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SURGE DETECTION BASED ON SPECTRAL CORRELATION MEASURE IN AXIAL FLOW COMPRESSOR

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Abstract

An anti-surge system is an important part for ensuring compressors or aircraft engines operating in safe states. In this paper, a novel approach for detecting surge in axial flow compressors is described. Dynamic pressure signals are adopted to extract features of aerodynamic instabilities. Firstly, the spectra of two windows of a single signal are calculated. Secondly, a measure is defined as the correlation efficient of two spectra to indicate the similarity of them. Then, when a compressor runs into non-stable states, the spectral correlation measure will drop dramatically. Finally, if the measure goes below a threshold, alarms should be sent out to activate anti-surge actions. This new technique is demonstrated with pressure data from two high speed compressors, and is shown useful to detect the onset of aerodynamic instabilities.

Introduction

The stable operating range of axial flow compressors even aircraft engines are restricted by surge boundaries of compressors. The surge boundary is a generally name of the stability boundary caused by two kinds of dynamic instability phenomena named as rotating stalls and surges, which may decrease the performance and/or destroy the structure of engines. Surges have uniform pressure on circumferential direction but heavy fluctuations on the axial direction, which may lead to severely vibration, combustion flame out, over-temperature of the compressor caused by the back flow, and even damage of the structure of an engine. However, rotating stalls have different characteristics such as keeping stable flow on the axis direction, having rotating cells on one or several cross sections which caused unevenness on circumferential direction. Generally, it is believed that the development of rotating stalls may lead to surges.

Traditionally, adequate surge margins are maintained to keep compressors and aircraft engines working steadily. This method, on one hand, protects the safety of engines, but reduces the efficiency on the other hand. Meanwhile, the surge boundary is not determined constantly. It may change with inlet distortion, acceleration procedures, degeneration of performances of components, etc. So, an anti-surge system, which detects stalls and surges and pushes the compressor out of the non-stable operating area, is also required besides of the surge margin.

Detecting stalls or surges accurately, reliably, and quickly is the key requirement of an anti-surge system. In recent several years, active control of aerodynamic instability is another proposal to reduce the surge margin and extend the stable operation range of compressors, which also need to detect aerodynamic precursors.

In the last several years, many methods were proposed and used to detect aerodynamic instabilities. The spectral analysis is one of them, which detects changes in pressure signals in the view of spectrum. The components of the spectra of pressure signal of stable operating states are equivalent except the frequencies of rotating speed, blade passing frequency and harmonics of them. While near stalls or during non-stable states, the energy of the signal is concentrated to stall frequencies or surge frequencies. Some other methods such as the wavelet analysis, the short time Fourier transform, etc, were also in the view of transformation view. They transform signals from the time domain to other domains to extract features for detection. Otherwise, characteristics of the time domain can be also used as features to detect the differences between stable and non-stable states. The variance method is one of them. It is based on the fact that the amplitude of the pressure signal increases near and during states of stalls or surges [1]. Meanwhile, a correlation measure was proposed to detect precursors of stalls and surges, which is based on the characteristics that, pressure signals have periodicities when a compressor keeping stable while have not near or during stalls or surges [2]. This method has a small amount of calculation and can catch precursors quickly before compressors run into deep stalls or surges. In the last several years, it achieved successes in many experiments of compressors even was used in the research of active control of aerodynamic instabilities [3-5]. For this method, a key signal is needed to align data of two revolutions.

This paper describes a new approach to detect compressor aerodynamic instabilities. Only one sensor is used to collect the signal of dynamic pressure of a compressor. It is somehow similar with the method of correlation measure. Two windows are used to cut out the signal for analysis. Then, the spectrum of each window is calculated. After that, a kind of cross-correlation coefficient is computed with two spectra. When a compressor operates in stable range, the coefficients keep at a high level. Otherwise, it will drop sharply to indicate stalls or surges. The effects of analytical windows, rotating speed of compressors, noise, and etc. are also discussed.

Experimental setup and instrumentation

Usually, when a new model of compressor is designed and manufactured, the performance map including the surge line should be gotten via experiments on a compressor test rig. A brief description of the experiment is following. Firstly, keep the rotating speed stable. Then, close the throttle slowly to decrease the air flow. It pushes the compressor to the surge line. Finally, when dynamic pressures have obviously fluctuations, i.e. the compressor goes into unstable ranges, turn up the throttle and let the compressor come back to stable operating points. Repeat this procedure with different rotating speeds, and record pressures, temperatures and airflow of the compressor. The performance map and the surge line could be measured by experiments.

In this paper, measured data of two compressors are used to demonstrate this method. One is named as C1 in this paper, which is mentioned in reference [6]. The total pressure of outlet was measured with dynamic sensor at 4 different rotating speeds, 85%, 90%, 95% and 100%. Another one is named as C2. It was a 7-stage high speed compressor. 10 channels of casing static pressures and the outlet total pressure were measured. In the following section, the outlet total pressure P7ST and one static pressure P1R60S are used to demonstrate this method. In both experiments, the sampling rate was settled at 10 kHz.

Methodology

The following fundamental observation motivated us to propose the current approach. When a compressor is far from aerodynamic instabilities, the main component of spectrum of pressure is focused on the rotating frequency (Fig 1). For a stable steady operation, when the analysis windows move along with time, the spectra are expected to be repetitive. The differences between spectra are caused only by the natural fluctuations and noises of the measurement system. While the compressor is in or near instabilities, the main components of spectrum not only focus on the rotating frequency, but also include the stall frequency and/or the surge frequency (Fig 2). In this way, the receptiveness of the spectra is disrupted when the precursors of aerodynamic instabilities occur.

