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In depth analysis of the nonlinear stability behavior of BWR-Systems

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Abstract

A new approach for nonlinear BWR stability analysis is presented: Application of system codes (like RAMONA) and Reduced Order Models (ROM´s) as complementary tools for revealing and understanding of the (linear and) nonlinear BWR stability behaviour. Within the scope of this work a ROM is defined as a system of (ordinary) nonlinear differential equations (dynamical system) which provides a solution type set close to the (partial) differential equations used in the system code. The objective of this work is to examine the stability properties of fixed points and periodical solutions of the nonlinear differential equation system describing the BWR stability behaviour. This work is a continuation of the previous work at the Paul Scherrer Institute (PSI, Switzerland) and the University of Illinois (USA) on this field [Dokhane, 2004; Karve, 1998; Van Bragt, 1998; Zhou, 2006]. The ROM developed at PSI (called PSI-Illinois-ROM) was upgraded by introducing the recirculation loop and modifying the feedback reactivity calculation. The effect of the subcooled boiling phenomenon on the stability properties was evaluated by using a profile fit model [Levy, 1967]. The upgraded ROM has been coupled with the BIFDD code [Hassard, 1981] which performs semi-analytical bifurcation analysis.
The new approach has been applied on three operational points (NPP Leibstadt, NPP Ringhals, NPP Brunsbüttel). As an example, in the scope of the poster presentation are presented the results for an operational point (KKLc7_rec4) NPP Leibstadt where an out-of-phase power oscillation has been observed experimentally. The stability boundary (SB) and the nature of the Poincarè-Andronov-Hopf bifurcation (PAH-B) have been determined by performing semi-analytical bifurcation analyses with the ROM using the bifurcation code BIFDD. For independent confirmation of these results, numerical integration of the ROM equation system has been carried out. It will be shown that unstable periodical solutions exist in the stable region of the SB close to KKLc7_rec4-OP. Thereby the power oscillation mode is out-of-phase.

Introduction

From theoretical and experimental studies, it is well known that for a boiling water reactor (BWR) plant there are operational points where slowly decaying or non-decaying power oscillations are observed. Global or in-phase oscillations and regional or out-of-phase oscillations are two kinds of observed power oscillations. Power oscillations have reactor safety relevance because the amplitudes could become large enough to violate operational limit values (e.g. critical power ratio) and fuel element failure can be expected.

The dynamics of BWRs → can be described by a → **system of coupled nonlinear partial differential equations**

From the nonlinear dynamics point of view, it is well known that nonlinear dynamic systems show under specific conditions very complex behavior which is reflected in the solution manifold of the corresponding equation system. Consequently, to understand the nonlinear stability behavior of a BWR, the solution manifold of the corresponding differential equation system must be examined.

Determination of:
- stable and unstable **fixed points**
- stable and unstable **periodic solutions**

Unstable periodic solutions, occurring in the neighborhood of subcritical bifurcations, have reactor safety relevance because they are appearing at the **stable side** of the (linear) stability boundary! Therefore, conceivably, unstable conditions are not recognized and operational safety limits could be violated. Hence, searching for unstable periodical solutions is one of the main tasks of this work.

Methodology

In the framework of this work, the System Code RAMONA5 and the upgraded PSI-ROM are used as complementary tools.

Detailed BWR-Model (RAM)
- System Code Analysis

Reduced order BWR-Model (ROM)
- Semi-analytical Bifurcation Analysis
- Numerical Integration

Characteristic:
Relative detailed physical models of all significant NPP-components

Advantage:
Stability characteristic of a BWR is modeled close to physical reality

Disadvantage:
- In general parameter tuning is necessary
- The behaviour of the algorithms used for the solution of the differential equations close to bifurcation points is not well-known

Characteristic:
- Minimum number of system equations
- Reduction of the geometrical complexity
- The most of the stability related effects are modeled

Advantage:
Coupling with methods of the nonlinear dynamics
→ **new stability indicators!!!**

Disadvantage:
- Many additional approximations
- Area of validity has to be known

What‘s New?

