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Compressor Rig Test Facility in Shanghai Jiao Tong University

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ABSTRACT

From 2015, Turbofan Technology and Engineering Institute of Shanghai Jiao Tong University has made great efforts to set up a compressor rig test facility. Since this time, the facility has been used extensively. All systems for control, surveillance and data acquisition have been developed in-house, and it has been possible to make continuous improvements over the years. Also, the mechanical performance has been perfected. After several compressor tests of operation, the facility is now running at its optimum with a high degree of availability. Main characteristics of the facility are as follow. The maximum drive power is 4.3 MW, and the maximum mass flow is 50 kg/s. The inlet pressure can be controlled by inlet valve. The exhaust pressure is controlled by pneumatic butterfly valve, and 600 kPa absolute pressure maximum can be reached. The maximum exhaust temperature can reach 260 °C. Meantime, effective noise reduction to the control room and to the surrounding environment has been done. The inlet system and test object are set up in aerodynamic anechoic chamber, which is 20 m long, 18 m wide and 11 m tall. For the motor and gear box, they are insulated in a power room, and the wall of the power room is paved with sound attenuation material. The main part of the test facility is the control system and data acquisition system. A state-of-the-art control system with several safety features and data logging for later retrieval is set up. The stat-of-the-art data acquisition and evaluation system are based on NI data acquisition hardware. In the data acquisition and evaluation system, a stall alarm model and blade flutter detection model are integrated in the system. Now, this facility has been used for validating the booster design of ACAE. In this paper, the design of the facility, the control system and data acquisition and some test results are introduced in detailed.

INTRODUCTION

High-performance aero engines are an important indicator of a country's comprehensive industrial level. The axial compressor, which is used to enhance the pressure ratio and efficiency, is one of the most important components of aero engines. After the design of each compressor, a performance test must be carried out on compressor rig test facilities, in order to get the characteristic curve of the compressor. Particularly, to prevent the occurrence of stall and surge in compressor's operation, the surge boundary and the suitable functional margin for robustness are supposed to be measured carefully. Meantime, not only the performance and the characteristic curve of the compressor, but also the dynamic data during stall or surge is of high interest for designers and researchers. Therefore, in testing the compressor is brought to stall on the rig test facility, which is always a risky but necessary endeavor, in order to get indispensable data. Figure 1 shows a typical non-dimensional characteristic curve of a compressor.

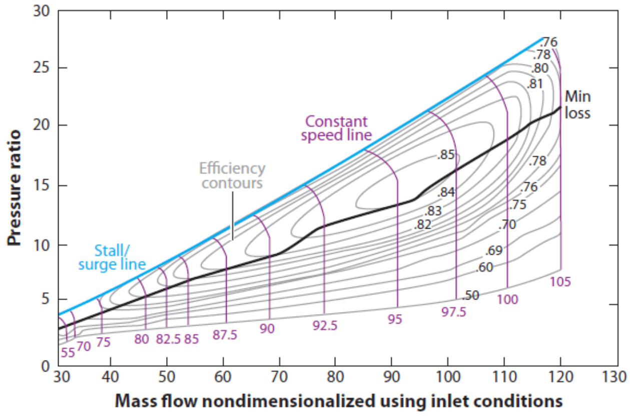

Figure 1 Typical non-dimensional characteristic curve of a compressor [1]

Since the last century, several compressor rig test facilities have been established. Among them, the Rotor 35~38 are the four most well-known transonic axial compressor rotor rig test facilities, and were built by NASA in 1970s. These four single-stage compressor test rigs were in conjunction with the advanced compressor at that time, and were used to study the effects of different pressure ratios and aspect ratios on the overall performance of axial compressors. Figure 2 gives the principal diagram of the rig test facility.