It must be pointed out that the spectra could be different between two operating condition. But for a steady rotating speed, it repeats itself window by window. Thus a priori knowledge of the spectrum of any points on the compressor map is not required.

The schema of an online detecting system is showed in Fig 3. The period of detecting is ΔT , which is as least as long as the time consumption of detecting algorithm. The detecting system works as a physical realizable system. So, at t_0 , only data before t_0 can be acquired. Let window X stands for the last analytical window, and Y stands for the analytical window *k* detecting periods before. The power spectrum is defined with Formula 1 and 2.

$$X_N(\omega) = \sum_{n=0}^{N-1} x(n) e^{-jn\omega} \qquad (1)$$

$$P_X(\omega) = \frac{1}{N} \left| X_N(\omega) \right|^2 \qquad (2)$$

Here, $x(n)$ is the discrete pressure signal, with sampling frequency Fs. N is the width of analytical windows.

As we known, the cross-correlation coefficient can be used to describe the similarity between the fluctuation parts of two waveforms. Here, we would like to describe the similarity between two waveforms, which are spectra of two analytical windows, including both AC component and DC component. Therefore, a modified cross-correlation coefficient, similar to the reference [2], is defined in Formula 3 to measure the similarity of spectra.

$$\rho_{XY} = \frac{\sum_{j=1}^{M} P_X(j) P_Y(j)}{\sqrt{\sum_{j=1}^{M} P_X^2(j) \sum_{j=1}^{M} P_Y^2(j)}} \qquad (3)$$

Here, M is the number of spectral lines of discrete spectra.

So, ρ_{XY} is supposed to be a value near 1 when the spectra of P_X and P_Y are similar. ρ_{XY} will decrease when P_X and P_Y have significant differences. It means that ρ_{XY} is an indicator of the similarity between spectra P_X and P_Y.

When a compressor operates in stable state, both window X and Y are samples of a same stationary process. P_X and P_Y have similar waveforms, and ρ_{XY} is a value close to 1. With the procedure of detection, X and Y move downwards. When $y(n)$ is a sample of stationary process, and $x(n)$ comprises at least a part of aerodynamic instability signal, the value of ρ_{XY} decrease quickly. When it is lower than a given threshold, an alarm can be sent to indicate the entry into unstable states.

Results and discussions

The results presented here are calculated with the data acquired on a test rig with above mentioned compressors. Firstly, results of spectral correlation measure ρ_{XY} in time are given. Then, effects of analytical window, noise, bandwidth, rotating speed, and other factors are discussed following.

Spectral correlation measure in time

The result of the compressor C1 is shown in Fig 4 and Fig 5. The rotating speed was kept at 85% relative speed. The outlet total pressure was adopted to detect aerodynamic instabilities. The sampling rate was settled at 10 kHz. Parameters of detecting system were set as following. The fixed threshold is 0.95. The points of data for analysis (N) are 2048, i.e. the length of analytical window is 0.2048 s. The detecting period ΔT is 0.005 s. k=1, i.e. X and Y are nearest windows.

It can be seen for Fig 5 that, the spectral correlation measure keeps on a high level when the compressor is stable. It decreases significantly when it entry into the process of surge. The reason is that X is composed with a part of precursors of surge while Y not, that results in different spectra P_X and P_Y. It leads to lower spectral correlation measure. However, the spectral correlation measure returns to a high lever when both X and Y are in the unstable segment.

The drop point of the outlet total pressure is usually considered as the beginning of surges. It can be seen from Fig 5 that the alarm signal can be sent out even at exactly the beginning of surges. It is faster than the variance method [6].

In the experiment of the compressor C2, not only an outlet total pressure but also casing static pressures were measured. The detecting result is shown in Fig 6 when the outlet total pressure P7ST is used, and Fig 7 is the result with the static pressure P1R60S. Here, the length of windows is 8192 sampling points. Both of Fig 6 and Fig 7 have drops when compressors run into unstable states, as same as the phenomena of the compressor C1.

Rotating speed effects

It is known that the pressures have different variance values when a compressor runs on different rotating speeds [8]. This phenomenon impacts the choice of threshold. Do rotating speeds have important effects on the spectral correlation measure? Four rotor speeds of the C1, respectively 85%, 90%, 95% and 100%, have been analyzed. The speed was kept steady at each point, and then the throttle was closed slowly to push the compressor into unstable operating range.

The results with the spectral correction measure are shown in Fig 8-Fig 10. (1) The curves of the spectral correlation measure have the same tendency, that is, the measure values are higher than 0.95 and keep stable when the compressor operates in stable states, while decrease dramatically in the process of enter into surges, and then return back to a high level when the compressor is totally in surge states. (2) If a fixed threshold ρ_T =0.95 is chosen, the surges could be detected within 0.010s after the occurrence at all these 4 speeds. It means that alarms can be sent out within 2 detecting periods. A conclusion can be drawn that the rotating speeds have little effects on the spectral correlation measure for a given compressor. So, it will be easier to choose a threshold of a detection system.

Analysis window effects

How to choose the length of analytical windows? It has definitely effects on the calculation amount. Does it impact on timeliness and reliability of detection? The data of the 85% speed of C1 are taken as an example to analyze its effects. In this case, *N* is chosen at 1024, 2048, 4096, 8192 and 16384, while ΔT and *k* are kept as same as before. The result of *N*=2048 is shown in above Fig 4 as mentioned before. Here, the partially enlarged views of N=1024 and N=16384 are shown in Fig 11 and Fig 12. Following phenomenon can be seen by comparing these two curves of the spectral correlation measure. When N=1024, the curve has obvious fluctuations even when the compressor operate at steady state. It even has values less than 0.95, the fixed threshold above, before entry into surges. The amplitude of fluctuations is smaller when *N*=16384.

