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Investigating Chaos in an Industrial Fluid Catalytic Cracking Unit

Rohit Ramachandran, Lakshminarayanan Samavedham, and Gade Pandu Rangaiah

Abstract— **A fluid catalytic cracking (FCC) unit is known to contribute approximately 40% of revenue in a typical petroleum refinery. The FCC unit in one of the Southeast Asian refineries is not performing up to expectations, and wide fluctuations in the riser temperature are observed. This undesired occurrence has an adverse effect on the refinery's profit. Our study aspires to identify the root cause of this problem by implementing a set of statistical tools that utilizes routine operating data to characterize the dynamics of the riser temperature. Results show that the riser temperature data are nonlinear, chaotic and/or contaminated with correlated noise. Implications are that linear controllers are inadequate for controlling the nonlinear/chaotic FCC unit, thus resulting in wide fluctuations. Further investigation of chaotic behavior by developing and using a dynamic model of the FCC unit is in progress.**

I. Introduction

THE FCC unit is the kernel of modern petroleum refining. Its main function is to convert atmospheric residue from the crude distillation unit (CDU) into a multitude of value added products such as gasoline, middle distillates and light alkenes. Control of an FCC unit is an important and challenging problem. Precise control of the FCC unit is important because it affects product quality, yield and cost. It is a challenging problem due to the intricate and interacting nonlinear dynamics between the riser and the regenerator in an FCC unit. This is further compounded by multiple steady states and input multiplicities [1].

II. Background

A. Chaos

Chaos is the breakdown of predictability and a state of disorder. A chaotic system is a dynamical system that is very sensitive to its initial conditions. Subtle changes in its initial conditions lead to rapid divergence of the system from one trajectory to another among the many possible trajectories. Identification of chaos and more importantly, pinpointing the degree of chaos using statistical tools are the first steps in studying control of chaotic systems.

B. Related Studies

Several research groups have developed different models to investigate and characterize the dynamics of various variables in the FCC unit. Han and Chung have reported sensitivity in initial conditions leading to inverse responses and nonlinear behavior between the riser and the regenerator in the FCC unit [2]. Abasaeed and Elnashaie showed that external periodic forcing of the regenerator air temperature can lead to chaotic behavior [3]. Morud and Skogestad have observed the occurrence of oscillations and instability in an ammonia reactor [4]. Such studies combined with the fact that chaos in industrial FCC units is relatively unexplored, motivated the present study.

C. Problem Statement

In one of the refineries, the riser temperature of the FCC unit was observed to have fluctuations of $\pm$ 5^{o}C about the set point which are higher than desired. This seemingly innocuous fluctuation affects the gasoline yield of the FCC unit which in turn has a direct impact on the profit of the company. Hence, along with our industry contact, we have attempted to ascertain the cause of this fluctuation and ameliorate the situation by implementing suitable corrective action(s).

III. Objectives

The final aim of our study is to reduce the riser temperature fluctuation to $\pm$ 1^{o}C as previous studies on other industrial FCC units have shown it to be possible [6]. To accomplish this, there are various intermediate objectives we need to address. Therefore the objectives of this study are to:

1) Select and implement a set of statistical/graphical tools that detect nonlinearity and chaos,
2) Use these tools to characterize dynamics of the riser temperature
3) Develop a dynamic model of the industrial FCC unit based on first principles.

The purpose of the first two objectives is to understand the nature of the riser temperature variations. Thereafter, appropriate corrective action may be determined and im-

R.Ramachandran, S. Lakshminarayanan, and G.P. Rangaiah (email: chegpr@nus.edu.sg) are with the Department of Chemical and Biomolecular Engineering, National University of Singapore.

plemented. The third objective serves to investigate the likelihood of chaotic behavior in the FCC model and evaluate corrective actions.

IV. STATISTICAL/GRAPHICAL TOOLS

A. *Tool for Detecting Nonlinearity*

Nonlinearity is a pre-requisite for chaos. The motivation behind implementing a set of nonlinear tools is that firstly, the plethora of linear methods has been exploited fully and still cannot account for certain structures in the time series data. Secondly, there could be prior knowledge that the system is nonlinear in nature and therefore linear methods would be deemed inappropriate. In the FCC unit, the process dynamics are known to be nonlinear but given the narrow operating range of the riser temperature, the general consensus might be to neglect this nonlinearity. However, this assumption may or may not be correct and we still need to investigate for nonlinearity nevertheless. Hence, the nonlinear tool utilized is the surrogate data (SM) method with time reversal (TR) as the discriminating statistic [7].