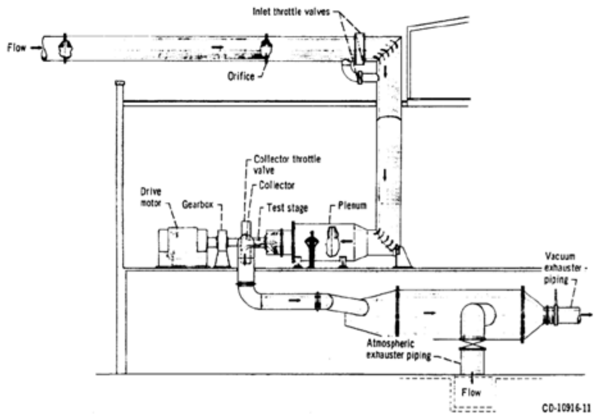

Figure 2 Principal diagram of the Rotor compressor rig test facility [2]

Another widely studied a single-stage transonic compressor rig is Darmstadt Rotor-1, which has been operated since the early 1990s at Technische Universität Darmstadt. The design represents a typical front-stage of a commercial turbofan high-pressure compressor [3]. Ambient air is led through a settling chamber, and a calibrated intake bell-mouth into the compressor stage. The rotor is driven by an 800 kW DC-drive. The principal diagram of DR-1 is shown in Figure 3.

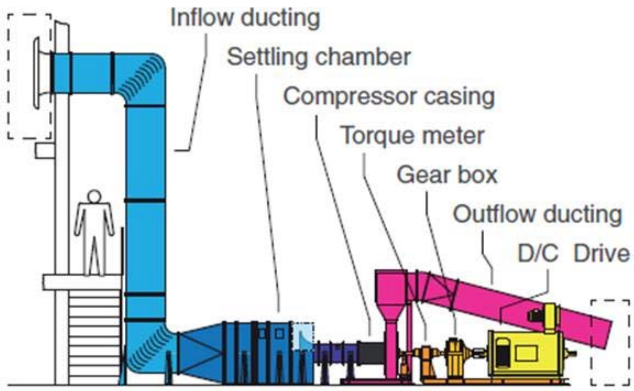

Figure 3 Principal diagram of the DR-1 compressor rig test facility [3]

In the Key Laboratory of Aeroengine in Beihang University, a low-speed axial compressor rig test facility has been put into use and it's designed for a 1.5 stage axial compressor [4]. The principal diagram of the test rig in Beihang University is shown in Figure 4.

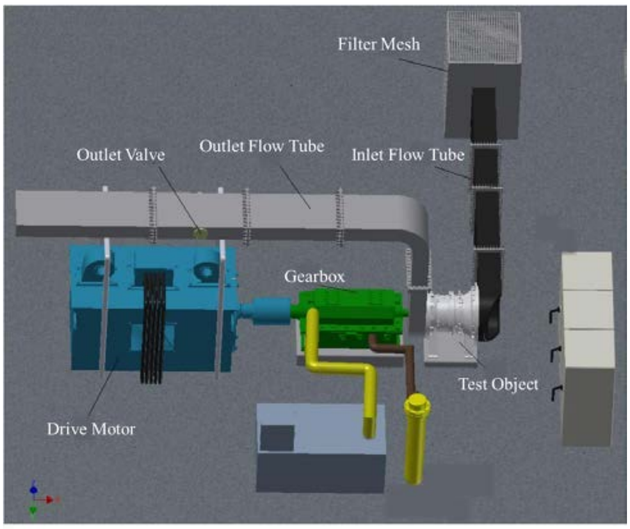

Figure 4 The compressor rig in Beihang University

In addition, Volvo Aero Corporation has also used the same type compressor rig test facility as in Turbofan Technology and Engineering Institute of Shanghai Jiao Tong University, in the interest of getting access to performance and many other important data, such as vibration, stall and surge, of different axial compressors [5]-[6].

THE DESIGN OF THE FACILITY

From 2015, Turbofan Technology and Engineering Institute of Shanghai Jiao Tong University has made great efforts to set up a compressor rig test facility. Since this time, the facility has been used extensively. Figure 5 gives the structure schematic diagram of the rig test facility.