Further analysis is based on the Table 1, in which, the average value of the measure $Avg(\rho_s)$, the variance $std(\rho_s)$ and the minimum $Min(\rho_s)$ during stable (They are calculated with values during 2-8s), and the minimum $Min(\rho)$ during whole process are calculated when different *N* are chosen. It can be seen for Table 1 that $Avg(\rho_s)$ increases while $std(\rho_s)$ decreases with longer *N*. The reason of this phenomenon is that with a fixed *k*, the windows X and Y have more common data with longer *N*, and that reduces the contribution of random noise to the spectral correlation measure. The occurrences of $Min(\rho)$, with the symbol $T_{\min,\rho}$, are delayed with longer *N*. The maximum difference is 0.0068s, which is less than two detection periods. It can be considered as no significant difference. Since the $Avg(\rho_s)$ and $Std(\rho_s)$ change with different *N*, the threshold should be chosen differently instead of a fixed value when detection systems are constructed. In order to compare the occurrences of alarms, the thresholds ρ_T with different *N* are calculated with Formula 4 before and fixed during detecting. The moments of the first alarms T_{al} are also given in Table 1. The biggest difference of T_{al} is 0.0042s, which is less than a detection period.

$$\rho_T = Avg(\rho_s) - 6std(\rho_s) \qquad (4)$$

Therefore, conclusions can be drawn as following. (1) The $Avg(\rho_s)$ increases while $std(\rho_s)$ decreases with longer *N*. (2) It has few effects on the detection results if the thresholds change with *N*. Obviously, it means increasing calculation amount with longer *N*. However, a detection system maybe does not work with a too small *N*. The detecting result with *N*=128 is shown in Fig 13. In which there is no significant decrease even when the compressor entry into surge state. So, it fails to give an alarm.

Table 1. Effects of different *N* (speed=85%)

N	$Avg(\rho_s)$	$std(\rho_s)$	$Min(\rho_s)$	$T_{\min,\rho}$	$Min(\rho)$	T_{al}
1024	0.9777	0.0071	0.9461	9.7473	0.8558	9.7473
2048	0.9884	0.0039	0.9654	9.7497	0.8226	9.7447
4096	0.9940	0.0020	0.9847	9.7495	0.8451	9.7445
8192	0.9969	0.0011	0.9915	9.7541	0.8890	9.7441
16384	0.9984	5.416E-4	0.9957	9.7533	0.9153	9.7431

Delta of Windows effects

Usually, the spectra are calculated window by window. When *k*=1, X and Y are nearest windows. ρ_{XY} is the correlation efficient of spectra of two windows. The results of calculation with different *k* are shown in Table 2. It can be seen that $Avg(\rho_s)$, $std(\rho_s)$ and even $Min(\rho_s)$ decrease with an increasing *k*. The common parts of X and Y are reduced, and then the stochastic components make more contribution to the ρ_{XY}. So this phenomenon comes. If the Formula 4 is adopted to choose thresholds, the biggest difference of the alarming moment is 0.0450s, i.e. 9 periods of detection. There is not significant difference when *k* is chose during the range 1-4. However, the difference is obvious and does not follow any rules during the range 5-10. It may be caused by increasing of randomicity.

Table 2. Effects of different *k* (speed=85%, N=2048)

k	$Avg(\rho_s)$	$std(\rho_s)$	$Min(\rho_s)$	$T_{\min,\rho}$	$Min(\rho)$	T_{al}
1	0.9884	0.0039	0.9654	9.7497	0.8226	9.7447
2	0.9777	0.0056	0.9563	9.7547	0.7039	9.7447
3	0.9676	0.0072	0.9385	9.7597	0.6064	9.7447
4	0.9582	0.0081	0.9289	9.7647	0.5418	9.7447
5	0.9493	0.0090	0.9184	9.7547	0.6018	9.7547
6	0.9411	0.0100	0.9087	9.7747	0.4785	9.7747
7	0.9327	0.0108	0.8955	9.7597	0.4816	9.7597
8	0.9246	0.0115	0.8833	9.7647	0.4155	9.7647
9	0.9174	0.0129	0.8666	9.7897	0.5372	9.7897
10	0.9100	0.0134	0.8699	9.7547	0.6303	9.7547

Noise effects

The noise of a measurement system should be strictly controlled to ensure the results of testing reflect to the real operation states of the experimental subjects. It is also important to control noise to ensure a detecting system having low missing or false alarms. The noise may come from sensors and data acquisition systems. The main part may be introduced by signal transmission lines. The noise of sensors can be estimated by the error of sensors. It is more difficult to estimate the noise of wires nevertheless. In order to simplify the problem, above signals are considered as "true signals". Then, the effects of noise are studied by adding noise to these "true signals". In this way, the results of research will also suit to general situations.

