CALIFORNIA INSTITUTE OF TECHNOLOGY
Department of Mechanical Engineering

ME 96
Turbomachine Experiment

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1 Introduction

By *turbomachine* we mean a fan, pump, compressor, or turbine that changes the energy level of a flowing fluid by means of momentum exchange. Sometimes the term *rotordynamic machines* is used for this class of machines to distinguish them from positive displacement devices. Turbomachines are second only to electric motors in their number and are wide-spread in practically all industries, ranging in power levels from a few watts to more than 100 MW. Because of the requirements of aircraft jet propulsion, new power plants (both steam and gas turbine) and rocket propulsion research, development continues actively in this field today.

The present experimental turbomachine is an axial-flow fan powered by a three phase induction motor. The fan (details in the appendix) is used on the MD-11 aircraft to cool electronic equipment in the cockpit. The fan consists of a *rotor* which receives axial non-swirling air from the inlet tube; the rotor imparts an angular velocity V_θ to this oncoming flow, which is subsequently straightened out to be purely axial in a stationary row of vanes termed a *stator*. These stator vanes also serve as heat-transfer surfaces needed to cool the drive motor that is mounted internally inside the hub of the stator. The rotor consists of a cylindrical hub structure on which equally spaced airfoil-shaped blades are mounted. The centroids of each radial blade section are aligned on a radial line (this is the stack line) and are set at various angles to the tangential direction to provide the requisite pressure rise (or enthalpy rise) of each radial section of the rotor.

The present facility inculdes a motor controller that provides a variable voltage and frequency drive (up to 400 Hz) for the compressor motor, permitting operation up to a synchronous speed of 12,000 rpm. The motor is a four pole, 3 phase, Y wound induction motor. The synchronous frequency in revolutions per minute (rpm) of the rotating field is given by:

$$\text{rpm} = \left(\frac{f(cycles/s)}{(P/2)}\right) 60\frac{s}{min}$$

where f is the frequency in Hertz of the supply (read from LED readout on wall–mounted motor controller) and P is the number of poles of the motor. Directions for operating the supply are given in the Appendix. An induction motor must operate at speed slightly less than the synchronous speed; the difference or *slip* is about 3% in the present case. For the purpose of the experiment we will assume the fan operates at 97% of the synchronous speed since we have no independent measurement of actual rotor speed.

A schematic of the apparatus is shown in the Appendix. It consists of a semi-elliptical inlet nozzle, upstream and downstream static pressure ports, the fan, and a manually adjustable throttle plate. The inlet nozzle provides a smooth inlet flow, the pressure ports enable determination of inlet flow and fan compression, and the throttle plate provides a means to adjust the load on the fan .This test apparatus is built to the AMCA 210-85 American National Standard Laboratory Methods of Testing Fans for Rating.[1]

2 Background

The energy level change brought about by a turbomachine is expressed as the total enthalpy rise (for a fan, compressor or pump) per unit mass of the fluid. In most turbomachines, this work is accomplished by momentum exchange with the rotor and the total enthalpy rise is given by a famous formula, the *Euler Turbine Equation*

$$\Delta h_t = \Delta(UV_\theta) \tag{1}$$

where Δh_t is the enthalpy increase in J/kg, U is the rotative speed of the impeller tip, i.e. $r\omega$ at a particular radius r (ω is the angular velocity), and V_θ is the component of the absolute velocity in the direction of U. For an isentropic, incompressible flow,

$$\Delta h_t = \frac{\Delta p_t}{\rho}$$

where Δp_t is the total pressure increase.

Closely associated with the Euler equation is the notion of geometric flow similarity: the velocity vector triangle formed by the tip speed U, absolute velocity V, and relative velocity W (see [2], fig. 12.18 for example) remains similar when flow rate and speed are changed. Then it follows that

$$\begin{aligned} V_\theta &\sim U \\ Q &\sim UA_m \end{aligned}$$

where A_m is the meridional cross section of the discharge flow. What follows, then are

$$\begin{aligned} \Delta p_t &\sim \rho D^2 \omega^2 \\ Q &\sim D^3 \omega \\ \text{Power} &\sim \rho D^5 \omega^3 \end{aligned}$$

where D is a reference length dimension such as the diameter of the pipe containing the compressor flow. By means of these relations, the flow rate, pressure rise, and power can be scaled to a standard reference speed and density. The scaling of these relations implies that the effect of Reynolds number is weak; this is approximately so if the Reynolds number ($Re = WL/\nu$) based on blade chord length L, realtive flow velocity W, and kinematic viscosity of air is about 10^5.

3 Experiment

There are several aims of this experiment: (1) to gain some knowledge of the typical behavior of a heavily loaded axial fan as a function of flow and operating speed and to relate this behavior to basic fluid mechanics; (2) to learn how to measure fan performance; (3) to learn basic similarity laws of fan performance; and (4) to make some qualitative dynamic measurements of flow phenomena in *stall* — a subject of much current turbomachine research.

