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Thomas Von Larcher, Uwe Harlander, C. Egbers. Multivariate data analysis methods for detecting baroclinic wave interactions in the thermally driven rotating annulus. EUROMECH Colloquium 525 - Instabilities and transition in three-dimensional flows with rotation, Jun 2011, Ecully, France. hal-00600409

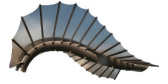
**HAL Id: hal-00600409**

**<https://hal.science/hal-00600409>**

Submitted on 14 Jun 2011

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## MULTIVARIATE DATA ANALYSIS METHODS FOR DETECTING BAROCLINIC WAVE INTERACTIONS IN THE THERMALLY DRIVEN ROTATING ANNULUS

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### 1 Motivation

Since the pioneering studies by R. Hide in the fifties of the last century [4], the elegant laboratory set-up of the differentially heated, rotating cylindrical gap of fluid is used by many authors to study the stability as well as the transition of fully 3D wavy flow patterns. They evolve from the release of potential energy through baroclinic instability that occur due to a radial temperature gradient and rotation. A vertically and horizontally sheared mean flow develops from which regular and complex wave flow patterns of different wave number can then emerge. These wave flows are called baroclinic waves due to the underlying instability mechanism, and the flow regimes, that develop in the annulus, depend mainly on two forcing parameters, i.e. on the temperature difference  $\Delta T$  and on the angular velocity  $\Omega$ . Note that the fluid viscosity is also a key parameter (e.g., [1]), but is kept fix in the experiments.

The rotating annulus, though being subject to detailed investigations since more than four decades, is still of interest not only in recent experimental research with respect to atmospheric sciences but also in the development of new numerical models where it then can be used as reference for the validation of new model concepts. For this purpose, the set-up might be particularly suited due to its relative simple geometry as well as due to the well definable forcing parameters. On the other hand, a rich flow behaviour is found that is either steady or time-dependent (e.g., [2], [5], [6]). The latter one, for example, undergoes changes in the wave amplitude or shape and also more types of complex flow patterns are known to exist, driven by e.g., wave-wave interactions and wave-mean flow interactions.

Our experimental set-up, described in detail in [7], is one of only few exclusive reference experiments within the priority program 'Multiple Scales in Fluid Mechanics and Meteorology' (MetStröm), that focus on the development of spatiotemporal, multiple scales numerical model concepts, see <http://metstroem.mi.fu-berlin.de>.

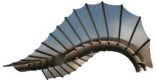
### 2 Data analysis methods

In our experimental study, we make use of non-intrusive measurement techniques of a quite different nature to better understand the transition from the regular wave regime to the quasi-chaotic regime at high rotation rates and to reveal the underlying dynamic processes of complex wave flow patterns. While the high accurate Laser-Doppler-Velocimetry (*LDV*) and Particle Image Velocimetry (*PIV*) is used for the acquisition of high resolution velocity data, a high sensitive thermographic camera, which resolution allows for resolving fine scale structures, measures time series of temperature distribution at the surface. These techniques allow us to detect the flow dynamics in the subsurface, as well as the dynamics of the surface flow.

Both time series data are analyzed by using multivariate statistical techniques. While the *LDV* data sets are studied by applying the Multi-Channel Singular Spectrum Analysis (*M – SSA*), the temperature data sets are analyzed by applying the Empirical Orthogonal Functions (*EOF*). In addition, the temperature data are processed in a way to become comparable to the *LDV* data, i.e. reducing the size of the data set in such a manner that the temperature measurements would imaginary be performed at equidistant azimuthal positions only. This approach initially results per se in a great loss of information. But applying the *M – SSA* to the reduced temperature data sets enables us not only to compare the different data analysis methods but also to reclassify the results yielded with the *LDV* data analysis.

#### 2.1 Exemplary analysis of a particular data set

An exemplary analysis run of one particular temperature data set is shown in figure 1. The dominating regular wave pattern of azimuthal wave number  $m=3$  has three vortices of lower temperature at the inner (cooler) sidewall and three relative warm regions near the outer (warmer) sidewall, see figure 1a. The narrow jet-stream circumventing the eddies transports heat and momentum. Figure 1b shows a spatio-temporal plot of the processed data. The drift rate of the dominating mode  $m=3$  is determined to  $0.025^{\text{rad/s}}$ . That wave mode is also found in the first component of the data reconstruction using the (EOF 1 and 2) of the (*M – SSA*), see figure 1c. At this parameter point, no higher mode than  $m=3$  is found.



### 3 Objectives

Our work presented here is based on a previous experimental study on baroclinic wave interactions by [3] who apply multivariate, statistical data analysis methods to velocity data. In addition, we use temperature data as well as velocity data, which are measured at the same parameter points but –unfortunately– not synchronous. The use of different data acquisition techniques allow us to match not only the information coming from the analysis of temperature and velocity data but also to match the analysis of the surface flow and of subsurface flows. For example, the results of the (*EOF*) analysis of velocity and temperature data can be used to calculate the turbulent radial heat flux ( $v'T'$ ), which is a key parameter for understanding the observed flow phenomena ( $v'$  ( $T'$ ) denotes the deviation from the mean velocity (temperature)).

With the use of the statistical analysis tools, we gain the knowledge of the variability of the flow regimes particularly in the transition between regular wave modes of different azimuthal wave number as well as in the transition to quasi-chaotic flow. Our work is a continuation of the efforts of the authors and colleagues to reach these goals and it should be regarded as part of an overall operation.

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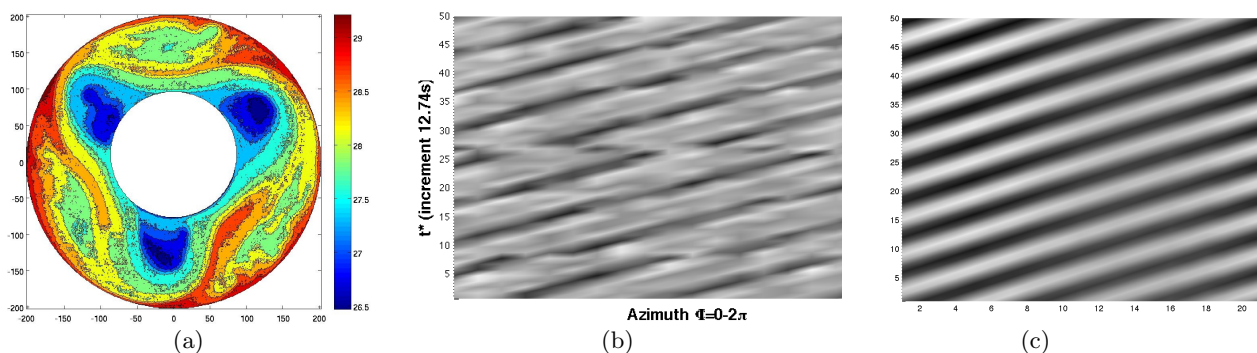


Figure 1: Exemplary analysis of a regular wave flow of wave number  $m=3$ . (a) View of surface temperature distribution, unit  $[\text{°C}]$ , (b) merge plot of temperature time series processed at 20 equidistant locations on mid radius, the anomaly at  $t^* \approx 27$  results from a malfunction during data acquisition, unit  $[\text{°C}]$ . (c) Reconstructed time series using EOF 1 and 2 computed of the temperature data set.