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SURGE CHARACTERISTIC IN FRONT OF EACH STAGE FOR A HIGH PRESSURE FIVE STAGE COMPRESSOR

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Abstract

Dynamic pressure measuring points are usually arranged at the compressor outlet to detect surge. In this paper, for a five-stage high-pressure compressor, the dynamic pressure signals at different circumferential positions of each stage are collected in parallel at high speed to investigate comprehensively the characteristics of stall and surge. The main conclusions are as follows: under the condition of IGV on / off angle at 0.8 speed, the modal wave appears about 0.8 s before surge, and its frequency is about 20 Hz; The closer to surge, the greater the amplitude of stall mode wave. At 1.0 speed, there is no modal wave before surge and no obvious cusp wave characteristics. In the direction of air flow, the amplitude of modal wave basically increases from front to back, and the surge amplitude increases gradually too. Axial propagation frequency of surge air flow is about 12-14 Hz; In front of each stage rotor, the surge amplitude of 1.0 speed is higher than 0.8 speed. The amplitude of blade passing frequency is significantly higher than that of the frequency of rotating frequency multiplied by the difference in the number of rotor blades, indicating that the blade passing frequency is dominant.

Keywords: surge, modal wave, high-pressure compressor, test scheme.

1. General Introduction

Turbofan engine is the most commonly used aerodynamic power device for military and civil aircraft in the world. The axial flow compressor is one of the core components of turbofan engine. With the development of Aeronautics Science and technology, high-performance engine has put forward higher and higher efficiency and stable working margin demand for fan and compressor components. In order to balance the contradiction between compressor efficiency and stable working margin, in recent decades, scholars at home and abroad have continuously improved these two indexes by improving design technology. On the other hand, by testing and analyzing the surge characteristics of compressor, the corresponding active/passive control technology is developed to delay and suppress stall and surge [1].

Stall and surge characteristics analysis, as well as early detection, is a huge system engineering, and also a worldwide problem that the international aviation industry strives to overcome [2-5]. In most cases, a certain degree of rotational stall always occurs before surge occurs, so it is important to timely capture the signs of rotational stall for surge prediction. At present, both at home and abroad, the precursors of instability can be classified as mode wave and cusp type [6-7], but they are much more complicated in engineering. The precursors of instability of compressors with different structures are quite different, and some of them even have no signs.

The study of rotating stall and surge of high-pressure compressor is very necessary because the new flow characteristics observed in high-pressure compressor test can not be observed in low Mach number compressor. For multi-stage compressors, it is not possible to accurately predict which stage of compressor is the first stage of rotating stall. Usually, dynamic pressure measuring points are arranged at the compressor outlet to detect surge.

In this paper, for a five-stage high-pressure compressor of a turbofan engine, the dynamic pressure signals at different circumferential positions of each stage are collected in parallel at high speed, the characteristics of compressor stall and surge signals are comprehensively analyzed, and the occurrence and development process of stall and surge are analyzed, so as to lay a foundation for the further exploration of instability online prediction methods.

2. Experimental Platform for Capturing Compressor Surge Characteristics

Experimental platform for compressor surge research is shown in Figure 1. This platform mainly consists of nine systems. High precision variable frequency power control system, could change the rotational speed of the compressor conveniently. Gear box, could multiply physical rotational speed of the power control system. Axis force automatic control system, could meet the requirement of axial-force rapid change before and after surge. Exhaust volute, could meet the uniform exhaust demand of compressor. Throttle valve, could cause the compressor approach surge by reducing the flow. Five-stage compressor, is the research object of this experimental platform. Blade angle adjustment system, could adjust the inlet guide vane (IGV) and stator (S1) angles of this five-stage compressor. Inlet flow tube and air inlet pressure stabilizing box, could ensure the uniformity of air flow at the inlet of compressor. This experimental platform could ensure that the high-pressure compressor safely enter and exit surge, and therefore, lay a foundation for capturing surge Characteristics.

In order to simulate the instability state of turbofan engine, as a component test, experiments for individual high-pressure compressor are conducted to make the five-stage compressor to approach surge by adjusting the throttle valve at the outlet. This paper mainly studies the flow mechanism of the surge /stall evolution process when IGV and S1 angles are decreased /increased relative to the designed value at 0.8 corrected rotational speed, as well as IGV and S1 angles are at designed angle value at 1.0 corrected rotational speed under the condition of uniform air flow intake.

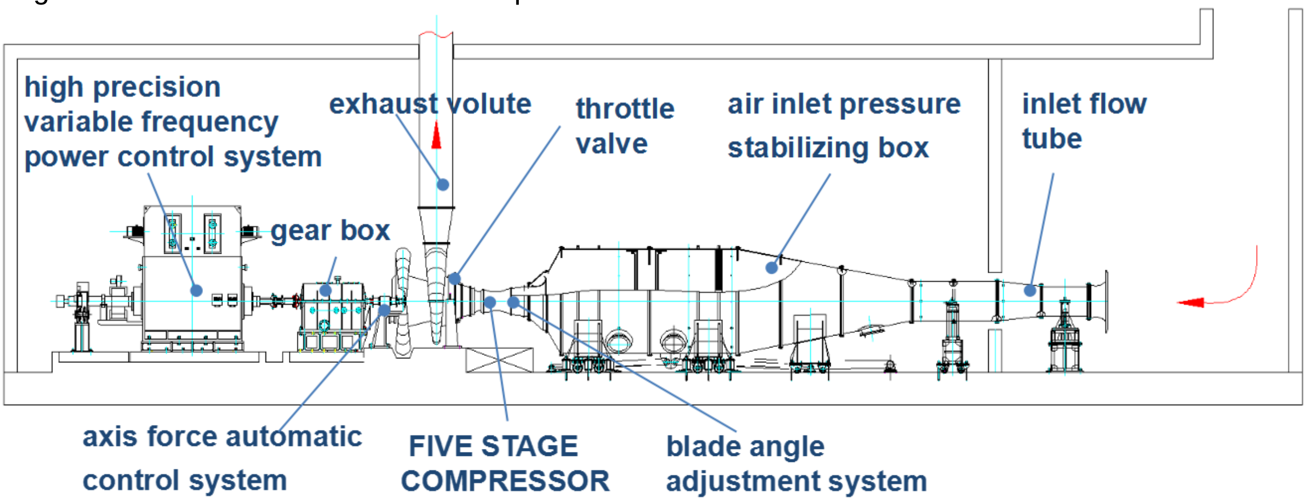


Figure 1 – Experimental platform for compressor surge research.

3. Test Scheme Design for Capturing Compressor Surge Characteristics

The modeling of rotating stall and surge is a complex problem, and modeling is the basis of further detection and control for compressor surge. Paduano and Mansoux established Mansoux model [8-9] based on the derivation of Moore-Greitzer model. Mansouxs model can quantitatively describe the development process of rotating stall of various compressors. According to Mansouxs modeling requirements, the layout scheme of circumferential and axial pressure-measuring points is designed to capture the evolution process from stable operation to stall and surge for this five-stage compressor.