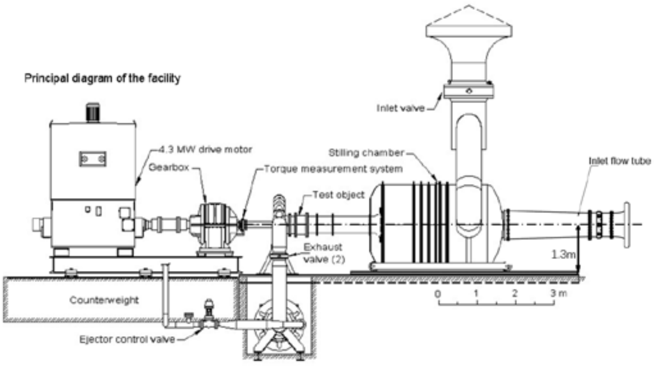

Figure 5 Principal diagram of the compressor rig test facility

The maximum drive power of the compressor rig test facility is 4.3 MW, and driven by an AC motor through a gear box, the maximum mass flow is 50 kg/s.

The test facility is equipped with two inlet flow tube, and one is placed horizontally and the other vertically. Only one inlet tube is put into use in test. The inlet pressure can be controlled by an inlet valve, which is placed over the stilling chamber. The ambient air flow is led through a calibrated intake bell-mouth, and is rectified by three wire meshes and a honeycomb rectifier in the stilling chamber, in which large dust and particles are prevented from entering the tube. The total temperature, the total pressure, and the static pressure are measured in the inlet flow tube, downstream of the stilling chamber. Mass flow is calculated using the inlet stagnation conditions, inlet duct static pressure and cross section area. A calibration function compensating for inlet duct total pressure loss is applied in the calculation.

The air flow enters the test object through the straight inlet section. Then the airflow is boosted and heated in the test object and discharged finally into the underground pipeline through the exhaust volute. The exhaust pressure is controlled by pneumatic butterfly valve, and 600 kPa absolute pressure maximum can be reached. Meantime, the maximum exhaust temperature can reach 260 °C. By adjusting the opening of the butterfly valve, the flow rate is accurately controlled by the stepping motor, and the compressor can be brought to stall or surge. A relief valve is also connected in parallel with the pneumatic butterfly valve, and it is used to relieve the pressure and increase the flow rate when surge or emergency occurs. An ejector augmentation in the exhaust makes it possible to run at sub atmospheric conditions down to 20 kPa absolute pressure. Main characteristics data of the facility are shown in Table 1.

Table 1 Main characteristics data of the compressor rig test facility

maximum drive power	4.3 MW
maximum mass flow	50 kg/s
maximum exhaust absolute pressure	600 kPa
maximum exhaust temperature	260 ℃

In addition, Effective noise reduction to the control room and to the surrounding environment been done. The inlet system and test object are set up in aerodynamic anechoic chamber, which is 20 m long, 18 m wide and 11 m tall. For the motor and gear box, they are insulated in a power room, and the wall of the power room is paved with sound attenuation material. The photo of the compressor rig test facility is shown in Figure 6.

Figure 6 The photo of the compressor rig test facility

Compared to the compressor test facility used in Volvo Corporation, we have made some modification to this facility. On the one hand, one more outlet flow tube has been implemented downstream of the volute, so that now there are three outlet flow tube in all, which significantly promotes the flow capacity, and correspondingly one more outlet valve is also mounted on the third outlet flow tube. On the other hand, two responsive ball valves with larger flow areas have been mounted in place of the original relief valves, as the original ones are proven to lack enough capability to relive the compressor from surge.

THE SYSTEM FOR CONTROL AND DATA AQUISITION

The main part of the test facility is the control system and data acquisition system. All systems for control, surveillance and data acquisition have been developed in-house on this rig test facility in SJTU, and it has been possible to make continuous improvements over the years. Through this system for control and data acquisition, the test facility is under the control and monitoring of the operators in the control room remotely. Figure 7 shows the principal diagram of all the systems.

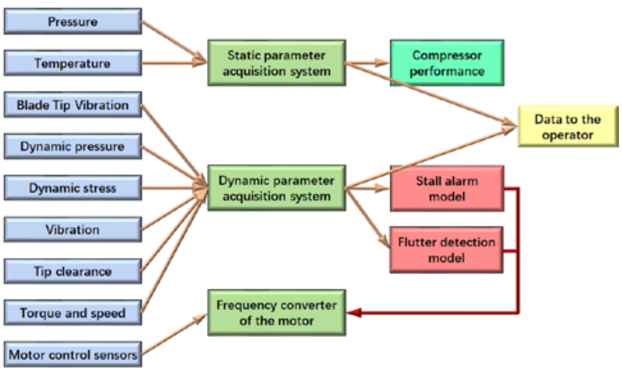

Figure 7 Principal diagram of all the systems

CONTROL SYSTEM

The control system, including the control and surveillance of the motor and the gear box, is an integral part of the test facility.