The nose is measured by the ratio of signal to noise defined in Formula 5. The results of detection with different *SN* are shown in Table 3.

$$SN = 10\log(P_s / P_n)\ dB \qquad (5)$$

Table 3. Effects of different S*N* (speed=85%)

SN	$Avg(\rho_s)$	$std(\rho_s)$	$Min(\rho_s)$	$T_{\min,\rho}$	$Min(\rho)$	T_{al}
∞	0.9884	0.0039	0.9654	9.7497	0.8226	9.7447
40.0	0.9884	0.0039	0.9655	9.7497	0.8225	9.7447
34.0	0.9884	0.0038	0.9656	9.7497	0.8227	9.7447
32.0	0.9884	0.0038	0.9656	9.7497	0.8228	9.7447
30.5	0.9884	0.0038	0.9654	9.7497	0.8222	9.7447
26.0	0.9884	0.0038	0.9661	9.7497	0.8224	9.7447
20.0	0.9884	0.0038	0.9660	9.7497	0.8212	9.7447
14.0	0.9884	0.0037	0.9661	9.7497	0.8202	9.7447
10.5	0.9884	0.0036	0.9705	9.7497	0.8215	9.7447
8.0	0.9884	0.0035	0.9725	9.7497	0.8214	0.7447
6.0	0.9884	0.0034	0.9713	9.7497	0.8176	9.7447
0.0	0.9882	0.0027	0.9762	9.7497	0.8218	9.7447
-6.0	0.9883	0.0023	0.9790	9.7497	0.8791	9.7497
-9.5	0.9881	0.0024	0.9788	9.7497	0.9267	9.7497
-12.0	0.9882	0.0024	0.9803	9.7497	0.9403	9.7497
-14.0	0.9881	0.0024	0.9785	0.7497	0.9532	9.7497

A very interesting phenomenon can be seen from Table 3 that the spectral correlation measure is hardly affected by random noise. It can detect surges correctly even when the *SN* is -14dB, i.e. the amplitude of noise is 5 times of signal's. Another phenomenon is that $std(\rho_s)$ decreases with increasing noise. Why are there these phenomena? It because that each frequency component of random noise has the same magnitude. For widows X and Y, there are two samples of random noise. They have two random spectra. The correlation coefficient of these two spectra is zero. So, it almost does not affect the spectral correlation measure even adding noise to the signal. With the conclusion that white noise has no effects on the spectral correlation measure, one can image it will have the same results with colored noise.

In addition to white noise, another type of noise is a sudden noise. A random noise lasting t_n *ms* with a zero mean is added at 4*s* to the original signal to simulate a sudden noise. It finds out that the noise does not affect the spectral correlation measure if it lasts very short time with small amplitude. When the amplitude or the duration is larger, the phenomenon in Fig 14 will appear, that is, two drops are shown in the chart. The first drop appears itself when the noise in window X but not in window Y. Similarly, the second drop appears when the noise in window Y while not in window X. When the mean of the noise is not 0, the phenomenon is same, and even more susceptible to the interference.

Spectral band effects

In order to study the effects of spectral band, the data of C1 at 85% speed is still used. There are two ways to get data with different bands. One is changing the setting of hardware. Experiments should be repeated when the cutoff frequency of low-pass filter is changed to different values. This is a reliable method, but is costly for both time and budgets. Another way is very simple. After the spectra of analysis windows are calculated, only components in selected bands are engaged to calculate the spectral correlation measure. In this way, it is equivalent to the effect of ideal low-pass filters being added to the original signal. Here, the later is adopted. The results with different spectra bands are shown in Table 4. It can be seen in the table that the mean values and variances of spectral correlation measure increases slightly with the decreasing of bands. If the threshold is also settled with Formula 4, the results of detection do not change obviously.

Table 4. Effects of different bands

Band kHz	$Avg(\rho_s)$	$std(\rho_s)$	$Min(\rho_s)$	$T_{\min,\rho}$	$Min(\rho)$	T_{al}
5.0	0.9884	0.0039	0.9654	9.7497	0.8226	9.7447
2.5	0.9886	0.0048	0.9596	9.7497	0.8258	9.7447
1.25	0.9887	0.0061	0.9563	9.7497	0.8352	9.7447
0.625	0.9890	0.0073	0.9483	9.7497	0.8472	9.7447
0.3125	0.9902	0.0073	0.9482	9.7497	0.8660	9.7447

Adaptive Detecting System

A threshold is one of the key parameters in a detection system. It has great effects to the results. It will postpone alarms with a lower threshold. But with a higher value, fault alarms may send out even when a compressor still operates in stable range. In above analysis, thresholds are selected as a fixed value or are calculated with Formula 4. In this section, the further study is carried out on the rules of choosing a threshold. Then, an adaptive detecting system is proposed.

In order to choose a threshold, the distribution of spectral correlation measure is researched firstly. When the C1 operates at 85% speed in stable range, the distribution of 1500 points of the spectral correlation measure is shown in Fig 15. It looks like the density function of a log-normal distribution. Then, a random variable is defined as Formula 6 for verifying this hypothesis.

$$\gamma = \ln(1-\rho_{XY}) \qquad (6)$$

The points of γ are plotted on a normal probability plot as shown as Fig 16. The γ is supposed to follow a normal distribution since most of the points are near the red line.

Further calculations show that the value Epps-Pulley test [8] is 0.0167. When the points are more than 200 and the confidence level α is 0.01, the quantile *p* is 0.0590. The value of Epps-Pulley test is less than *p*. So, the γ obeys to a normal distribution and the spectral correlation measure obeys to a log-normal distribution.

As analyzed above, the spectral correlation measure is affected with the length of analysis windows, and bands of signals. When a measurement system and/or the testing pieces are modified, the range of spectral correlation measure may change accordingly. To improve the adaptive ability, a detection system with an adaptive threshold is proposed.

In the detection system, the γ is taken as the feature for detecting. The threshold is calculated with Formula 7.

$$\gamma_T = \gamma_m - C_T\sigma_\gamma \qquad (7)$$

Here, γ_m is the average value of γ in stable situation; σ_γ is the standard variance of γ; C_T is a coefficient which can be used to adjust the reliability of the detection.

