CHARACTERISTICS OF FAN STALLING BASED ON CORRELATED DIMENSIONS

Gu Yongxia[1], *Zhou Zhongning*[2], *Li Yimin*[2]

(1. College of Mechanical Engineering, Beijing Technology and Business University, Beijing, 100037, P. R. China;
2. College of Electric Power Engineering, China University of Mining and Technology, Xuzhou, 221008, P. R. China)

Abstract: Different from the previous qualitative analysis of linear systems in time and frequency domains, the method for describing nonlinear systems quantitatively is proposed based on correlated dimensions. Nonlinear dynamics theory is used to analyze the pressure data of a contrarotating axial flow fan. The delay time is 18 and the embedded dimension varies from 1 to 25 through phase-space reconstruction. In addition, the correlated dimensions are calculated before and after stalling. The results show that the correlated dimensions drop from 1.428 before stalling to 1.198 after stalling, so they are sensitive to the stalling signal of the fan and can be used as a characteristic quantity for the judging of the fan stalling.

Key words: fan with contra-rotating axis; fan stalling; correlated dimensions; phase-space reconstruction

CLC number: TD441 **Document code**: A **Article ID**: 1005-1120(2011)04-0362-05

INTRODUCTION

The fan flowing with a contra-rotating axis owns a complex non-linear system. It has been a challenge for a long time to observe the fan running state and to diagnose if it runs wrong or smoothly. Pressure signal in this kind of fans consists of rich state information, which is valuable for monitoring the fan running state. With the chaos and fractal theory to study nonlinear dynamic systems, we can grasp the law[1]. In this paper, the method for non-linear dynamics analysis is used to analyze pressure data and to calculate correlated dimensions[2] in normal state and in stalling state.

1 FRACTAL THEORY

1.1 Phase-space reconstruction based on time sequences

Phase-space reconstruction, a method for time sequences with a single variable, is applied in this paper. For discrete time sequences which delay for time τ, its auto-correlated function can be expressed as[3]

$$C = \frac{\sum_{i=1}^{N-\tau}(x_i - \bar{x})(x_{i+\tau} - \bar{x})}{\sum_{i=1}^{N-\tau}(x_i - \bar{x})^2} \tag{1}$$

where $\bar{x}$ means the average of the time sequences.

Time delay is τ and $y(t), y(t+\tau), y(t+2\tau), \cdots, y(t+(m-1)\tau)$ are chosen as coordinates. An m-dimensional space is constructed. The situation showing how the trajectories are distributed and indicating that their structures (attractors) of this reconstructed phase space can reflect the system movement. Because three is the maximum dimension drawn out visually, chose the symbol m to be 2 or 3 in that we need to scratch the surface how the system feature varies according to the performance of the attractor of the phase space. When the system features are analyzed, we can see that the attractors in the 2-D phase plane which is represented as $[y(t), y(t+\tau)]$ or in thd 3-D phase space which is represented as $[y(t), y(t+\tau), y(t+2\tau)]$ reconstructed are similar to the ones in the phase plane represented as $(y, \dot{y})$ or the phase

Foundation items: Supported by the Natural Science Foundation of Jiangsu Province (BK2005018); the Graduate Research and Innovation Plan of Jiangsu Province (CX07B-061Z).

Received date: 2011-02-03; **revision received date**: 2011-04-04

E-mail: gyxchina@163.com

space represented as $(y, \dot{y}, \ddot{y})$. First of all, when the trajectories of the reconstructed phase space tend to a point at last (That is, the attractor mentioned above is a point), it means that the system is stable. Secondly, if the trajectories eventually form a curve which is able to close down (The attractor is such a curve), it indicates that the system is in a periodic motion. Again, if the trajectories finally accumulate mussily into a limited confine, it means that the system is in a random motion. Furthermore, if there are some special structures (so-called strange attractors) in the distribution of trajectories, the system movement will be chaotic[4].

1.2 Correlated dimension

In fractal theory, many scholars define the concept of fractal dimension from many different angles. However, correlated dimension, having a clearer sense of time sequences, is a method which can calculate much more accurate and easy.