Motor speed regulation of this test facility is controlled by an ABB frequency converter. The frequency converter makes it possible to run the motor with a frequency in the range from 15 Hz to 60 Hz. This corresponds to a motor speed of 440-1790 rpm. The frequency converter also requires 400 V/3 phase.

To monitor the vibration of the motor and the gearbox, a Laser Doppler Vibrometer is applied to the measurement of the shaft vibration. Meanwhile, the temperature measurement system has been added into the whole system as well, in order to monitor the performance of the motor and the gearbox.

The control system is connected to the computer in the monitor room remotely, and it can monitor real-time signals of motor, gear box, water cooling cycle, oil lubrication, etc. Specially, on the operating interface of the control system, the vibration and the temperature of the motor and the gear box are shown, and an alarm threshold is set for these four values. The operating interface of the control system is shown in Figure 8.

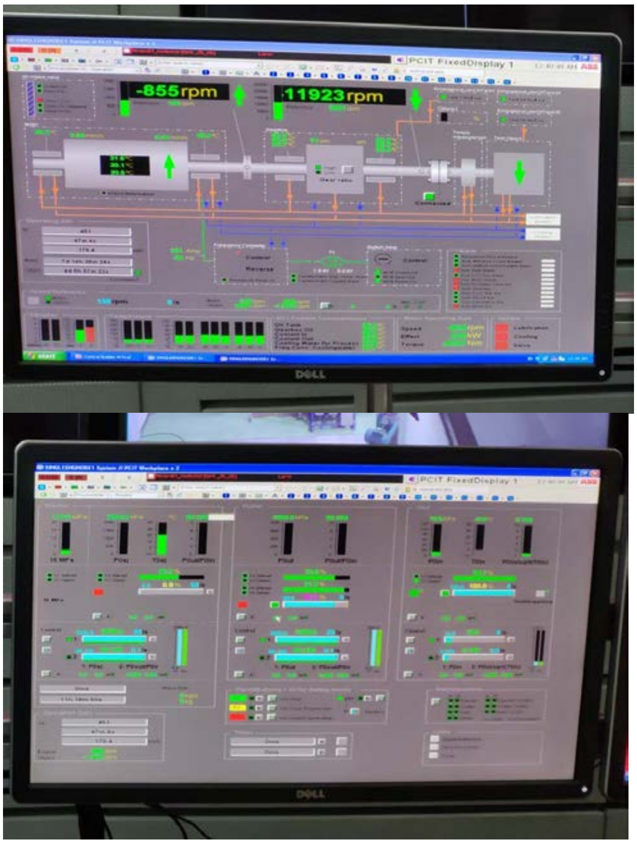

Figure 8 Operating Interface of the control system

DATA ACQUISITION SYSTEM

The data acquisition system includes two parts: one is for the static parameter, running at a lower sampling rate; the other is for the dynamic parameter, and running at a higher sampling rate of more than 10k Hz. All the data are obtained through the NI Multichannel Digital Acquisition System PXIe-1085, which runs at least 200 channels, 24 bits and has a transmission rate of 204.8 kS/s. Through a set of LabVIEW program developed in-house these data are preliminarily processed and shown on the computer in the monitor room remotely.

The static parameter acquisition system mainly measures the total temperature, total pressure, static pressure, air flow angle and other physical quantities of each section under different working conditions of the compressor, and hence the flow rate, pressure ratio, efficiency and other parameters are calculated. To acquire the pressure data, a great many pitot tubes, total pressure combs and rakes etc. in conjunction with pressure scanning valves PSI9116 containing more than 500 channels, are put into use. As for the total temperature measurement, total temperature probes and thermocouples of N-type, T-type and K-type, more than 128 channels in total, are mounted in the case. Thus, the compressor characteristics curve is obtained through the LabVIEW program and drawn on the monitor screen. The interface of the static parameter acquisition program is shown in Figure 9.