The distribution of dynamic pressure measuring points for this five-stage compressor is shown in Figure 2. The layout method of measuring points with the combination of fully ring uniform distribution and sector uniform distribution is adopted. Five points shall be arranged in front of R1, with an interval of 21.2 degrees between adjacent measuring points (A in Figure 2); Twelve points shall be arranged in front of R2 (B in Figure 2), with an interval of 30 degrees. Nine points shall be arranged in front of R3 (C in Figure 2), of which 5 adjacent measuring points are 20 degrees apart and 5 adjacent measuring points are 24 degrees apart. Ten points are arranged in from of R4 (D in Figure 2), of which 5 adjacent measuring points are 21.2 degrees apart, and the other 5 adjacent measuring points are 19 degrees apart. Four points are arranged at the exit (E in Figure 2), two points are arranged at 319 degrees, one on the windward side and the other on the leeward side. Each measuring point in Figure 2 is numbered to facilitate subsequent analysis. According to the designed test scheme, a high-performance compressor high-performance compressor with multi-stage pressure test interface is designed and produced to ensure the smooth development of compressor instability test, and then surge characteristics at each stage are expected to be obtained.

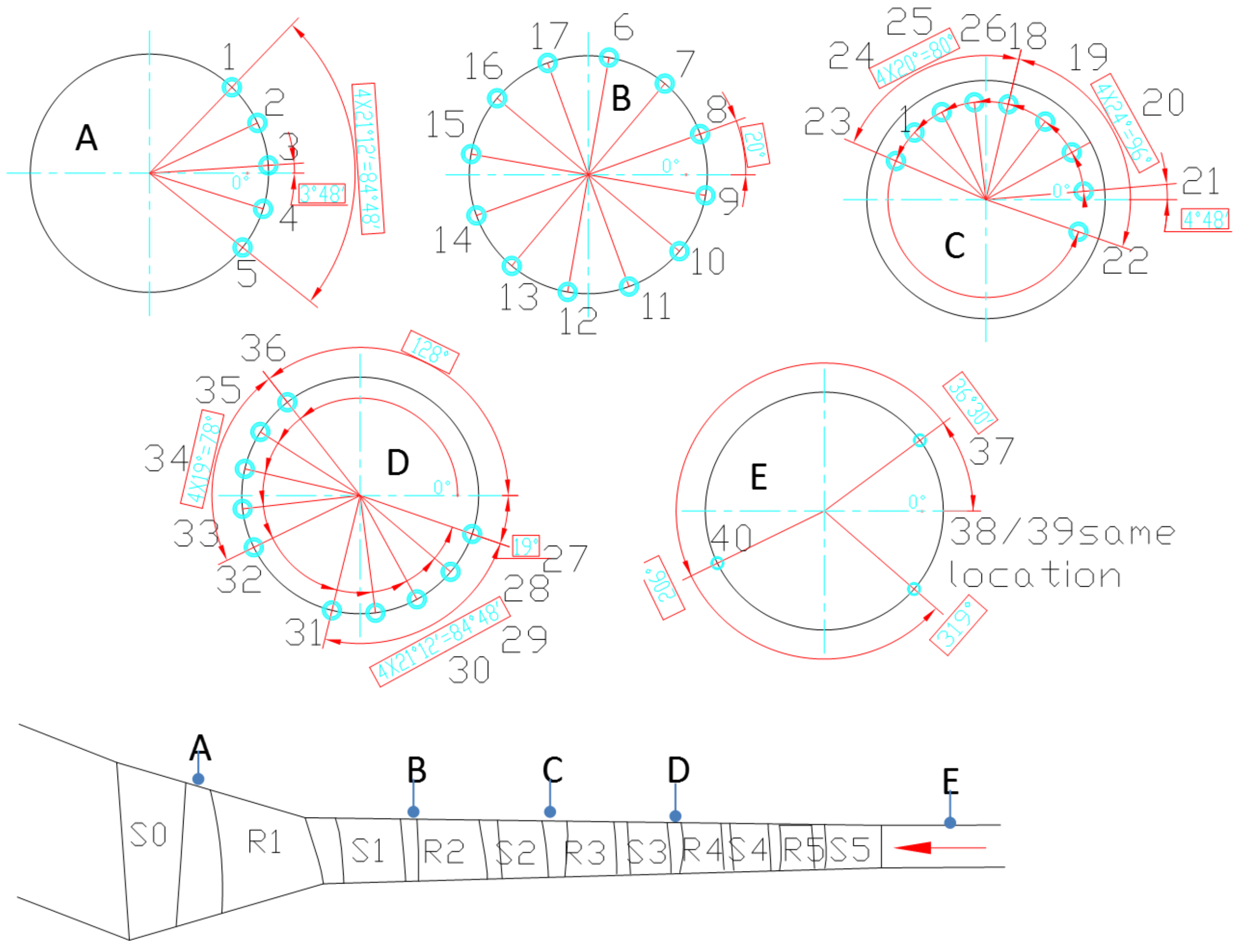


Figure 2– Distribution of dynamic pressure measuring points.

4. Modal Wave Characteristics Before Surge

The dynamic pressure at different circumferential positions of each stage is collected in parallel at high speed, and signals are analyzed in time domain and frequency domain. The sampling rate of the pressure is 40960 Hz for all the measuring points. The signal is band-pass at 0.8 corrected rotational speed and 3000 Hz low-pass filter at 1.0 corrected rotational speed.

This paper focuses on the following three aspects concerning surge characteristics: with/without modal wave before surge, the frequency and amplitude of surge, and physical meaning of frequency signal in frequency domain.

The premonitory modal wave of surge occurs at 0.8 speed whether IVG angle and S1 angle are decreased (IGV on) or increased (IGV off), and disappear at 1.0 speed.

4.1 Time Domain Characteristics of Surge at 0.8 Speed and IGV On

The dynamic pressure during the process of surge at 0.8 corrected rotational speed under the condition of decreased IGV angle is shown in Figure 3. The X-axis represents the time, and its main unit is 0.5 seconds. The Y-axis represents the pressure (gauge pressure), and its main unit is 0.5 x10^5 Pa. The comparative analysis of time domain characteristic of surge signals at different stages at 0.8 corrected rotational speed under the condition of decreased IGV angle is shown in Figure 4. The X-axis represents the time, and its main unit is 0.05 seconds, which could display the pressure characteristic more clearly. The implication of Y-axis is the same as that of Figure 3.

The premonitory modal wave of surge is observed in Figure 3, which occurs about 0.8 seconds before surge, and its frequency is preliminarily calculated to be about 20 Hz according to the characteristics in the time domain.