The scheme of the on-line detecting system is shown in Fig 17. At the begging, the dynamic pressure is considered as stable situation. So, the strobe opens to estimate the γ_m and σ_γ. With a prefixed C_T, the threshold γ_T can be calculated . After on-line learning, the spectral correlation measure ρ_{XY} and then the γ can be calculated. When γ is greater than γ_T, a warning signal should be sent out immediately. If there is no warning, the γ is used to update γ_T. Then, it goes to the next detection period.

Summary

In this paper, the spectral correlation measure is defined to describe the comparability of two spectra of two windows of a single dynamic pressure. This method is demonstrated with two compressors. Similar conclusions have yielded as following.

(a) The measure shows a consistent behavior for different compressors, different rotating speeds, different lengths of analytical windows, different signal to noise ratios, and even different bandwidths of hardware.

(b) The average values of the spectral correlation measure in stable operating range increase with lower variances when the length of analytical windows increase, or the delta of windows decrease.

(c) The spectral correlation follows a normal-log distribution. An adaptive detecting system is designed with a feature converted from the measure, which makes it easy to choose the threshold, and makes the ratio of fault alarms controllable.

(d) Anther advantage is that the key phase signal is not necessary for this method.

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References

[1] M Gao, W Chu, Y Wu, et al. Experiment of the algorithm of detecting the stall inception for the subsonic compressor. Journal of propulsion technology, 2012, 33(3), pp. 398-404.

[2] Manuj Dhingra, Yedidia Neumeier, and J V R Prasad. Stall and Surge Precursors in Axial Compressors. 39th AIAA / ASME / SAE / ASEE Joint Propulsion Conference and Exhibit, 20-23 July 2003, Huntsville, Alabama, AIAA

2003-4425.

[3] F Lin, Z Tong, S Geng, et al. A summary of stall warning and suppression research with micro tip injection. Proceedings of ASME Turbo Expo 2011, June 6-10, 2011, Vancouver, British Columbia, Canada, GT2011-46118.

[4] Y Liu, M Dhingra, J V R Prasad. Correlation measure-based stall margin estimation for a single stage axial compressor. Journal of engineering for gas turbines and power, 2012, Vol 134, 011603.

[5] Y Liu, M Dhingra, J V R Prasad. Active compressor stability management via a stall margin control mode. Journal of engineering for gas turbines and power, 2010, Vol 132, 051602.

[6] C Li, B Xiong, C Wu. Compressor surge detecting based on short-time energy. Measurement and control, 2010, 29(3), pp. 1-2.

[7] C Li, S Xu, Z Hu. Experimental Study of Surge and Rotating Stall Occurring in High-speed Multistage Axial Compressor. Procedia Engineering 99, 2015, pp. 1548-1560.

[8] C Li, B Xiong, W Han. Surge detection of an axial compressor based on statistical characteristics. Journal of Aerospace Power, 2010, 25(12), pp. 2656-2659.

