Time Frequency based Algorithm for Online Detection of Thermal Hydraulic Instabilities in AHWR

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Abstract :

Advanced Heavy Water Reactor (AHWR), a natural circulation boiling water reactor, is reported to be prone to xenon instabilities. Xenon induced spatial instabilities are suppressed by the spatial power control program of AHWR. However, thermal hydraulic instabilities characterised by flow oscillations of the order of tens of seconds, are more challenging in terms of detection and control. In AHWR, the operating procedure is carefully formulated so as to avoid thermal hydraulic instabilities during start-up and operation. Nevertheless, the availability of an on-line monitoring mechanism to indicate the onset of such instabilities would aid the operator to monitor the operational state of the reactor and to take up immediate corrective measures in case of the onset of thermal hydraulic instabilities during unanticipated operating conditions. In this context, a time frequency representation based algorithm suitable for online implementation, is developed to detect the onset of the oscillations by continuous monitoring of the channel flow signals. Validation of the algorithm is carried out with data simulated using a homogeneous equilibrium model capable of demonstrating thermal hydraulic instabilities in the Main Heat Transport system of the AHWR.

Introduction

Advanced Heavy Water Reactor (AHWR) [1] is a 300 MWe, vertical, pressure tube type, heavy water moderated reactor which employs natural circulation of boiling light water for core cooling. The Main Heat Transport System (MHTS) of AHWR consists of four horizontal steam drums connected to common inlet header through downcomers. Fig.1 shows a simplified schematic of MHTS of AHWR showing a single heat transport loop consisting of a steam drum, downcomer, feeder, coolant channel and tail pipe. Subcooled light water is transported from the steam drum to the channel through the feeder originating from inlet header. Boiling takes place inside the channel and the resulting steam-water mixture is transported to the steam drum through the tail pipe.

AHWR, like many other natural circulation reactors, is prone to thermal hydraulic instabilities under certain operating conditions. It is reported that Ledinegg type instabilities (static in nature) and density wave instabilities (dynamic in nature) may occur in AHWR [1]. Ledinegg instabilities are suppressed in AHWR by operating at a high pressure (7 MPa). However, density wave instabilities can still be experienced if the operating conditions are not strategically controlled and therefore are of primary concern. Density wave instabilities manifest as flow oscillations of increasing

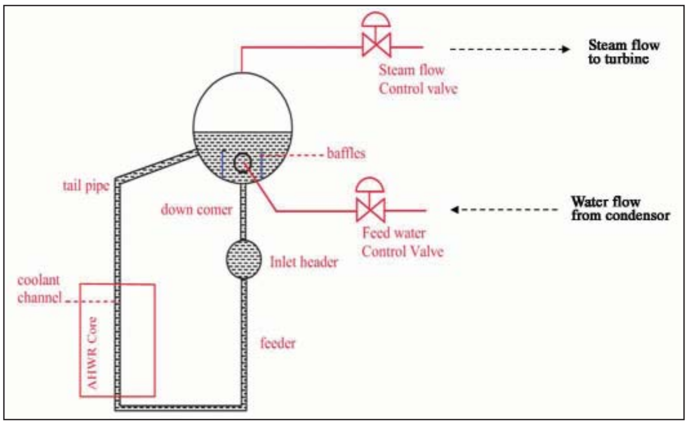

Fig. 1: Main Heat Transport System of AHWR (Schematic)

amplitude in response to any perturbation in system variables like flow, enthalpy, etc. These instabilities are caused due to multiple regenerative feedback effects between the flow-rate, vapour generation rate and pressure drop. Under certain operating conditions the feedback tends to become out-of-phase with a perturbation and results in self-sustained oscillations. In any natural circulation based reactor operating at a constant power, the fission power and core inlet subcooling essentially govern the stability conditions [2]. In AHWR, the core inlet temperature is varied (by controlling the feed water temperature) based on the operating power so as to avoid density wave instabilities during normal operation of the reactor. However, availability of real time stability information at the operator's console is still very beneficial to ensure smooth operation.