3.1 Instrumentation

This experiment is equiped with a water–equivalent manometer, two differential pressure transducers, and a linear gauge. The manometer is used to calibrate the pressure transducers that are in turn used to measure the pressure drop across the inlet nozzle and the pressure rise across the fan. The pressure transducers are also capable of resolving time–varying changes in the static pressures. The linear gauge is used to measure the throttle opening.

3.2 Experimental Variables

The following are the variables which the operators of this system are free to adjust:

- Throttle setting — The throttle plate is adjusted by rotating the plate on the threaded lead screw. Throttle displacements can be measured using the provided linear gauge. to adjust the operating point of the fan. *Always* start the fan with the throttle plate at least two inches open. The fan should not be operated at shut-off conditions (i.e. throttle closed) for more than **five seconds maximum** since flow through the fan is used to cool it; operation at shut–off can lead to thermal overload and damage to the fan.

- Fan speed — The maximum fan speed is about 12,000 rpm (400 Hz drive frequency). For the purpose of this experiment the maximum spedd has been limited to 10,500 rpm (350 Hz drive frequency). Operation at frequencies above about 200 Hz is very noisy and the use of provided ear protection is encouraged. The minimum frequency is limited by the ability to measure the pressure differences with the provided pressure transducers.

The directions for starting the fan and adjusting the speed are given in the Appendix under “Operating the System.”

3.3 Inlet Flow

The flow rate entering the compressor is determined by measuring the pressure drop across the inlet nozzle. From Bernoulli’s equation:

$$\frac{\rho({V_2}^2 - {V_1}^2)}{2} = p_1 - p_2, \tag{2}$$

Where V represents the flow velocity, p represents the static pressure, and ρ represents the density. The subscripts, 1 and 2, represent the conditions before and after the nozzle respectively. Since condition 1 is the ambient air of the laboratory, V_1 is zero; therefore, the velocity downstream of the nozzle (upstream of the fan) is determined by the pressure difference across the nozzle:

$$V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{3}$$

So, the theoretical volumetric flow rate Q_{ideal}, assuming uniform flow across the pipe, is:

$$Q_{ideal} = AV_2 = A\sqrt{\frac{2(p_1 - p_2)}{\rho}}, \tag{4}$$

where A is the cross-sectional area of the pipe.

However, the real rate is actually less than this theoretical value due to boundary–layer effects in the nozzle and other fluid losses. To accommodate the difference between the actual and the ideal flow rates, it is customary to define a *discharge coefficient*:

$$c_d = \frac{Q_{actual}}{Q_{ideal}} \tag{5}$$

The value of the discharge coefficient is determined by making measurements of the actual velocity profile across the pipe just downstream of the nozzle. This was done before for a very similar facility with the same inlet nozzle and 0.98 was the value found for the discharge coefficient. Therefore, the actual flow rate for this facility is approximately:

$$Q_{actual} = c_d A\sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{6}$$

So, at each throttle position, the flow rate through the compressor can be determined from the measurement of the pressure drop across the inlet nozzle.

3.4 Fan Performance Curve

Incompressible turbomachines, fans and pumps, are tested at constant speed and fluid density; the *performance curve* is a plot of total pressure rise and input power vs. flow rate all at constant rotative speed and density. We are not able to measure the power in the present experiment. In American industrial practice the pressure rise is given in inches of water and the flow rate in cubic feet/minute and the pressure rise and power are corrected to a standard density for air (0.075 lbm/ft^3 or 1.205 kg/m^3) corresponding to 0.1013 MPa pressure and 293K temperature. In this experiment we will use SI units: pressure rise in Pascals and flow rate in cubic meters/second.

The performance curve for the present experiment is to be measured for three different rotative speeds. At each speed, make measurements at a sufficient number of flow rates to map the performance curve; start at a wide–open throttle setting and closing the throttle toward the shut off then increase the throttle opening until the fan returns to normal operation. Use the inlet nozzle pressure difference to measure the flow rate. As the throttle plate is closed, the fan will eventually reach a point at which the head rise abruptly and drastically falls. This is a result of rotating stall, an instability in compressors. The stall point should be determined for decreasing flow rates, and the bottom of the stall region should be found as well as shut–off point. As the throttle plate is reopened, the compressor will recover from stall (*stall–recovery point*), signaled by a rapid pressure rise. It is useful to keep track of the throttle opening to enable careful mapping of the stall point and the stall–recovery point.

3.5 Unsteady Behavior

At some operating conditions the performance of the fan becomes unsteady and the measured pressures will oscillate. In particular, at the peak of the performance curve (just before stall) and in deep stall (the bottom). These pressure oscillations are indicative of a phenomenon known as rotating stall.