Take the time period when the pressure value suddenly decreases as the half cycle of surge, and then calculate that the axial propagation frequency of surge air flow is about 12 Hz. The surge amplitude value is defined as the difference between the first highest peak and the first lowest peak of the pressure value, and the relative surge amplitude value is defined as the surge amplitude divided by the pre surge pressure value. The surge amplitude of the compressor increases gradually from the first stage to the fifth stage, and the relative surge amplitude also increases gradually. The surge amplitude at the outlet is 2.42 x10^5Pa, and the relative surge amplitude is 0.65, which is the largest in all stages.

During surge process, the static pressure before R2 (line B in Figure 4) rises first and then decreases, and the static pressure after R2 (line C in Figure 4) decreases first and then rises. In addition, the static pressure after R2 (line C) decreases before that after R3 (line D in Figure 4), so it is judged that the first stage of surge is the second stage rotor.

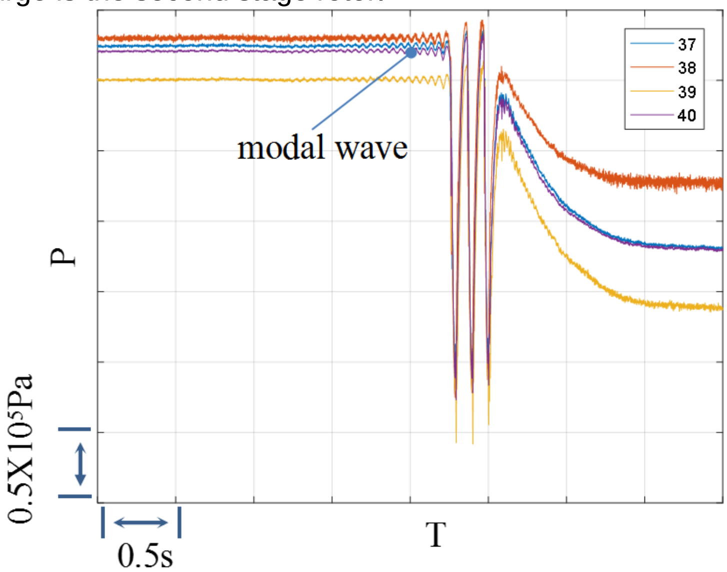


Figure 3– Time domain signal characteristics of the outlet pressure at 0.8 corrected rotational speed under the condition of decreased IGV angle.

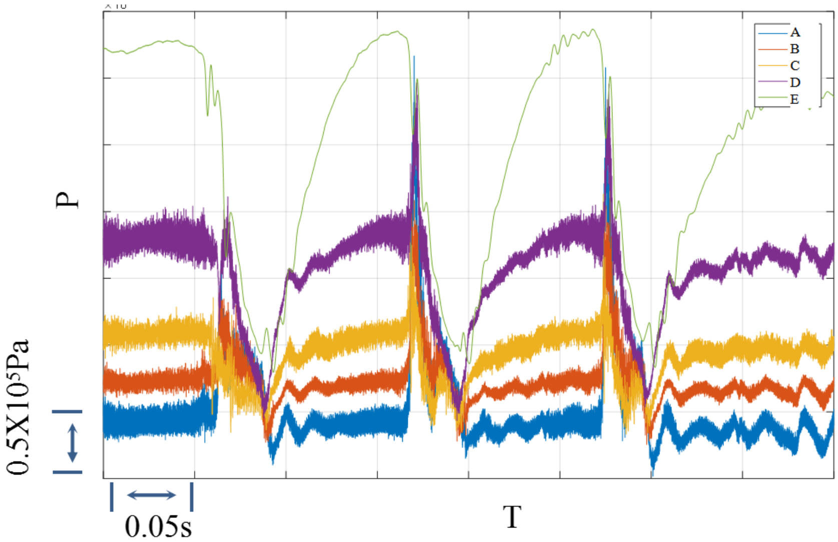


Figure 4– Comparative analysis of time domain characteristic of surge signals of each stage at 0.8 speed under the condition of decreased IGV angle.

4.2 Frequency Domain Characteristics of Surge at 0.8 Speed and IGV On

Frequency domain signal of the pressure before first stage rotor during the process of surge at 0.8 corrected rotational speed under the condition of decreased IGV angle is shown in Figure 5. The X-axis represents the frequency, and its main unit is 1000 Hz. The left Y-axis represents the time, and its main unit refers to 0.5 seconds. The right Y-axis represents the pressure value (gauge pressure), and its main unit is 50 Pa.

In the process of frequency domain analysis, the frequency resolution is 1Hz, and the time resolution is 1 second. During surge process, there is always a broadband signal within 400 Hz. The frequency of modal wave before surge is 21 Hz, which is consistent with the characteristics of time domain signal, and modal wave magnitude could also be obtained from Figure 5. The rotation frequency of the rotor is 153.8 Hz, the number of R1 blades is 37, and then the blade passing frequency (BPF) of R1 is 5691.Therefore, in Figure 5, the 5692 Hz represents the BPF of R1, and 11383 Hz represents twice the BPF of R1, as shown in Table 1.