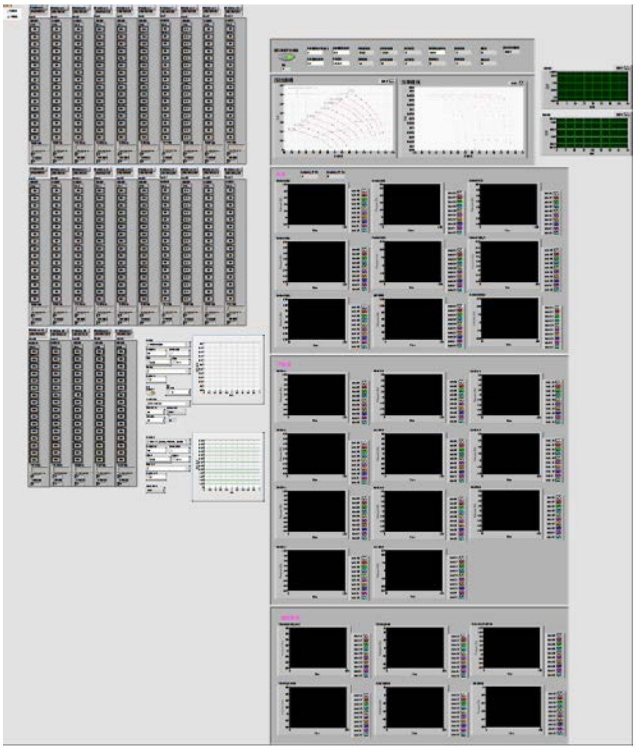

Figure 9 Interface of the static parameter acquisition program

The dynamic parameter acquisition system constantly measures the dynamic pressure, dynamic stress, blade vibration, tip clearance, torque and rotating speed of compressor shaft in real time, to determine if the compressor is brought to stall or other emergencies happen. The sensors related are listed as follows: Kulite pressure transducers for the dynamic pressure, strain gauges for the dynamic stress, accelerometers for the vibration, eddy current sensors for the tip clearance, and torque meter for the torque and rotating speed. Written by LabVIEW, the interface of the dynamic parameter acquisition program is shown in Figure 10.

Figure 10 Interface of the dynamic parameter acquisition program

As the transition process of compressors from stable to unstable flow condition is the main focus of numerous scientific endeavours, various criteria for prestall inception has been promoted. Many technologies based on the mathematical characteristics of the data, such as the spectrum features or the irregularity of the data, in order to determine and predict the occurrence of stall and surge, have been applied into experiments [9][10]. Due to the complexity of existing methods, a new stall alarm model is integrated in the system, to determine the happening of stall or surge automatically by the computer. To achieve this, a new method based on the variance on the time domain is applied in this model. Figure 11 illustrates the procedure of how this method works.

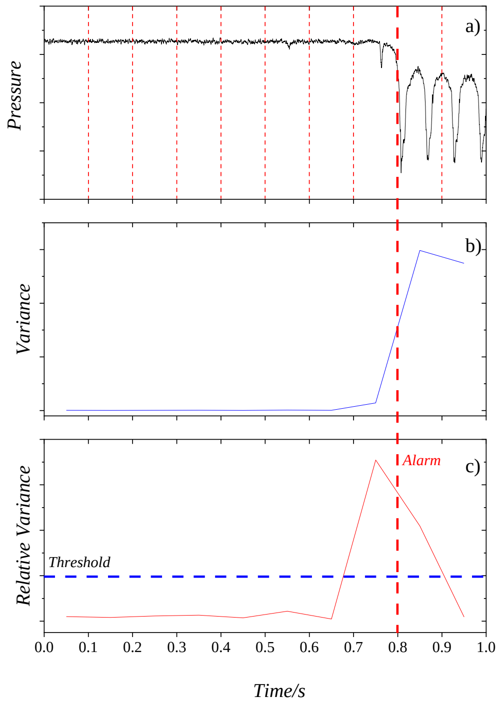

Figure 11 The procedure of stall alarm model; a): A pressure signature divided by different windows, measured by a Kulite transducer placed between the section; b): The variance of the data in different windows; c): The variance ratio of two adjacent windows.