Let's take a pair of points in an m-D phase space for instance

$$x_m(t_i):(x(t_i), x(t_i+\tau), \cdots, x(t_i+(m-1)\tau))$$

$$x_m(t_j):(x(t_j), x(t_j+\tau), \cdots, x(t_j+(m-1)\tau))$$

Euclidean distance between them is $\varepsilon_{ij}(m)$

$$\varepsilon_{ij}(m) = \| x_m(t_i) - x_m(t_j) \| \tag{2}$$

A critical distance ε (ε is a small positive number) is given and it is the radius of a super ball in the m-D space. We get the number of pairs of points, whose distance between each other is less than ε, and it is recorded as follows what proportion these pairs accounted for in all pairs

$$C(\varepsilon, m) = \frac{1}{N(N-1)} \sum_{i,j} \theta(\varepsilon - \| x_i - x_j \|) \quad i \neq j \tag{3}$$

In the equations above, $N = n-(m-1)$, τ means the phase point, and θ means Haiweisaide (Heaviside) function and it meets

$$\theta(x) = \begin{cases} 1 & x \geqslant 0 \\ 0 & x < 0 \end{cases}$$

Select a proper radius ε of a super ball, and in scale-scale zones there exist

$$C(\varepsilon, m) = \varepsilon^{D_2(m)} \tag{4}$$

$$D_2(m) = \lim_{\varepsilon \to 0} \frac{\ln C(\varepsilon, m)}{\ln(\varepsilon)} \tag{5}$$

where $D_2(m)$ means the correlated dimension.

2 TEST RESULTS AND NONLINEAR ANALYSIS

2.1 Acquisition of pressure data of flow fields[5]

A KDF-5 fan which flows with a contrarotating axis and low noise is used in this paper. The of the fluid-solid coupling test rig of the impeller system is shown in Fig. 1. The dynamic pressure sensors are used to measure the pressure fluctuation of the fan in different conditions and to acquire basic experimental data, as shown in Fig. 2. The main parameters of the fan are that the fan flows at a speed varing from 125 m^3/min to 250 m^3/min, the total pressure varing from 300 Pa to 2 800 Pa, the rated power 2 * 5.5 kW, and the rated speed 2 940 r/min. In addition, the main parameters of the fan in the first stage are eight blades, variable cross section of distortion curve. On the other hand, the main parameters of the fan in the second stage are six blades, variable cross section of trapezoidal distortion.

UTekL V2007 system for the dynamic signals collection is used. Sample frequency is chosen as 5 120 Hz, which is a little higher for satisfying the needs of anti-mixed and digital filtering of data preprocessing in the future. To ensure accurate measurement, we set the sample data to be 1 024 or 2 048 and the sample time is set to be 3.41 min and 6.83 min. In the test, the speed of the fan is 2 940 r/min and the sample frequency is 5 120 Hz. The 3 072 sample data are equivalent to the information of the fan that rotates for 30 times. The analysis result can fully characterize the fan running information.

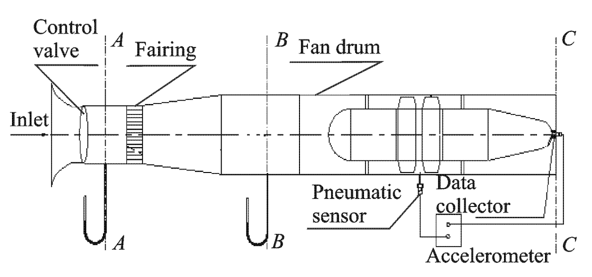

Fig. 1 Test device

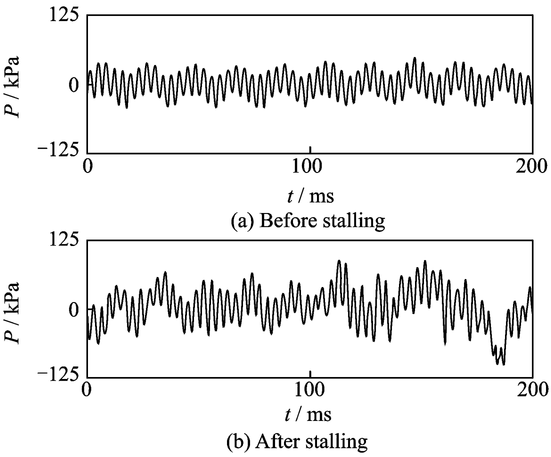

Fig. 2 Pulse signal of air flow

2.2 Phase space reconstruction

The experimental method for analyzing the fan impeller system needs special methods to cope with because it may have many freedoms, and noise may have bad effects on it. To verify whether the system is chaotic, at first, we must get its attractor. However, what we get are just some data of time sequences of the pressure fluctuation in the flow field between the two levels of the impellers. If we had only such data, we would have inevitably lost a lot of information about the attractor evolution. Therefore, it is necessary to use the data of time sequences to reconstruct higher-dimensional phase space[6].

In this paper, the method to delay for a certain time is used to process the pressure data of the flow field between the fans which flow with two-level rotating axis and to reconstruct the phase space of the fan impeller system and attractors[7]. When the delayed time is taken as 2, 10, 15, 18, the attractor characters are given in Fig. 3.

2.3 Selection of delay time based on correlated function

Auto-correlated function is used to analyze the collected pressure data, and τ is set to be 18.