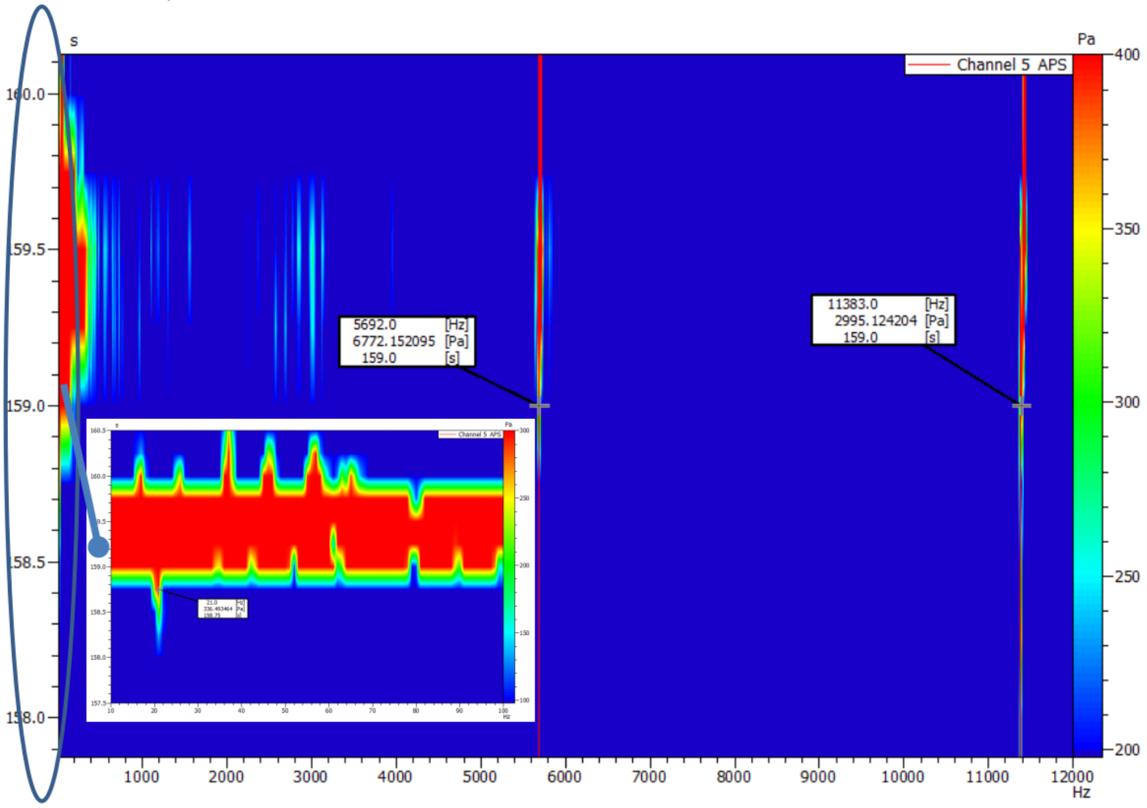


Figure 5– Frequency domain signal of the pressure before first stage rotor during the process of surge.

Table 1 Physical implication of frequency domain signal before first stage rotor

Frequency （Hz）	Physical implication	Amplitude（Pa）
5692	BPF of R1	6772
11383	Twice the BPF of R1	2995

Frequency domain signal of the pressure before second stage rotor during the process of surge is shown in Figure 6. The physical meaning of X-axis and Y-axis is the same as that in Figure 5. There is always a broadband signal within 400 Hz during the process of surge. The frequency of modal wave before surge is 21 Hz, which is consistent with the characteristics of time domain signal. In frequency domain, 2923 Hz is 19 times rotation frequency, and the rotor blades number difference between R2 and R1 is 19, indicating the interaction between R2 and R1. 5692 Hz is the BPF of R1, 8441 Hz is the BPF of R2, and 11383 Hz is twice the BPF of R1, as shown in Table 2. The amplitudes corresponding to 2923 Hz and 11383 Hz are 433 Pa and 600 Pa respectively, which are one order of magnitude smaller than those corresponding to BPF. Therefore, the BPF is dominant in the signal.

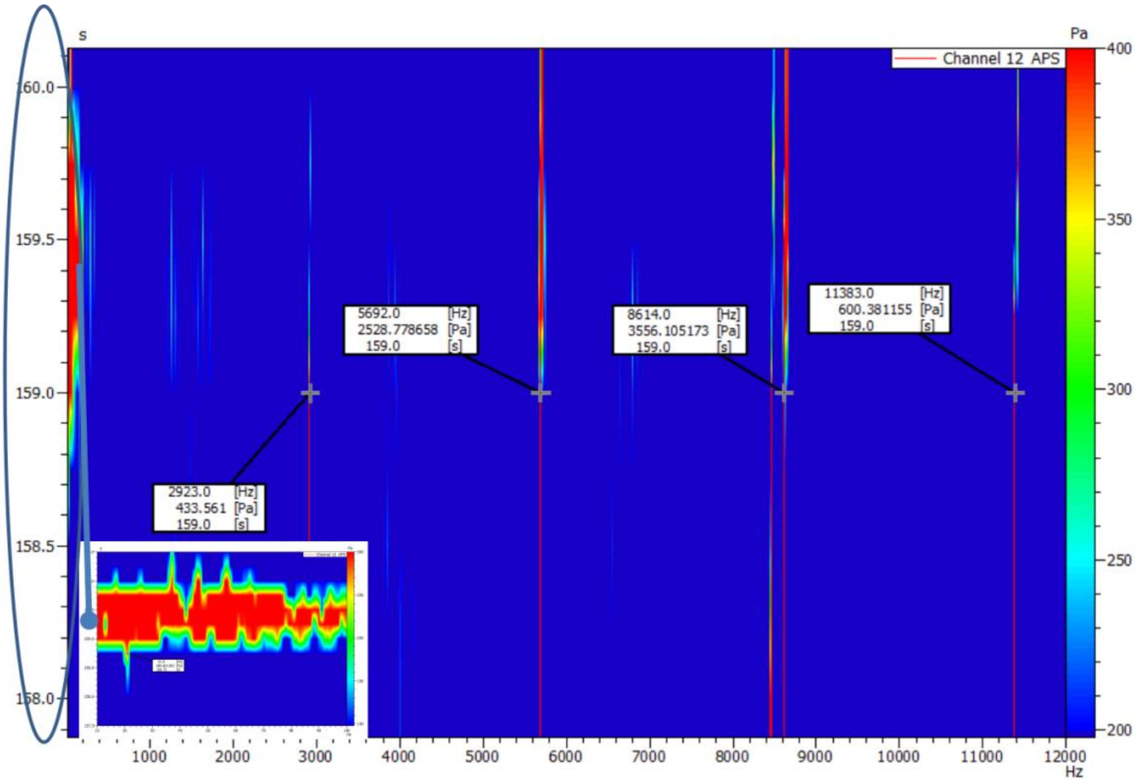


Figure 6– Frequency domain signal of the pressure before second stage rotor during the process of surge.

Table 2 Physical implication of frequency domain signal before second stage rotor

Frequency （Hz）	Physical implication	Amplitude （Pa）
2923	19 times the rotation frequency. There is a difference of 19 rotor blades between R2 and R1, and therefore this value indicates he interaction between R1 and R2	433
5692	37 times the rotation frequency, i.e., BPF of R1	2528
8414	56 times the rotation frequency, i.e., BPF of R2	3556
11383	74 times the rotation frequency, i.e., twice the BPF of R1	600

Frequency domain signal of the pressure before third stage rotor during the process of surge is shown in Figure 7. The physical meaning of X-axis and Y-axis is the same as that in Figure 5. The frequency of modal wave before surge is 21 Hz. The biggest difference between the frequency domain signal before R3 and that before R2 lies in the wide-band signal around 922 Hz and 3648 Hz during the process of surge, which may indicate the separation of R2 gas flow during the process of surge. Evidence of R2 being the first stage of surge is also found in the frequency domain. The same as the frequency domain signal before R2 is the 5692 Hz, i.e., BPF of R1 and 8414 Hz, i.e., BPF of R2, as shown in Table 3.