Nature of Density Wave Instabilities

It is necessary to study the effect of power and core inlet subcooling on the flow oscillations caused due to density waves instabilities. Density wave instabilities are simulated for a given combination of power and core inlet subcooling by initially maintaining steady state conditions and then introducing a small perturbation in power. For an unstable combination of power and core inlet subcooling, this perturbation leads to unstable oscillations in flowrate, density, pressure and enthalpy. The frequency of the flow oscillation is computed by studying the amplitude spectrum of the channel flowrate signal. The amplitude spectra of a time-domain signal can be obtained by carrying out a Fourier transform of the given signal. Fig.2 and 3 show comparison of normalised channel flowrates during onset of density wave instabilities and their single sided amplitude spectra at different powers and core inlet subcooling values respectively. The figures clearly indicate that the frequency of oscillation tends to increase with increasing power and decrease with increasing core inlet subcooling.

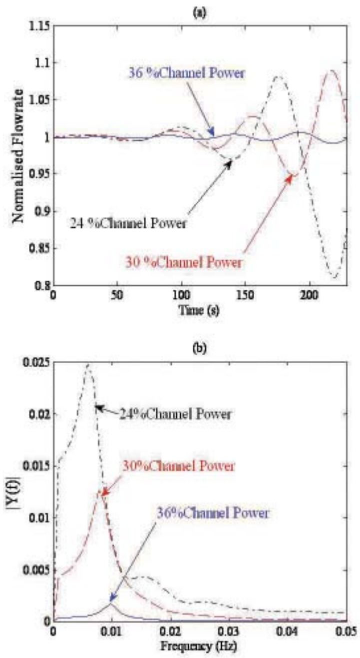

Fig. 2: (a) Normalised response of channel flow-rates at different power levels to a perturbation in power at a fixed inlet subcooling of 24K, (b) Single sided amplitude spectra (|Y(f)|) of the normalised channel flowrates

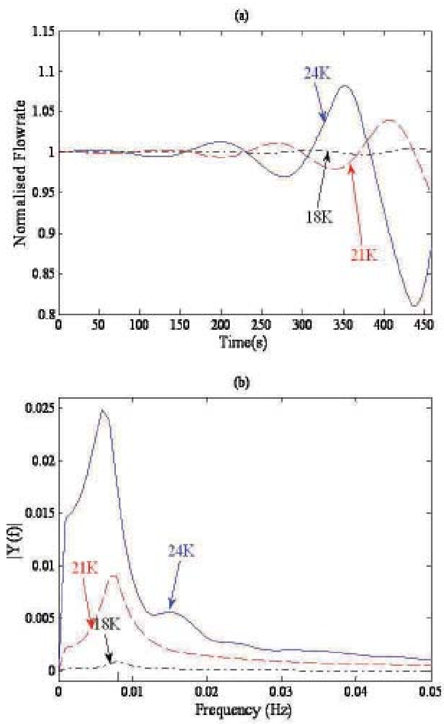

Fig. 3: (a) Normalised response of channel flow-rates at different core inlet subcooling to a perturbation in power around the operating power level of 24% channel power, (b) Single sided amplitude spectra (|Y(f)|) of the normalised channel flowrates

Similarly, it can also be observed that the amplitude of oscillation tends to decrease with increase in fission power and increase with increase in core inlet subcooling. These observations indicate that the frequency of density wave instabilities vary with time and are determined by the instantaneous operating condition.

Detection of Density Wave Instabilities

In boiling channel systems, density wave instabilities are undesirable as they may cause mechanical vibrations, system control problems etc [3]. In some cases they may rupture the heat transfer surface due to boiling crisis (dry-out, burnout) [2]. In AHWR, the design methodology is formulated to avoid such phenomena. Nevertheless, it is necessary and advisable to detect the onset of these instabilities during plant operation and make this information available to the operator. The onset of these instabilities can be detected by continuously acquiring the channel flow signals and sensing the presence of oscillations, followed by computation of the decay ratio of these oscillations. Decay ratio is defined as the ratio of two consecutive maxima of the impulse response. Decay ratio greater than unity would mean an unstable scenario, a value less than unity would mean a stable scenario. The simplest approach to compute the decay ratio could be to detect the magnitude of peaks of the oscillations whenever they appear and then compute the ratio of magnitude of present peak to that of the previous peak. However, this approach is not practical since the frequency of oscillation tend to vary with time. This problem can be addressed by using a time-frequency framework to describe the time varying flow signals rather than a conventional time-domain approach. A Time Frequency Representation (TFR) [4] gives the distribution of energy of a signal in time-frequency plane. The most widely TFRs are Short-time Fourier transform and Wigner-Ville distribution. However, in this work Wigner-Ville representation is preferred owing to its mathematical simplicity and the adaptability for real time applications. Fig.4 shows the Wigner-Ville time frequency distribution for a typical signal with linear variation in frequency. An algorithm based on Wigner-Ville time frequency representation is employed to predict a quantity called Instantaneous Decay Ratio (IDR) which would serve as a real time stability parameter. The algorithm also computes Accumulated Decay Ratio (ADR) defined as the accumulative multiplication of IDRs (in time) which projects the long term stability trend of the reactor.