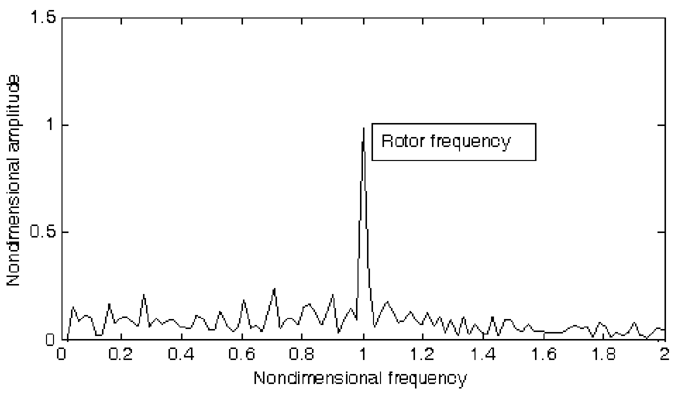

Fig 1. Spectrum of stable pressure signal

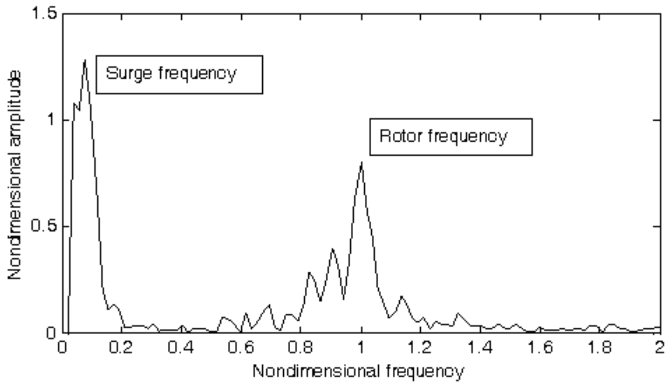

Fig 2. Spectrum of pressure signal in surge state

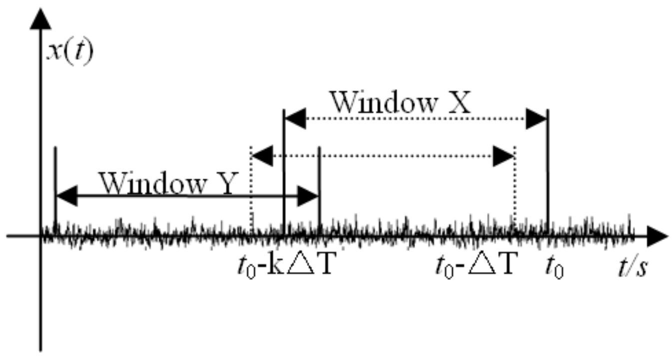

Fig 3. Scheme of detecting system

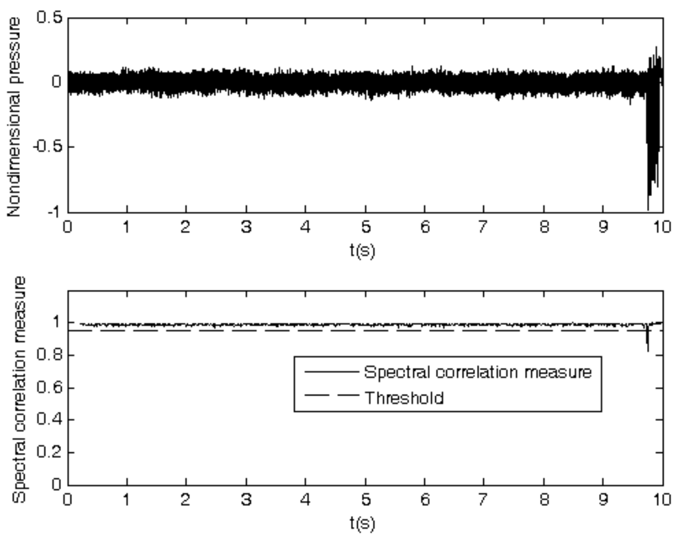

Fig 4. Detecting result of the C1 at 85% speed

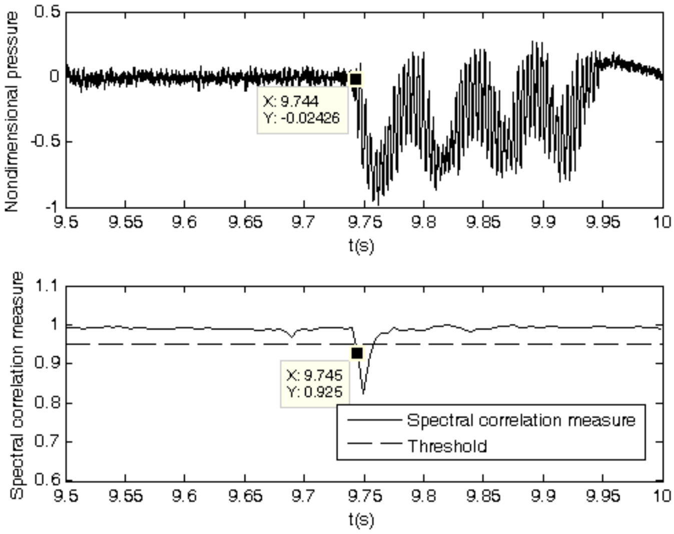

Fig 5. Enlarged view of result of the C1 at 85% speed

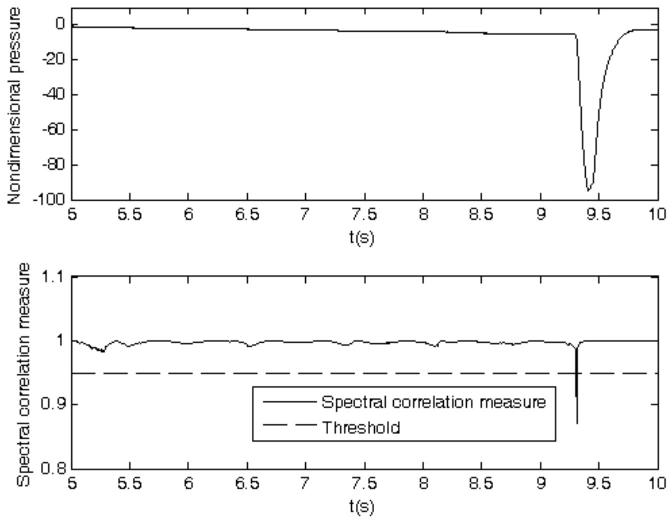

Fig 6. Detecting result of the C2 with total pressure of outlet