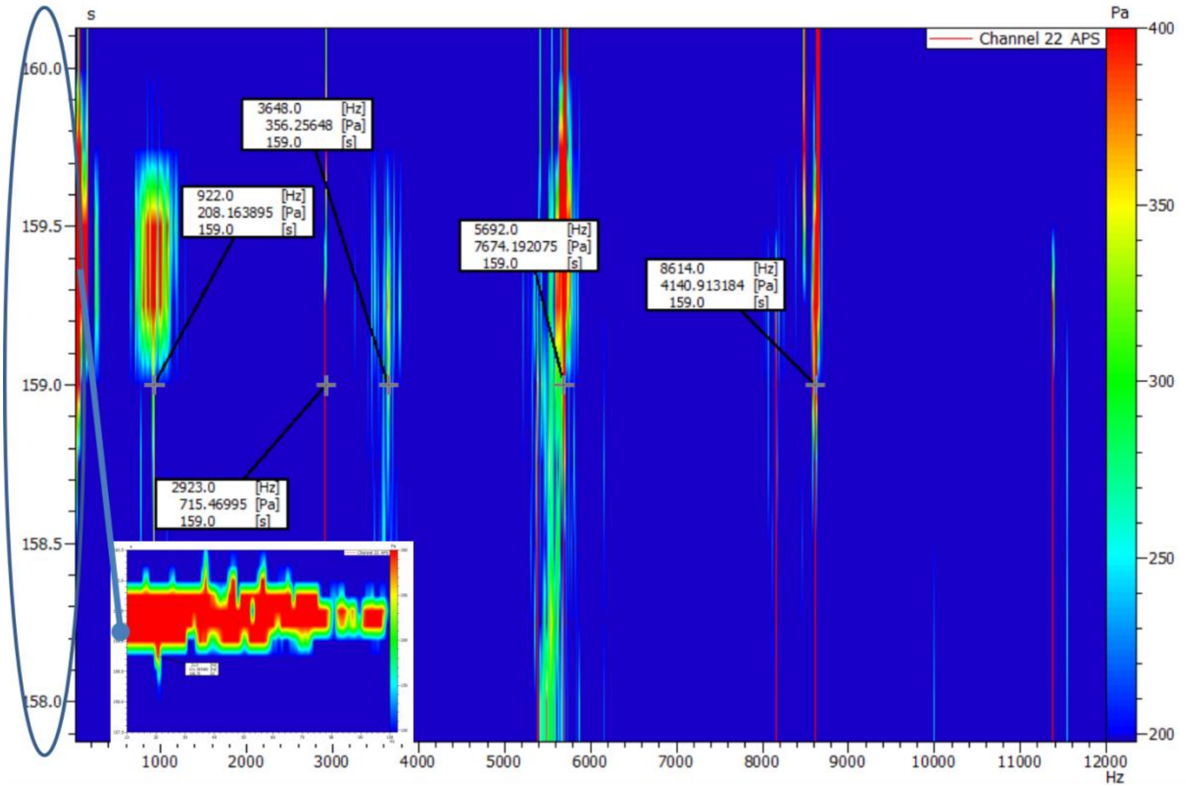


Figure 7– Frequency domain signal of the pressure before third stage rotor during the process of surge.

Table 3 Physical implication of frequency domain signal before third stage rotor

Frequency （Hz）	Physical implication	Amplitude （Pa）
around 922	The wide-band signal around 922 Hz in the surge process indicates the flow separation from R2, and it also indicates that R2 is the first stage of surge	208
2923	19 times the rotation frequency. There is a difference of 19 rotor blades between R2 and R1, and therefore this value indicates the interaction between R1 and R2	715
around 3648	4 times of 922Hz, implicating flow separation from R2	356
5692	37 times the rotation frequency, i.e., BPF of R1	7674
8414	56 times the rotation frequency, i.e., BPF of R2	4140

Frequency domain signal of the pressure before fourth stage rotor during the process of surge is shown in Figure 8. The physical meaning of X-axis and Y-axis is the same as that in Figure 5. There is always a broadband signal within 400 Hz during the process of surge. The frequency of modal wave before surge is 21 Hz. The biggest difference from the frequency domain signal before R3 lies in the wide-band signal characterizing R2 gas flow separation near 922 Hz and 3684 Hz have disappeared. Compared with that before R3, in addition to 5692 Hz corresponding to BPF of R1 and 8614 Hz corresponding to BPF of R2, there is 11076 Hz more, which corresponds to BPF of R3. Moreover, 2923 Hz represent the interaction between R1 and R2. 5384 Hz represent the interaction between R1 and R3. 1864 Hz and 9230 Hz indicates R3 and R4 interaction. The amplitude corresponding to the frequency of rotor and rotor interaction is small, as shown in Table 4.

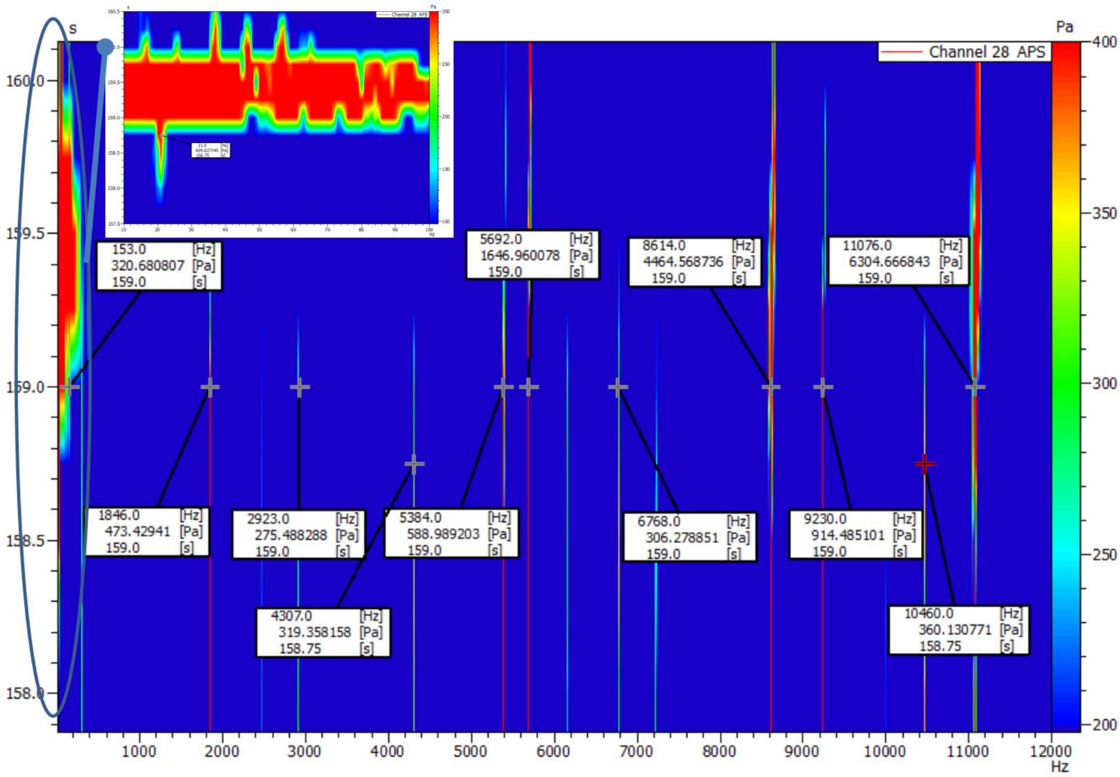


Figure 8– Frequency domain signal of the pressure before fourth stage rotor during the process of surge.