2.4 Correlated dimensions of impeller system attractors

Actual measured signal is often interfered with a great deal of other useless information and these noise signals having impact on the calculation of correlated dimensions[8], may lead to correlated dimensions that cannot converge to a stable value. Therefore, there will be a method to denoise for the signals which are about to be measured before correlated dimensions are calculated.

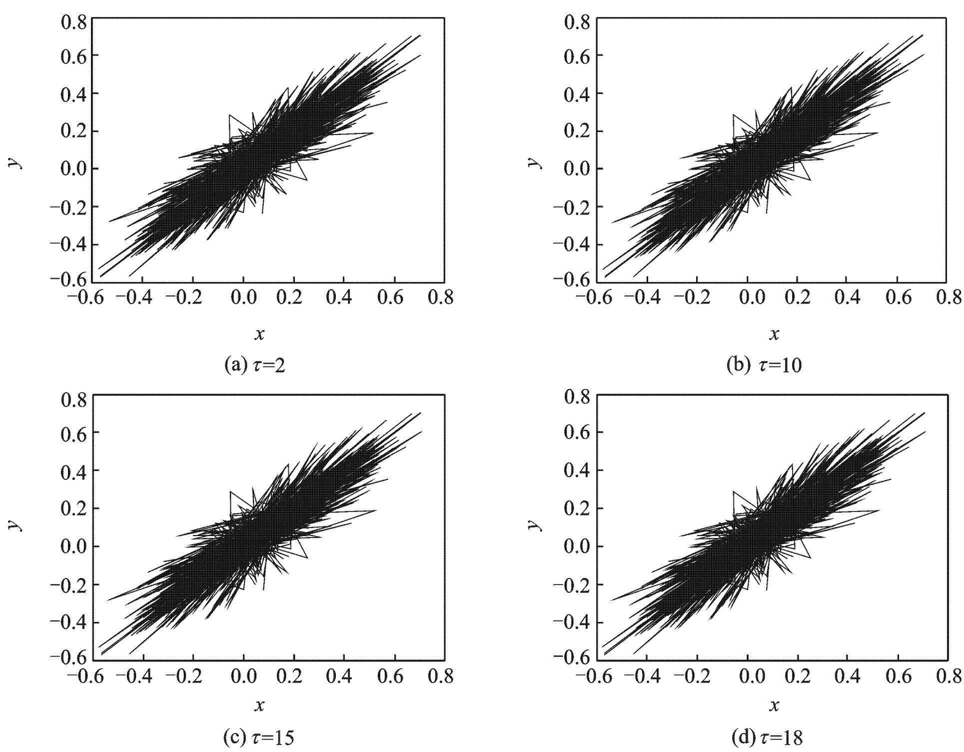

Fig. 3 Phase space and attractor

Because wavelet analysis of the method to denoise for non-stationary signals has advantages that don't exist in Fourier analysis at all, a soft threshold wavelet denoising method is chosen. The measured signals are firstly denoised, then the correlated dimensions are calculated.

The value of ε cannot be too large or the distances between all points and the point (x_i, x_j) cannot exceed it, so the equation $C(\varepsilon, m)=1$ is not able to reflect the dynamic characteristics. At the same time, the value cannot be too small, or incidental noise will appear. According to plentiful analysis and calculation, the value of ε ought to accord with the following equation: $\varepsilon = \varepsilon_{ij}(m)_{\min} + 2(\varepsilon_{ij}(m)_{\max} - \varepsilon_{ij}(m)_{\min})/3$. We chose a curve which can be drawn in accordance with the following formula: $\ln\varepsilon - \ln C(\varepsilon, m)$. If we chose this kind of curve, the slope will not increase any longer with the increasing embedded dimensions. Then we could acquire correlated dimensions in different conditions. On the other hand, m should be chosen critically as well, when the curve is drawn according to the formula $\ln\varepsilon - \ln C(\varepsilon, m)$. If m is too small, it may not be able to gain the saturated part of its slope. m ranges from 1 to 25 in this paper. This curve expressed by the formula $\ln\varepsilon - \ln C(\varepsilon, m)$ has a saturated part in all conditions which are different from each other, that is, its slope is a constant which will not vary with the change of m any more.

In order to distinguish correlated dimensions between the normal state of the fan and the stalling state of the attractors, and to analyze the data of the two states respectively, the following steps are performed. First of all, the correlated dimensions of the attractors of the pressure signal before the stalling state must be obtained. Then the curves of the related integration $\ln C$ and the natural logarithm $\ln\varepsilon$ of ultra-sphere radius are drawn, as shown in Fig. 4. What's more, curves of different dimensions are used to obtain their correlated dimensions and curves with embedded dimension in the same Cartesian coordinate system are drawn, as shown in Fig. 5. In the normal working state of the fan, with the embedded dimensions increasing, the correlated dimensions of the pressure signals gradually tend to a fixed value, which is the correlated dimension of the pressure signal in the flow filed among the fans.