B. *Tools for Detecting Chaos*

Before testing for chaos, nonlinearity should be checked first to avoid spurious conclusions as there is only a fine line between chaos and correlated noise. To mitigate this problem further, we select and implement a gamut of chaos quantifiers instead of a single quantifier. In this manner, greater confidence in the conclusion will be instilled if the results of various quantifiers are congruent. The tools implemented are Lyapunov exponents (LE) [8], spatio-temporal entropy (STE) return maps, auto-correlation function (ACF), and correlation dimension [9].

V. ANALYSIS OF RISER TEMPERATURE DATA

Prior to the characterization of the dynamics of the riser temperature data, a perfunctory study was done to analyze the effects of linear feedback control (using a PID controller) on a state variable that is exhibiting chaos. The Lorenz system of differential equations is simulated and the state variable ‘x’ is chosen as the controlled variable, whilst ‘σ’ which is the Prandtl number (a dimensionless parameter that can be varied depending on the choice of kinematic viscosity and thermal diffusivity) is the manipulated variable. Results show that for different controller tuning parameters, ‘x’ may either still exhibit the same level of chaos, exhibit reduced level of chaos or not exhibit chaos at all. It is also noted for the record that for a linear process, no linear controller (with any controller settings) is able to render the controlled state behaviour chaotic. This shows that if a variable (in a closed-loop configuration) shows chaos, this can only be due to the innate nature of the process and not as a result of the controller. A nonlinear controller on the other hand may mitigate, augment or have no effect on the level of chaos present in the system. Hence, this justifies the analyses of closed-loop (with a linear feedback controller) data that are carried out in the present study.

Results of analyzing the riser temperature data (obtained from routine operation in closed-loop) using the statistical/graphical tools for nonlinearity and chaos are summarized in Table 2. For consistency, three sets of riser temperature data on different days are analyzed. It can be seen that the first and second Lyapunov exponent (LE_1 and LE_2) are positive. A positive LE_1 is an indicator of inherent chaos and/or correlated noise and a positive LE_2 indicates that random noise is present as well. Since the riser temperature data are embedded in three dimensions, LE_2 is expected to be zero if the data were purely chaotic. LE_3 is negative for all three sets and this is expected as the third Lyapunov exponent is always negative. The STE intimates that the data are neither purely random nor completely deterministic reinforcing the belief that chaos may be present. Hence, the results in Table 2 show for all sets, that the data are possibly chaotic and / or contaminated with noise. The difference in the significance value (which is in terms of standard deviation of the difference between $TR_{original}$ and $TR_{surrogate}$) insinuates that the data are nonlinear [10]. Therefore, since the data are nonlinear, testing for chaos is not without reason.

TABLE 1
RESULTS OF ANALYZING RISER TEMPERATURE DATA VIA STATISTICAL ANALYSES

Indicator	Value (set 1, taken on day 1)	Value (set 2, taken on day 2)	Value (set 3, taken on day 3)
LE_1	0.5218	0.5231	0.3861
LE_2	0.0379	0.0381	0.0166
LE_3	-0.8808	-0.8854	-0.8196
STE	84%	84%	85%
$TR_{original}$	-0.21	-0.21	-0.22
$TR_{surrogate}$	0.002	0.001	0.002
Significance	2.35	2.32	2.20

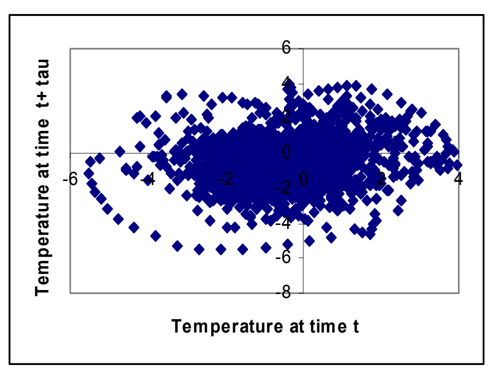

Fig. 1. Return map of riser temperature data (set 1)

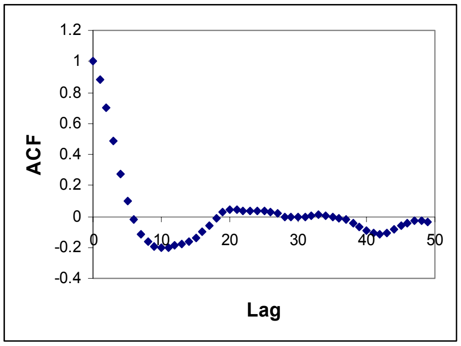

Fig. 2. ACF of riser temperature data (set 1)