Table 4 Physical implication of frequency domain signal before fourth stage rotor

Frequency（Hz）	Physical implication	Amplitude（Pa）
153	rotation frequency.	320
1846	12 times the rotation frequency. There is a difference of 12 rotor blades between R3 and R4, and therefore this value indicates the interaction between R3 and R4.	473
2923	19 times the rotation frequency. There is a difference of 19 rotor blades between R2 and R1, and therefore this value indicates the interaction between R2 and R1.	275
4307	28 times the rotation frequency. There is a difference of 28 rotor blades between R2 and R4, and therefore this value indicates the interaction between R2 and R4.	319
5384	35 times the rotation frequency. There is a difference of 35 rotor blades between R1 and R3, and therefore this value indicates the interaction between R1 and R3.	589
5692	37 times the rotation frequency, i.e., BPF of R1	1646
6768	44 times the rotation frequency	306
8614	56 times the rotation frequency, i.e., BPF of R2	4464
9230	60 times the rotation frequency, i.e., 5 times of 12 times rotation frequency, indicating the interaction between R3 and R4.	914
10460	60 times the rotation frequency	360
11076	72 times the rotation frequency, i.e., BPF of R3	6304

Frequency domain signal of the pressure at the outlet during the process of surge is shown in Figure 9. The physical meaning of X-axis and Y-axis is the same as that in Figure 5. There is always a broadband signal within 300 Hz during the process of surge. The frequency of modal wave before surge is 21 Hz. 153 Hz represents the rotation frequency of rotor. The high-frequency signal above 500 Hz at the compressor out disappears because the location of measuring point is far from the rotor outlet, and the high-frequency shed vortex is dissipated and transformed into heat energy.