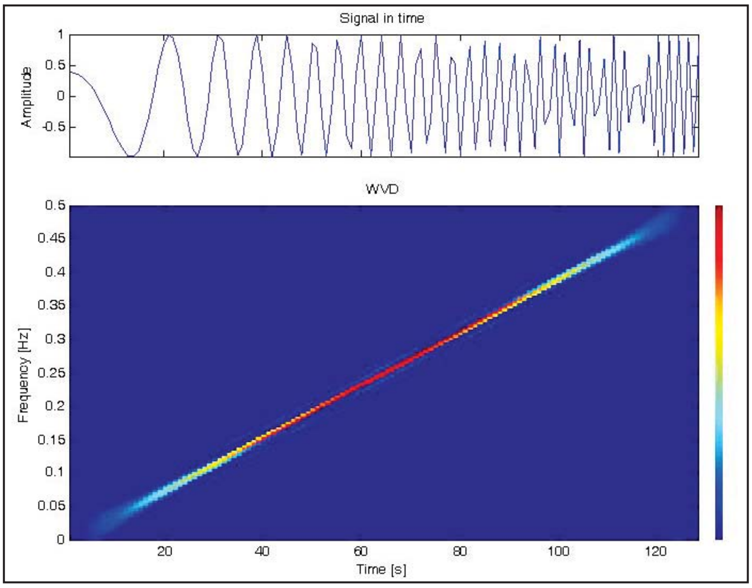

Fig. 4: A signal with linear frequency modulation (above) and WVD of the signal (below).

Algorithm for Computation of Decay Ratios

Fig.5 shows the schematic representation of the proposed algorithm which computes of IDR and ADR based on MHT channel flow information acquired at discrete time instants and infers about instability. The real signal sequence is converted