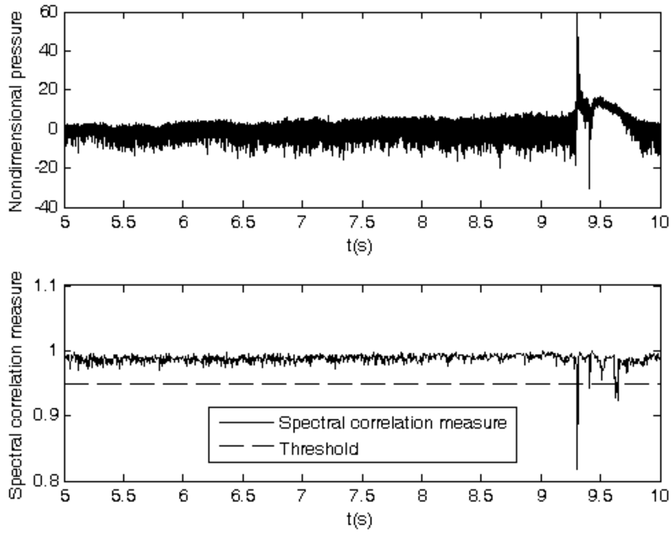

Fig 7. Detecting result of the C2 with static pressure

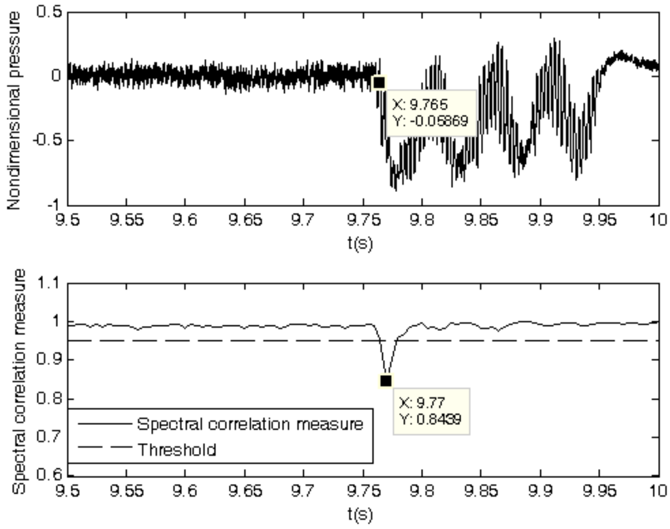

Fig 8. Detecting result of the C1 at 90% speed

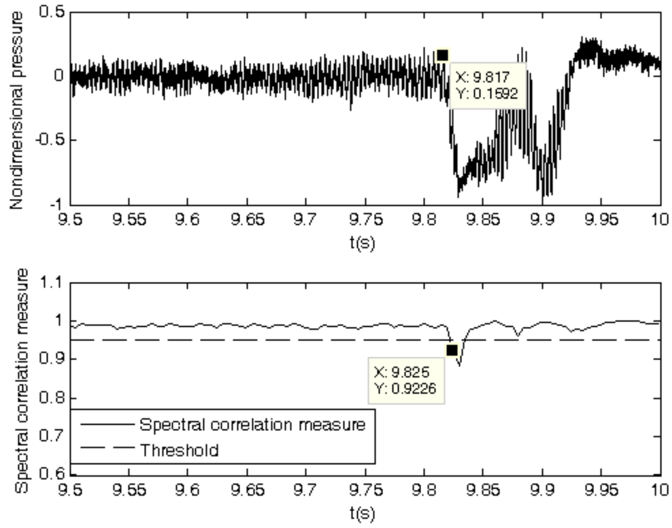

Fig 9. Detecting result of the C1 at 95% speed

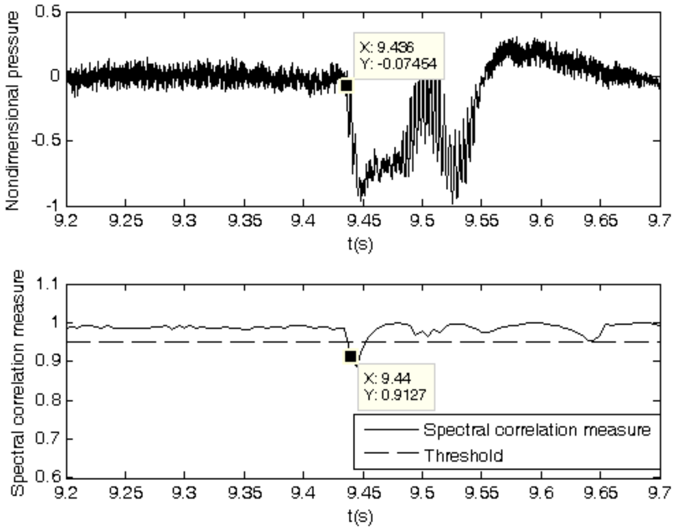

Fig 10. Detecting result of the C1 at 100% speed

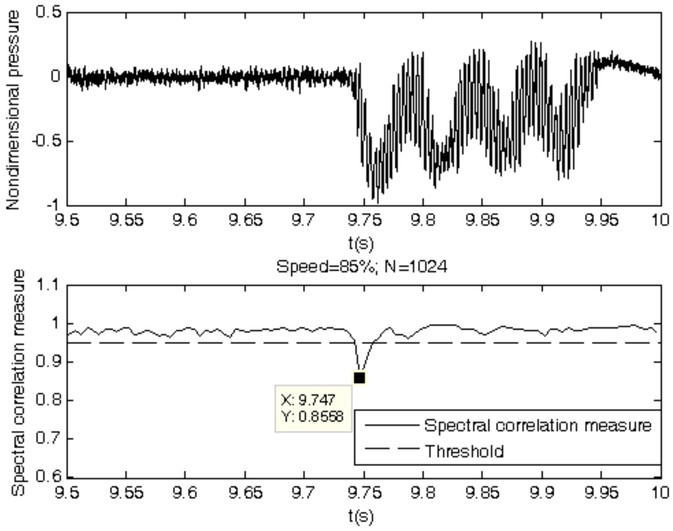

Fig 11. Detecting result of the C1 at 85% speed with N=1024

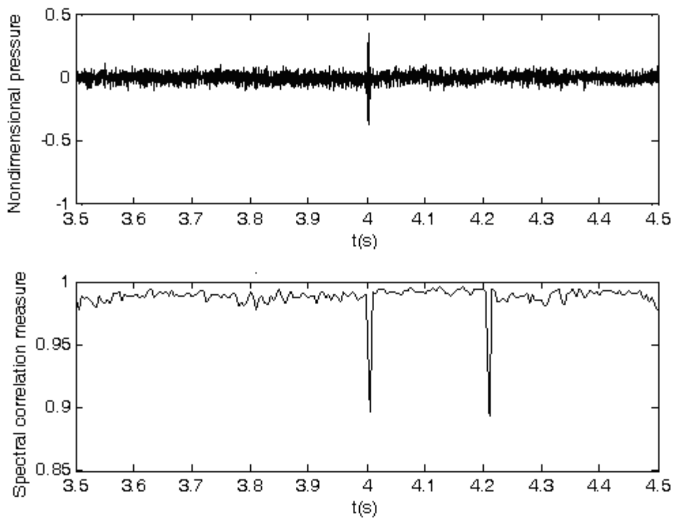