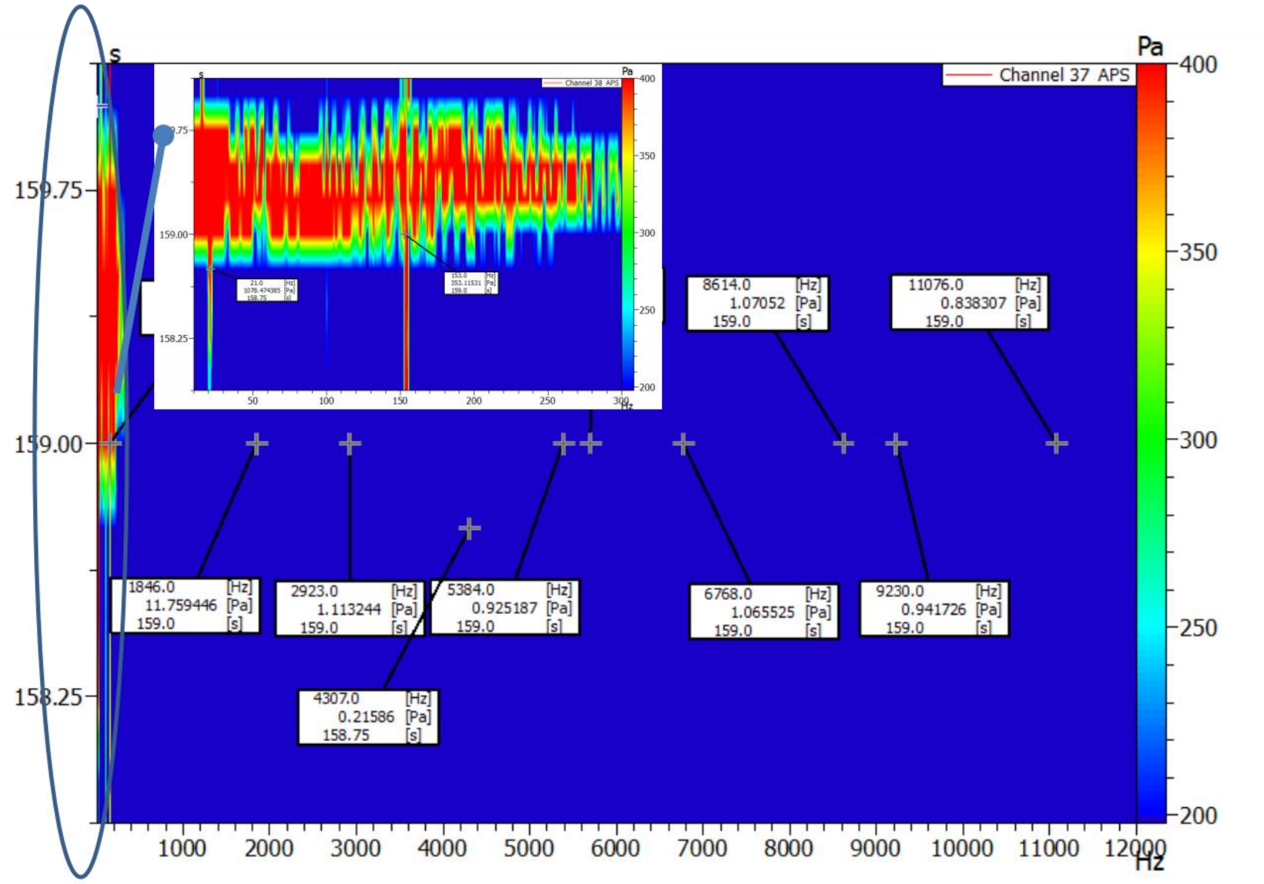


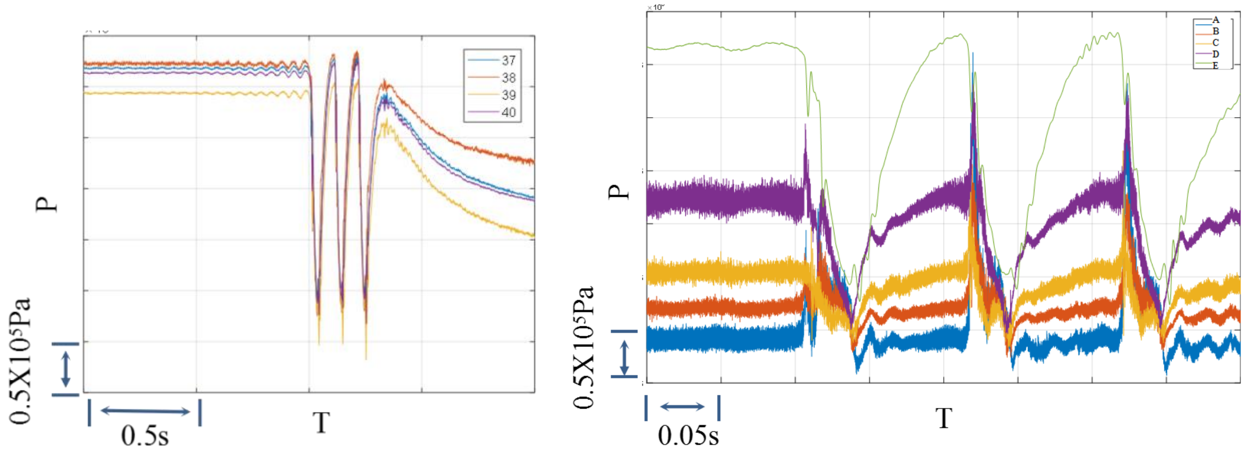
Figure 9– Frequency domain signal of the pressure at the outlet during the process of surge.

4.3 Characteristics of Surge at 0.8 Speed and IGV off

The dynamic pressure during the process of surge at 0.8 corrected rotational speed when the IGV angle is off is shown in Figure 10. The modal wave appeases about 0.8 seconds before the occurrence of surge, and its frequency is preliminarily determined to be about 20 Hz according to the characteristics in the time domain. From the first stage to the final, the surge amplitude increases gradually.

Judge that the first stage of surge is the second stage rotor, which is the same as that when the IGV is on. During surge process, the static pressure after R2 decreases first, while the static pressure before R1, R2 and R4 increases first and then decreases. Therefore, the second stage rotor surge first.

Characteristics of surge in Frequency domain when the IGV angle is off is similar to that when IGV angle is on, and the BPF is dominant in the signal.



(a) Pressure at the outlet (b) Pressure before each stage

Figure 10– Time domain signal characteristics at 0.8 corrected rotational speed under the condition of increased IGV angle during surge process.

4.4 Modal wave characteristic Analysis

The pre surge modal wave appeases no matter IGV angle is on or off relative to the design at 0.8 corrected rotational speed. The modal wave frequency is about 21 Hz when IGV angle is on and 20 Hz when IGV angle is off. The modal wave frequency is basically identical at the same corrected rotational speed.

The occurrence time of modal wave is about 0.8 seconds before surge. At 0.5 seconds before surge, the modal wave amplitude value of all measuring points at the same stage are averaged to obtain the average value of each stage, as shown in Figure 11. Regardless of the IGV angle on or off, the amplitude of the modal wave increases gradually from first stage to final stage along the air flow direction. The modal amplitude value increases from 298.8 Pa in front of the first stage rotor to 1011.5 Pa at the outlet of the compressor when IGV is on, and from 206.7 Pa to 617.3 Pa when IGV is off. Amplitude of modal wave is higher when IGV is on compared with that when IGV is off. Moreover, from the time domain diagram, it can be seen that the closer to the surge time, the higher the amplitude of modal wave.

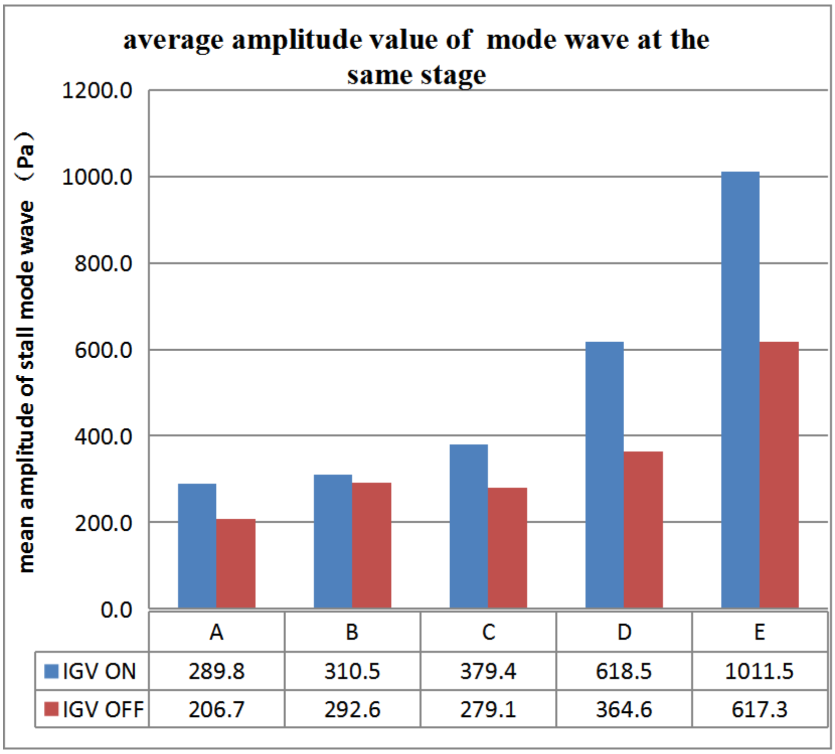
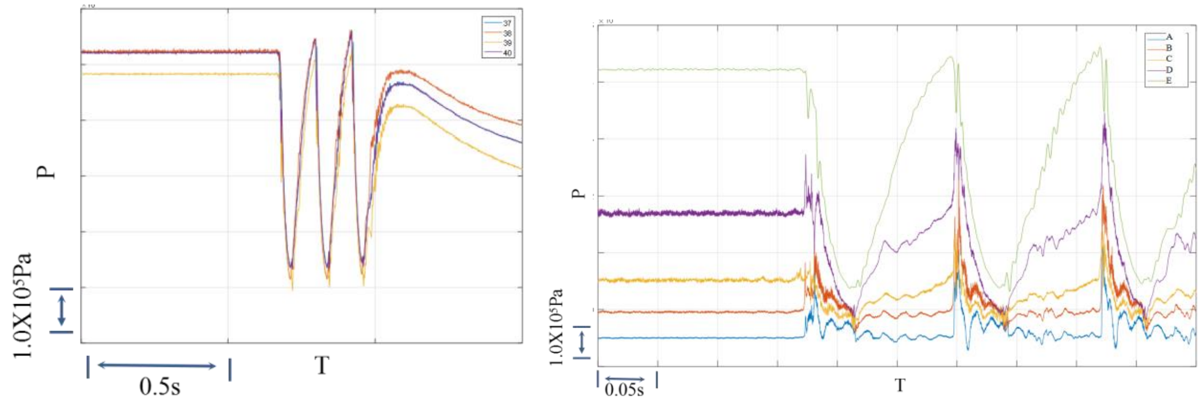


Figure 11 – Average amplitude of stall mode wave of each stage at 0.8 corrected rotational speed at 0.5s before surge.