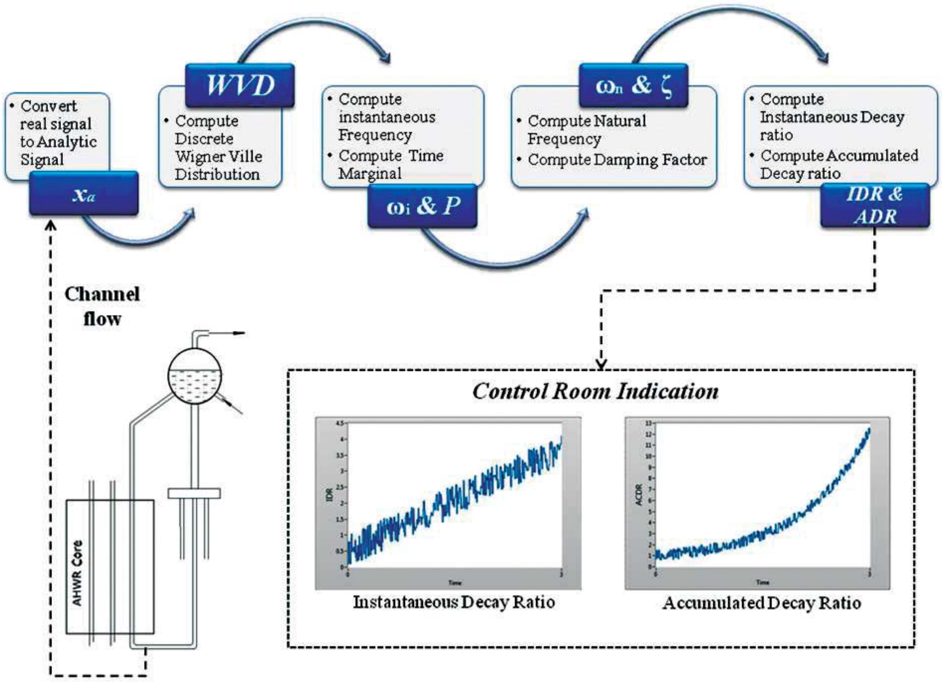

Fig. 5: Time frequency based algorithm for computing decay ratio

into analytic signal by removing the negative frequency components from the Fourier transform of the real signal and doubling the positive frequency components. Inverse transform of the resultant spectrum gives the analytic signal. It may be noted that conversion of the real signal into an analytic signal is necessary to eliminate the low frequency artefacts which appear in the Wigner time frequency distribution otherwise. The signal is then transformed into a zero mean signal and it is used to compute the Wigner-Ville time frequency distribution (WVD). The WVD involves FFT operation on the local autocorrelation of the analytic signal (localised product of time shifted signal at each discrete time instant). Instantaneous frequency (normalised first moment of frequency) is computed by taking the frequency weighted average of the magnitude of WVD at each discrete time instant. Time marginal (instantaneous power of the signal) is computed by adding the magnitude of WVD at each discrete time instant and multiplying the sum with the frequency resolution of the system. The natural frequency is computed using instantaneous frequency and the time marginal. The damping factor (computed from the natural frequency and time marginal) is used to compute IDR. The ADR is the accumulative product of local IDRs.

Online implementation

The proposed algorithm is suited for online implementation on a computer based system. The channel flow information can be sampled and acquired periodically, say every second, by a data acquisition module. A moving window (of width 200 s) of channel flow signal with certain degree of overlapping (of width 5 s) is fed to the algorithm and the decay ratios based on latest window of the flow signal are computed and continuously displayed on the operator console.

Validation of the algorithm

The effectiveness of the decay ratio based algorithm for instability detection is established using simulated channel flow data for various stable and unstable scenarios obtained using a one-dimensional finite difference based homogenous equilibrium model of the MHT loop of AHWR, consisting of a single downcomer, tailpipe, boiling channel and riser. The model consists of mass, momentum and energy balance equations to represent the dynamics of coolant flow in the MHTS. It is assumed that there is no relative velocity between the two phases and the vapour and liquid in the channels and the riser sections are in thermodynamic equilibrium. Control volume-based spatial discretization and forward difference scheme discretization in time are employed to derive the difference equations for mass, momentum and energy conservation for various meshes in the MHTS. For a given operating power and core inlet subcooling, the steady-state distribution of system variables pressure, enthalpy, density and flow are computed using steady state equations. With the steady-state distribution as the starting point, time-dependent difference equations are solved for each mesh during transient conditions. A small perturbation is introduced in the channel power and the response of the system variables - pressure, enthalpy, density and flow is observed.

Fig.6 and Fig.7 show the preprocessed channel flow (converted into a zero mean signal), respective instantaneous decay ratios and accumulated decay ratios computed by the algorithm during the onset of stable and unstable oscillations respectively. Fig. 6 shows that the IDR value remains below unity indicating an instantaneous stable behaviour. The ADR shows a gradually decreasing trend showing a globally stable behaviour. Similarly, Fig. 7 shows that the IDR value remains above one indicating unstable behaviour throughout the time window and the ADR value gradually increases showing a globally unstable behaviour. The figures indicate that the decay ratio based algorithm effectively operates on the channel flow signal and gives the stability information of the system.

