.