4.5 Modal Wave Disappears at 1.0 Speed

The dynamic pressure during the process of surge at 1.0 corrected rotational speed is shown in Figure 12. Different from 0.8 corrected rotational speed, there is basically no modal wave. Take the time period when the pressure value suddenly decreases as the half cycle of surge, the axial propagation frequency of surge air flow is about 14 Hz at 1.0 corrected rotational speed, which is similar to 12 Hz at 0.8 speed.

According to figure 12, it is judged that the first stage of surge is the fourth or fifth stage rotor. during the process of surge, the static pressure before R4 increases first and then decrease, while the static pressure at the outlet decreases first and then increases. Therefore, it is judged that the first surge stage does not lie in from R1 to R3.

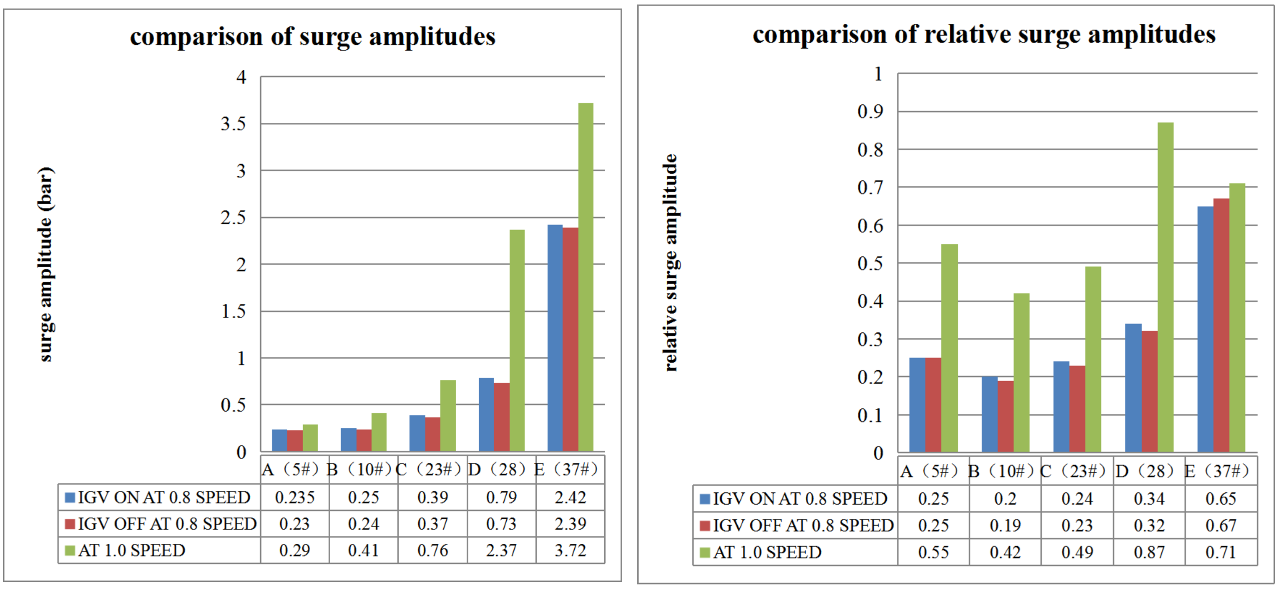


(a) Outlet Pressure (b) Pressure at each stage

Figure 12 – Time domain signal characteristics at 1.0 corrected rotational speed during the process of surge.

5. Surge Amplitude Analysis

The surge amplitude and relative surge amplitude at each stage at 0.8 and 1.0 corrected rotational speeds are shown in Figure 13. The surge amplitude at 1.0 speed is higher than that at 0.8 speed, especially before R4 and at the outlet. At 0.8 speed, the surge amplitude before the same stage basically remains unchanged, regardless of whether the IGV angle is on or off. The relative surge amplitude increases gradually from the first stage to the outlet. At 1.0 speed, the relative surge amplitude also shows an increasing trend, but the amplitude before R4 is higher than that at the outlet.



	A（5#）	B（10#）	C（23#）	D（28）	E（37#）
IGV ON AT 0.8 SPEED	0.235	0.25	0.39	0.79	2.42
IGV OFF AT 0.8 SPEED	0.23	0.24	0.37	0.73	2.39
AT 1.0 SPEED	0.29	0.41	0.76	2.37	3.72

	A（5#）	B（10#）	C（23#）	D（28）	E（37#）
IGV ON AT 0.8 SPEED	0.25	0.2	0.24	0.34	0.65
IGV OFF AT 0.8 SPEED	0.25	0.19	0.23	0.32	0.67
AT 1.0 SPEED	0.55	0.42	0.49	0.87	0.71

Figure 13 – Comparison of absolute/ relative surge amplitudes.

6. Conclusions

In this paper, the pressure signal during the process of surge is analyzed in time domain and frequency domain, mainly focusing on the characteristics of modal wave before surge, the frequency and amplitude of surge, and physical meaning of frequency signal in frequency domain.

In order to simulate the instability state of turbofan engine, and compare the surge characteristics at different speeds and IGV/S1 angles，the conditions of IGV angle on/off relative to the design angle at 0.8 corrected rotational speed, as well as 1.0 corrected rotational speed are selected to be investigated. The main conclusions are as follows:

a) Under the condition of IGV on / off angle at 0.8 speed, the modal wave appears about 0.8 s before surge, and its frequency is about 20 Hz; The closer to surge, the greater the amplitude of stall mode wave. At 1.0 speed, there is no modal wave before surge and no obvious cusp wave characteristics.

In the direction of air flow, the amplitude of modal wave basically increases from front to back, and the amplitude of modal wave under the condition of IGV angle on is higher than that of IGV angle off; At 0.5 s before surge, the amplitude of modal wave increases from 289.8 Pa in front of the first stage rotor to 1011.5 Pa at the outlet of the compressor under the condition of IGV angle on. Under the condition of IGV angle off, the amplitude of modal wave increases from 206.7 Pa in front of the first stage rotor to 617.3 Pa at the outlet of the compressor.
b) From the front to the back of the compressor, the surge amplitude increases gradually, and the axial propagation frequency of surge air flow is about 12-14 Hz; In front of each stage rotor, the surge amplitude of 1.0 speed is higher than 0.8 speed, especially in front of the fourth stage rotor and at the outlet of the compressor. At 0.8 speed, the surge amplitude before the same stage of compressor basically remains unchanged, regardless of whether the IGV angle is on or off.
c) There is blade passing frequency and its higher-order frequency in the dynamic pressure signal in front of each stage of rotor, which represents the action of a single blade on the fluid; The interaction between rotor and rotor is characterized by the frequency of rotating frequency multiplied by the difference in the number of rotor blades; The amplitude of the former frequency is significantly higher than that of the latter, which indicates that the blade passing frequency is dominant.

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8. Copyright Statement

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