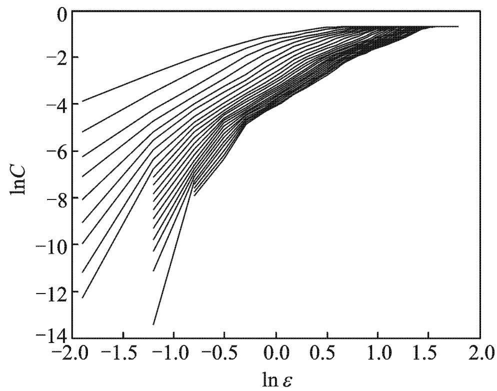

Fig. 4 Lines drawn according to $\ln\varepsilon - \ln C$ before stalling

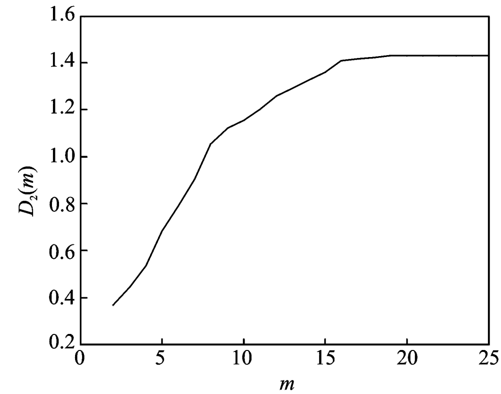

Fig. 5 Embedded dimension and correlated dimension before stalling

The same method is used to calculate the correlated dimensions after the fan stalling so that the fractal characteristics of the stalling signals are studied. As shown in Figs. 6-7, the correlated dimension decreases a little compared with the state before stalling. We can conclude that the correlated dimension drops from 1.428 before stalling to 1.198 after stalling.

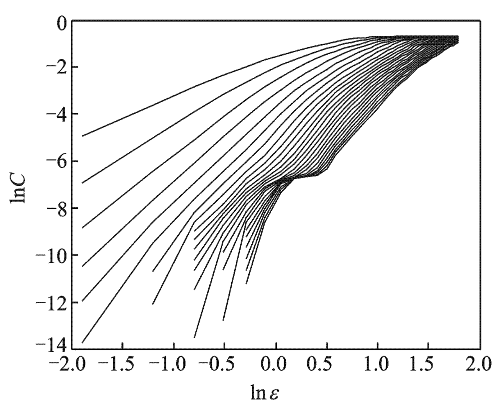

Fig. 6 Lines drawn according to $\ln\varepsilon - \ln C$ after stalling

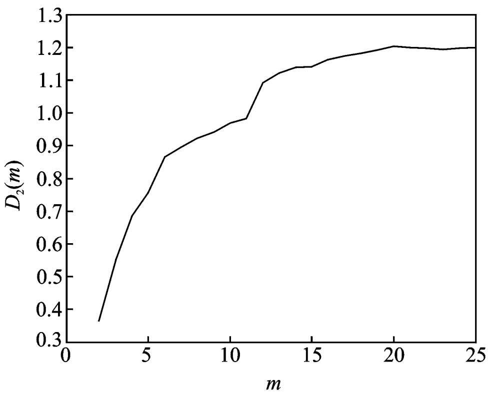

Fig. 7 Embedded dimension and correlated dimension after stalling

3 CONCLUSIONS

(1) Through the analysis of the pressure signals of the flow field before the fan stalling and the reconstruction of the phase space, the correlated dimensions of the corresponding state are obtained. The correlated dimension decreases from 1.428 before stalling to 1.198 after stalling.

(2) The results show that fractal analysis theory of complex signals is effective. The correlated dimensions are sensitive to the stalling signals of the fan and can be used as an important characteristic for the detection of the fan stalling.

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基于关联维数的风机失速特征研究

谷勇霞[1]　周忠宁[2]　李意民[2]

(1.北京工商大学机械工程学院,北京,100037,中国; 2.中国矿业大学机电学院,徐州,221008,中国)

摘要:针对非线性系统的特点,区别于以往对线性系统使用的时域、频域定性分析法,用分形维数定量刻画系统运行状态。运用非线性动力学理论,通过相空间重构选取延迟时间为18,嵌入维数为1到25,计算了风机失速前后压力信号的关联维数。研究发现关联维数由失速前的1.428下降到失速后的1.198。研究结果表明关联维数对失速信号是敏感的,可以用作判断风机失速的特征量。

关键词:对旋轴流风机;风机失速;关联维数;相空间重构

中图分类号:TD441

(Executive editor: Sun Jing)

基金项目:江苏省自然科学基金(BK2005018)资助项目;江苏省研究生科研创新计划(CX07B-061Z)资助项目。