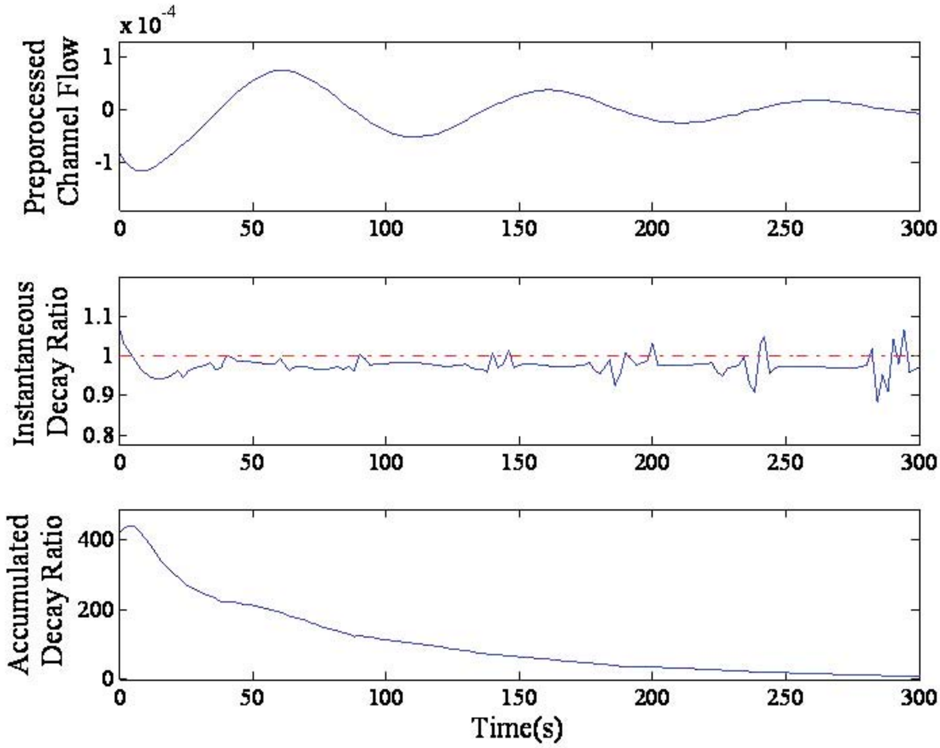

Fig. 6: Pre-processed Channel flow signal for a stable case of 24%Channel Power and core inlet subcooling of 12K and the time-variation of Instantaneous Decay Ratio and Accumulated Decay Ratio.

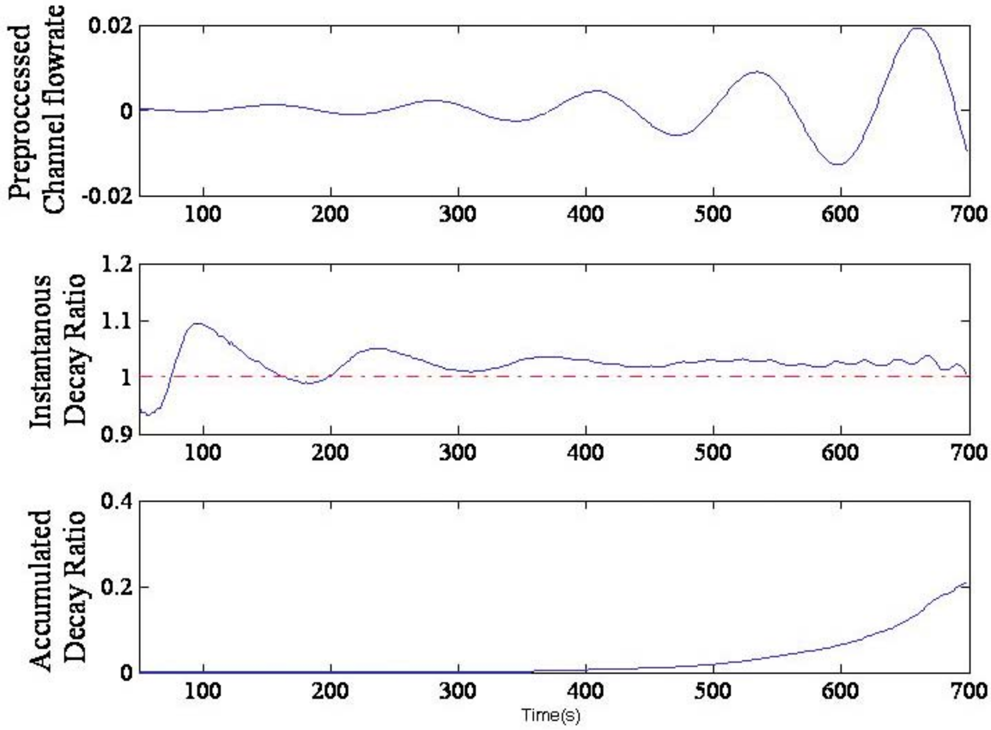

Fig. 7: Pre-processed flow signal for an unstable case of 24%Channel Power and core inlet subcooling of 18K and the time-variation of Instantaneous Decay Ratio and Accumulated Decay Ratio.

Conclusion

The decay ratio estimation based on Wigner -Ville time frequency representation is employed to devise an algorithm capable of handling time-varying nature of the density wave instabilities. The algorithm is found to be very effective in providing the stability information of the system during stable and unstable scenarios simulated using a homogenous equilibrium flow model. The algorithm is suitable for online implementation due to its computational simplicity. Implementation of this algorithm on hardware with real time data acquisition and computational capabilities would yield a system that is capable of indicating the stability status of the AHWR in real time. Such an instability monitoring system would be of immense benefit to the plant operator in taking up immediate corrective measures in the event of onset of instabilities.

References

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