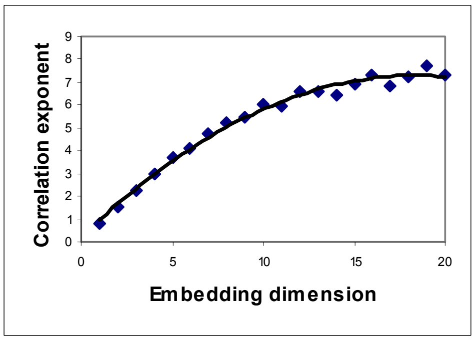

Fig. 3. Correlation dimension of riser temperature data (set 1)

Figs. 1 to 3 depict return map, ACF and correlation dimension of the riser temperature data taken on day one. Both Figs. 1 and 2 show that the riser temperature data are not entirely random and some deterministic structure is inherent. However, from these results, one cannot ascertain if chaos is present. This is attributed to the fact that for experimental systems, the reconstruction of chaotic attractors is not as good as compared to the attractors of mathematical systems [11]. Fig. 3 shows that the change in correlation exponent per embedding dimension is decreasing and tending toward saturation as embedding dimension increases. For a non-chaotic signal which has no spatial structure, this change is constant. Hence, Fig 3. suggests that chaos could be present. This inference and the trend in Fig 3 are similar to those for the experimental data reported in [5].

VI. Modeling of the FCC Unit

After reviewing FCC models available in the open literature, the model developed by Rohani's group was selected [12] because it features most of the important variables we wish to investigate for chaotic behavior. Furthermore, this model is the closest representation of the FCC unit under the present investigation and hence very little modification is required. After the necessary modifications were carried out, the FCC unit will be simulated using the model of [12] and validated by predicting the measured operating data. Upon successful validation of the model, investigation of chaotic behavior in the various variables will be carried out. Currently, this work is in progress.

VII. Conclusions

Several statistical tools for characterizing nonlinearity or chaos in data sets are successfully implemented. Subsequently, the tools were used to characterize the dynamics of the riser temperature data of an industrial FCC unit. Results show that the data are nonlinear and contaminated with chaos and / or colored noise with conclusive evidence that the data are chaotic due to several quantifiers confirming presence of chaos. A dynamic model of the FCC unit is being implemented which will facilitate an in-depth study of chaotic behavior of the FCC unit.

VIII. Acknowledgment

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References

[1] A. Arbel, Z. Huang, I.H. Rinard, and R. Shinnar, "Dynamics and Control of Fluidized Catalytic Crackers. 1. Modeling of the Current Generation of FCC's," in *Ind. Eng. Chem. Res.,*vol. 34, 1995, pp. 1228–1243.

[2] I.S. Han and C.B. Chung, "Dynamic Modeling and Simulation of a Fluidized Catalytic Cracking Process. Part 1: Process modeling," in *Chemical Engineering Science,* vol. 56, 2001, pp. 1951–1971.

[3] A.E Abasaeed and S.S.E.H. Elnashaie, "On the Chaotic Behavior of Externally Forced Industrial Fluid Catalytic Cracking Units," in Chaos, Solitons and Fractals*,* vol. 9, 1998, pp. 455–470.

[4] J.C. Morud and S. Skogestad, "Analysis of Instability in an Industrial Ammonia Reactor," in *AIChE Journal,* vol. 44, 1998, pp. 888–895.

[5] R. Mosdorf and M. Shoji, "Chaos in Bubbling-Nonlinear Modeling and Analysis," in *Chemical Engineering Science,* vol. 58, 2003, pp. 3837–3846.

[6] P. Grosdidier, A. Mason, A. Aitolahti, P. Heinonen, V. Vanhamaki, "FCC Unit Reactor-Regenerator Control," in *Computers Chemical Engineering, vol* 17, 1993, pp. 165–179.

[7] T. Schreiber, A. Schmitz, "Surrogate Time Series," in Physica D, vol 142, 2000, pp. 346-382.

[8] K. Briggs, "An Improved Method for estimating Liapunov Exponents of Chaotic Time Series." in Physics Letters A, vol 151, 1990, pp. 27-32.

[9] http://www.physics.unlv.edu/~thanki/thesis/node14.html (accessed on 20th February 2005)

[10] Bendat, J.S, Piersol, A.G, Random data: Analysis and Measurement Procedures, John Wiley and Sons, January, 1986

[11] http://www.cmp.caltech.edu/~mcc/Chaos_Course/Lesson12/Experiment.pdf (accessed on 13th September 2004)

[12] C. Jia, S. Rohani, and A. Jutan, "FCC Unit Modeling, Identification and Model Predictive Control, a Simulation Study," in *Chemical Engineering and Processing, vol.* 42, 2003, pp. 311–325.