The principle of time-domain variance method is to add rectangular windows to the signals in each sampling period, and compare the variance of data in each window. The variance Vi of the data in window i can be described as:

$$V_i = \frac{1}{N-1}\sum_{j=1}^{N}\left(p_{i,j} - \overline{p}_i\right)^2 \qquad (1)$$

Here, the N denotes the sample number within one window. Calculate the variance ratio of two adjacent windows, which is also considered as the relative variance, and it is defined as followed:

$$V_i^r = \frac{V_i}{V_{i-1}} = \frac{\sum_{j=1}^{N}\left(p_{i,j} - \overline{p}_i\right)^2}{\sum_{j=1}^{N}\left(p_{i-1,j} - \overline{p}_{i-1}\right)^2} \qquad (2)$$

If the variance ratio of two adjacent windows exceeds a certain threshold, the alarm of surge will be triggered. As a criterion for the determination of the surge, the threshold, which is determined by experience, characterizes a relative value, but also reflects the fluctuation of the pressure signature. Obviously, within a certain range, the shorter the length of the window is, the more accurate the determination will be, but the more computing resources will be occupied as well. As soon as a surge is identified by the stall alarm model, it sends a signal to the relieve valve and the frequency converter of the motor so that the compressor can withdraw from surge or stall. During experiments, the occurrence of stall or surge is recognized automatically by the stall alarm model within one second. The result of this model is shown in Figure 11 c), in which the threshold is indicated as blue, and the red line indicates when the stall alarm is supposed to be triggered. Obviously, the mechanism of this stall alert model lies in that the variance of the pressure signature will have a “step” as a surge occurs, seen in Figure 11 b).

In consideration that each compressor must undergo vibration surveys to establish that the vibration characteristics are acceptable throughout the flight envelope, a flutter detection model is set up in the data acquisition system. Through the algorithm of Blade Tip Timing (BTT), the vibration parameters of each blade are calculated from the data of the casing mounted probes. The occurrence of flutter phenomenon is determined and alarmed when every blade shows the same vibrational amplitude and frequency, and in the meantime, all blades form a particular nodal diameter pattern. Figure 12 shows the results of BTT on a stall condition. When the compressor stalled, the vibration of the blades is violent.

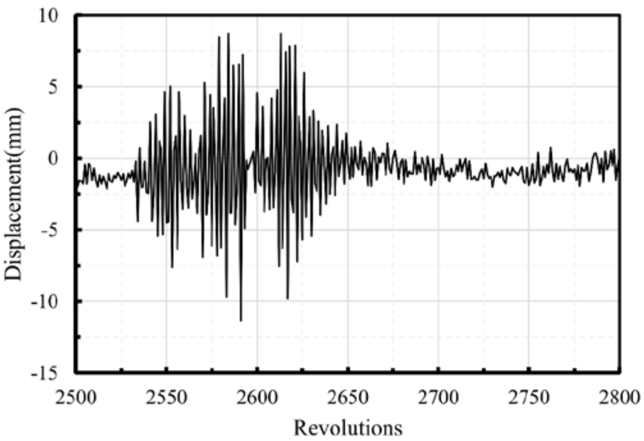

Figure 12 The result of the BTT on stall condition

CONCLUSIONS

A compressor rig test facility has been established in Turbofan Technology and Engineering Institute of Shanghai Jiao Tong University. All systems for control, surveillance and data acquisition have been developed in-house, and it has been possible to make continuous improvements over the years. After several compressor tests of operation, the facility is now running at its optimum with a high degree of availability. The maximum drive power of the test facility is 4.3 MW, and the maximum mass flow is 50 kg/s. The inlet pressure can be controlled by inlet valve. The exhaust pressure is controlled by pneumatic butterfly valve, and 600 kPa absolute pressure maximum can be reached. Meantime, effective noise reduction to the control room and to the surrounding environment been done. A state-of-the-art control system and data acquisition system is set up, and with the stall alarm model and the flutter detection model integrated, the two systems have many safety features. Now this test rig has been used for several projects, and the results show that this test rig facility works well.

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