Main Weak Points of PSI-ROM:

Neutron kinetic model:
- Calculation methodology for the mode-feedback reactivities is insufficient

Thermal-hydraulic model:
- Constant external pressure drop as boundary condition
- Subcooled boiling is not considered

Main ROM Extensions:

- **New calculation methodology** for mode-feedback reactivities is developed.
- Thermal-hydraulic model is extended by the **recirculation loop**.
- The **effect of subcooled boiling** on the BWR stability behavior has been **estimated** by a simple subcooled boiling model based on a profile fit model [Levy, 1967].

→ **Furthermore, a new approach for the calculation of the ROM input parameters has been developed.**

New approach for nonlinear BWR stability investigation with RAMONA5 and ROM

1) Selection of an operational point (OP) of interest (reference OP)

2) All ROM inputs will be calculated from the specific RAMONA5 model and its steady solution

RAM — steady state run in ref. OP
ROM — steady state run in ref. OP

RAM-Output
- $\dot{m}_{tot}$,
- axial void profile, (radially averaged)
- channel pressure drops,
....

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ROM-Output
- $\dot{m}_{tot}$,
- axial void profile,
- channel pressure drops,
....

3) Nonlinear stability analyses in the neighborhood of the ref. OP

ROM Analysis
→ Semi-Analytical Bifurcation Analysis with BIFDD
- Examination of stable and unstable **fixed points**
- Examination of stable and unstable **periodic solutions**

→ Numerical Integration of the ROM equations
- Verification of the results, optained from the semi-analytical bifurcation analysis

System Code Analysis with RAMONA5
- Reproduction of the optained results from the ROM-Analysis for choosen parameters
- Detailed investigation in a close neighborhood of the ref. OP

Bifurcation Analysis using BIFDD

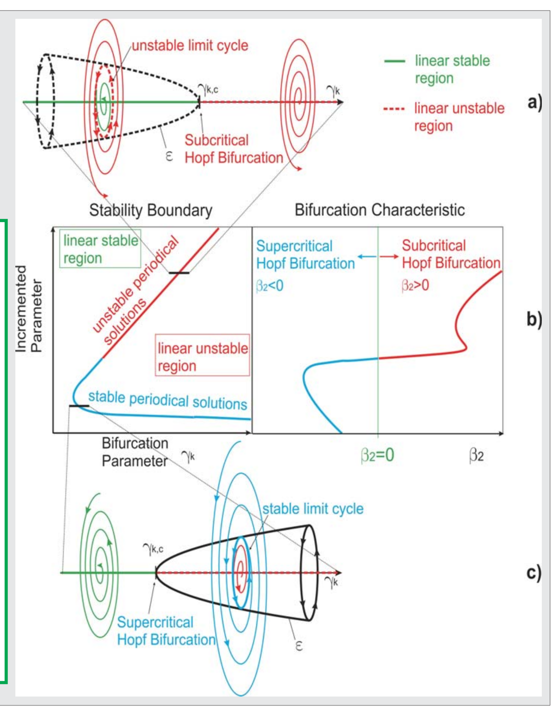
The Poincarè-Andronov-Hopf bifurcation (PAH-B) theorem guarantees the existence of stable and unstable periodic solutions of nonlinear differential equations, if the Hopf conditions are satisfied.

1) Examination of the fixed points, where the Hopf-Condition is fulfilled
→ Stable and unstable **fixed points** (Stability Boundary)

2) Center Manifold Reduction

3) Transformation into the Poincarè Normal Form

4) The bifurcation characteristics can be examined from the resulting equation system
→ Stable and unstable **periodic solution** (determined by β_2)