Fig 14. Detecting result of the signal with noise

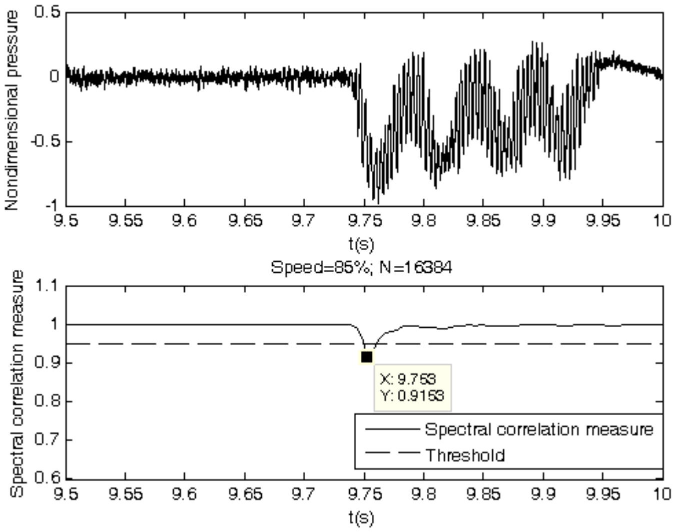

Fig 12. Detecting result of the C1 at 85% speed with N=16384

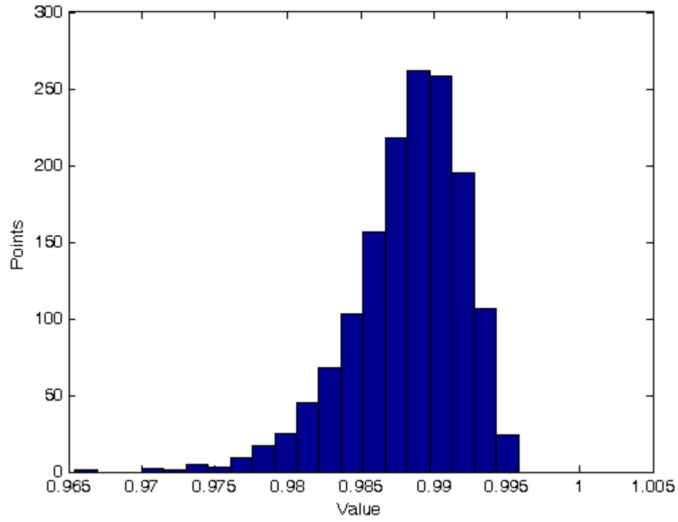

Fig 15. Distribution of the spectral correlation measure

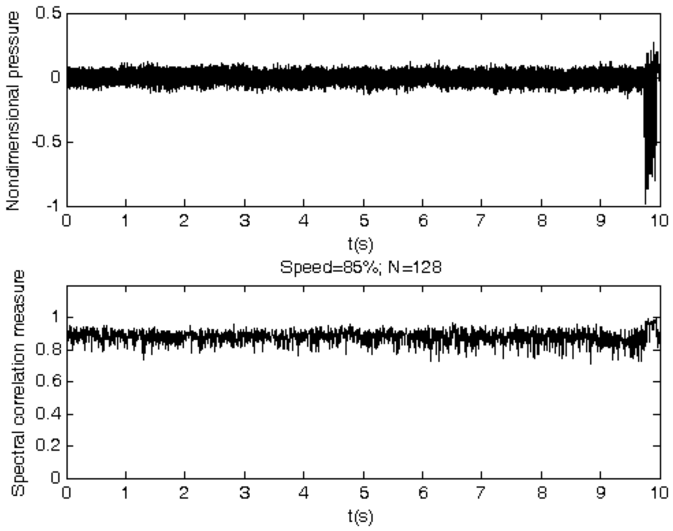

Fig 13. Detecting result of the C1 at 85% speed with N=128

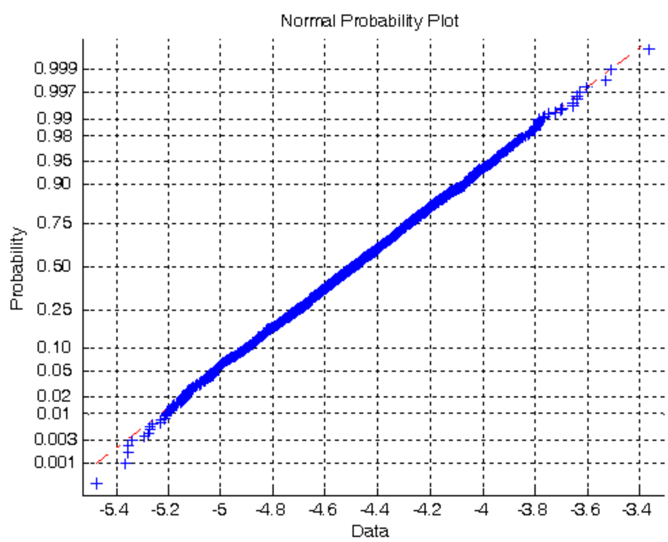

Fig 16. Normal probability plot of γ

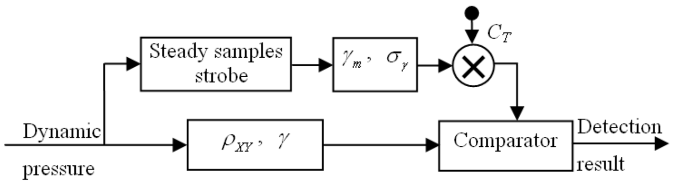

Fig 17. Scheme of an adaptive detecting system