Results

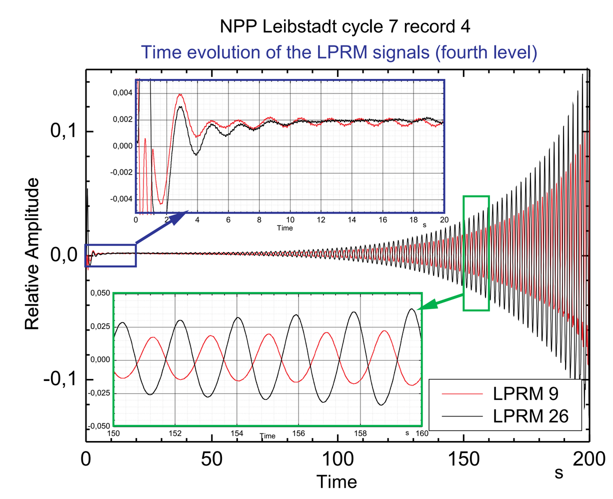
A nonlinear stability investigation was performed for KKLc7_rec4-OP of the NPP Leibstadt where increasing regional power oscillations have been found experimentally. To this end, the following OP was selected to be the reference OP:

Reference OP*

$$\text{Power} = 59.5\% \quad (1867.11\ MW)$$
$$\text{Flow} = 36.5\% \quad (4072.12\ kg/s)$$
$$\text{Subcooling} = 125.0 \cdot 10^3\ kJ/kg$$
$$\text{Pressure} = 69.7\ bar$$

* This OP is close to KKLc7_rec4-OP

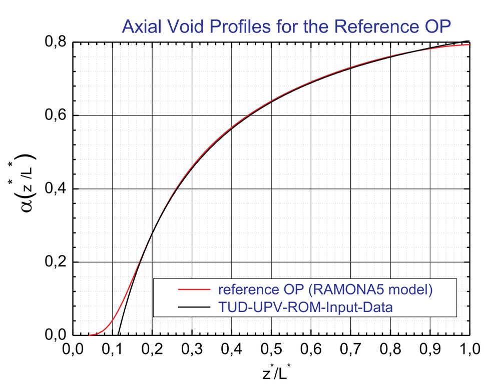
RAMONA5 analysis for the reference OP



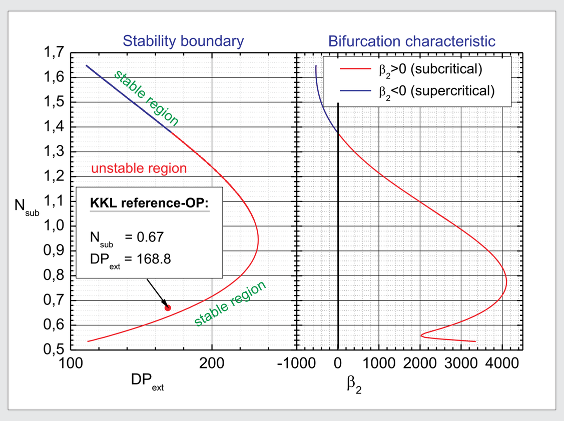
Comparison of steady state pressure drops and axial void profiles of RAMONA5 and ROM

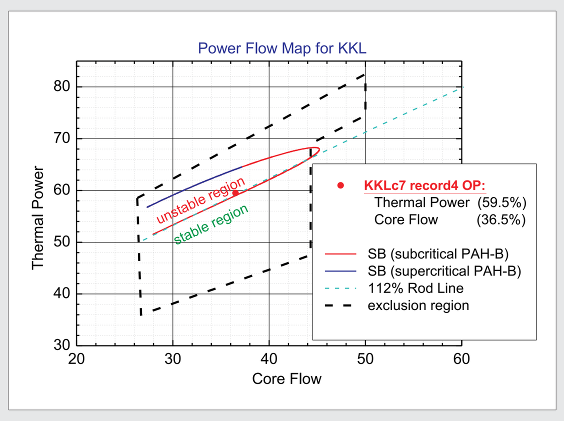
All design parameters of the ROM are calculated from the specific KKL-RAMONA5 model and its steady state solution for this reference OP. As a result, the thermal hydraulic states provided by RAMONA5 and ROM are physically equivalent for the reference OP.

Pressure drop	RAMONA5	ROM
$\Delta P^*_{ch,inlet}$	$-1.654 \cdot 10^4\ Pa$	$-1.641 \cdot 10^4\ Pa$
ΔP^*_{ch}	$-2.777 \cdot 10^4\ Pa$	$-2.763 \cdot 10^4\ Pa$
$\Delta P^*_{ch,exit}$	$-2.956 \cdot 10^4\ Pa$	$-2.984 \cdot 10^4\ Pa$
DP^*_{ext}	$-7.387 \cdot 10^4\ Pa$	$-7.387 \cdot 10^4\ Pa$



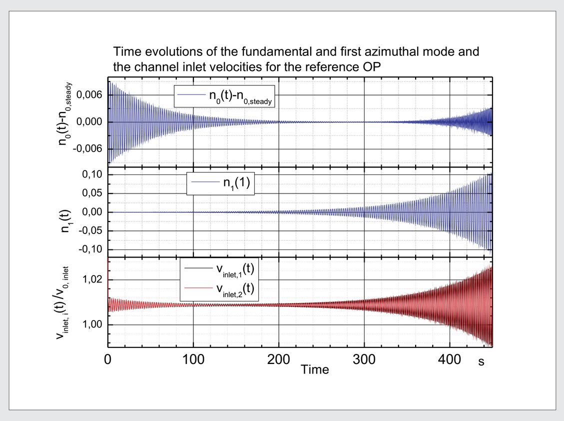
Semi-Analytical Bifurcation Analysis using BIFDD



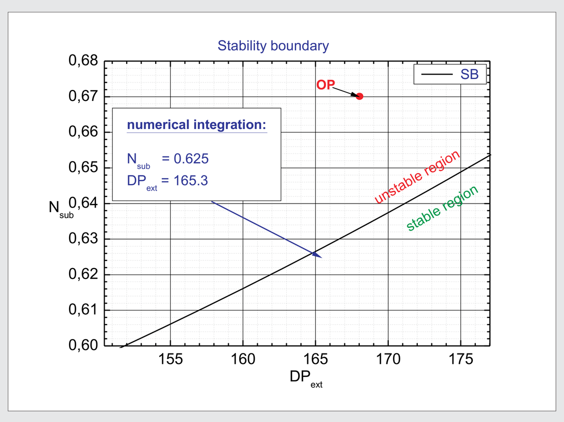


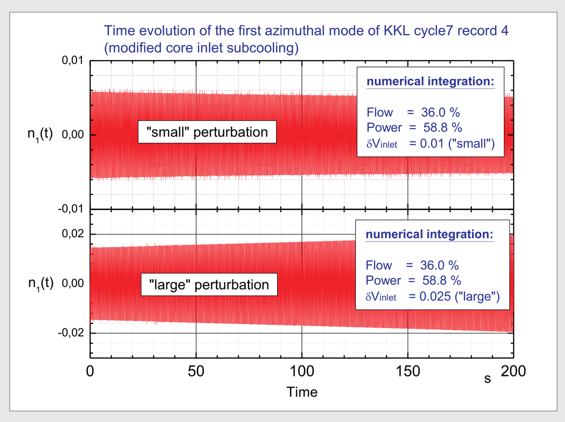
Numerical Integration

In a first step, numerical integration of the ROM equation system is performed for the reference OP. The results confirm the existence of an increasing regional power oscillation.



Semi-analytical bifurcation analysis predicts the existence of unstable periodical solutions in the linear stable region close to the reference OP. Next numerical integration is carried out in an OP where an unstable periodical solution exists. A small perturbation imposed on the system lead to an stable behavior while a sufficent large perturbation lead to an unstable behavior.





Conclusions

- The BWR stability behavior in the reference OP and its close neighbourhood can be analysed reliably by the new ROM. In this operational region the results of RAMONA5 and ROM are equivalent.

- A comparative study with RAMONA5 and ROM (not here presented) where selected parameters which are significant for the stability behavior (like the core inlet subcooling) were varied in the range of interest, has been shown, that the dependence of the stability behavior regarding parameter variations are consistent.

- Unstable periodical solutions in the stable region close to the reference OP are predicted by the semi-analytical bifurcation analysis.

- Numerical integration of the ROM equation system confirms the prediction of the semi-analytical bifurcation analysis.

- Hence, the new ROM is qualified for BWR stability analysis in the framework of the approach demonstrated in this poster contribution.