The onset of this condition is best visualized in the blade-fixed frame of reference. As the throttle opening is reduced, the flow rate through the compressor is decreased, so the axial velocity v is reduced. However, the tip speed of the compressor blades remains constant, since the compressor is running at constant speed. Therefore, the angle of incidence of the air flow with respect to the blades is reduced translating to an increase in the angle of attack of the blades. At larger angles of attack the blades will stall (flow will separate from the upper side of the airfoil shape) just as an aircraft wing will stall at large angles of attack. When a blade stalls, the flow that normally passes through the now-stalled region is diverted to the neighboring blades. The angle of attack of the preceding blade then falls and the angle of attack of the following blade rises. This decreases the tendency of the preceding blade to stall while increasing the tendency of the following blade to stall. Therefore, in the blade-fixed frame of reference, the stalled region of the blade row (stall cell) appears to move in the opposite direction of the compressor rotation. In the lab-fixed frame of reference the stall cell rotates in the same direction as the compressor, but at a lower speed. As the stall cell rotates around the inlet tube it creates an oscillation in the pressures measured at the pressure ports. From a measurement of the oscillation frequency of the pressure, it is possible to determine the speed of the rotating stall cell.

4 Measurements

These are the measurements that are to be made on the apparatus:

- Air density — For the purpose of this experiment we may assume the air to be a perfect dry gas with a gas constant of 287 J/kgK (in practice we measure the absolute humidity and so determine the effect of water vapor on the density). The local barometric pressure and temperature are measured on the wall-mounted barometer to calculate the density.

  The pressure rise across the fan is small compared to the absolute pressure (less than 2 percent) so that the flow may be considered as effectively incompressible. The "best" effective density is the average of the inlet and discharge densities. For the purpose of this experiment, the inlet stagnation density may be used as the reference density.

- Calibrate the Differential Pressure Transducers — Both pressure transducers should be calibrated using the water-equivalent differential manometer. A lab View VI (Virtual Instrument) is provided on the data acquisition system to facilitate this process. The throttle plate is set to a small opening (about 1cm), the number of desired points for the calibration is entered into the appropriate field on the VI control panel, and the color code of the transducer to be calibrated is selected. Upon running the VI, the user will be prompted to enter the pressure reading from the manometer into the appropriate field and click the continue button. The compressor speed will be ramped under computer control and the user will be prompted for pressure readings until the desired number of points is acquired. The VI will determine the best fit line to the data and prompt the user for a pressure that encompasses your expected measurements.

- Performance Curves — Measure performance curves of the compressor at three operating speeds. Be sure to carefully resolve the stall onset, stall bottom, and stall-recovery points. A Lab View program may be available to aid you in this process.

- Repeatability — For one of the compressor speeds used above, repeat the performance curve measurements two more times to assess the repeatability of the measurements. Base this repeatability on how well you can reposition the throttle plate. It is not necessary to repeat every point on the original performance curve, choose about 5 points that are distributed throughout various portions of the performance curve.

- Unsteady Behavior — During the measurement of one of the performance curves, record time series of oscillatory pressure near stall onset and in the bottom of stall to determine the frequency content of these signals. A Lab View VI may be available to aid you in this measurement. If not, temporary use of the oscilloscope to determine the frequency content is recommended. Look at both the frequency and amplitude.

- Speed Curves (Optional) — If time and group interest permits, modify a copy of the LabView VI used for calibration to make measurements of performance along a speed curve. At a fixed throttle setting (you can repeat for several throttle settings if you like), step through a range of compressor speeds and measure the differential pressure. Be sure to wait long enough at each speed setting before measuring the pressures. Take note of any apparent stall phenomena and the throttle opening(s) used ... it may be necessary to take longer time averages of pressure under oscillating conditions to get a measure of mean performance. This exercise is intended to give you an opportunity to explore the use of LabView in a data acquisition and control situation. If you are unable to achieve measured results in a reasonable time, don't fret, view this as an opportunity to learn more about LabView remember this is optional and it is up to you whether you include any of this in your lab report. If you do include speed curves in your report, print out your LabView VI for the appendix.

5 Report

Your results should include:

1. For each of the three speeds, plot Δp vs. Q; indicate by error bars the uncertainty of the measurements use estimates of measurement uncertainties of the instrumentation along with results from your repeatability measurements.
2. Using the scaling laws outlined in Section 2, non–dimensionalize the performance curves plotted above to test the similarity of the compressor performance.
3. Carefully identify the stall, stall-bottom, and stall–recovery points on your performance curves.
4. Speed Curves if you decide to measure and include them. Identify points where stall or rotating stall were observed.

Your discussion should include:

1. Describe the performance curves noting any features of special interest.
2. Discuss the results of the scaling calculations.
3. The design flow rate for the fan is 0.566 m^3/s (1200 ft^3/min) when the exciting frequency is 400 Hz. Predict the performance of this compressor, based on a similarity discussion, using your acquired data.
4. If you decided to measure and include speed curves, describe these curves and note any features of special interest.

5. *(optional)* The action of the rotor of the fan is that of a row or cascade of airfoils and the primary feature of interest for an airfoil is the lift coefficient, c_l . With the aid of Eq. 13.8 (see [2]), make an estimate of the lift coefficient c_l for the design condition for the tip radius.

References

[1] AMCA 210-85, *American National Standard Laboratory Methods of Testing Fans for Rating*, the Am. Soc. of Heating, Refrigeration Engineering and the Air Movement and Control Assoc., Inc., 30 W. University Dr., Arlington Heights, IL 60074, 1985.

[2] R. Sabersky, A. Acosta, and E. Hauptmann, *Fluid Flow*, Chapters 12 and 13.

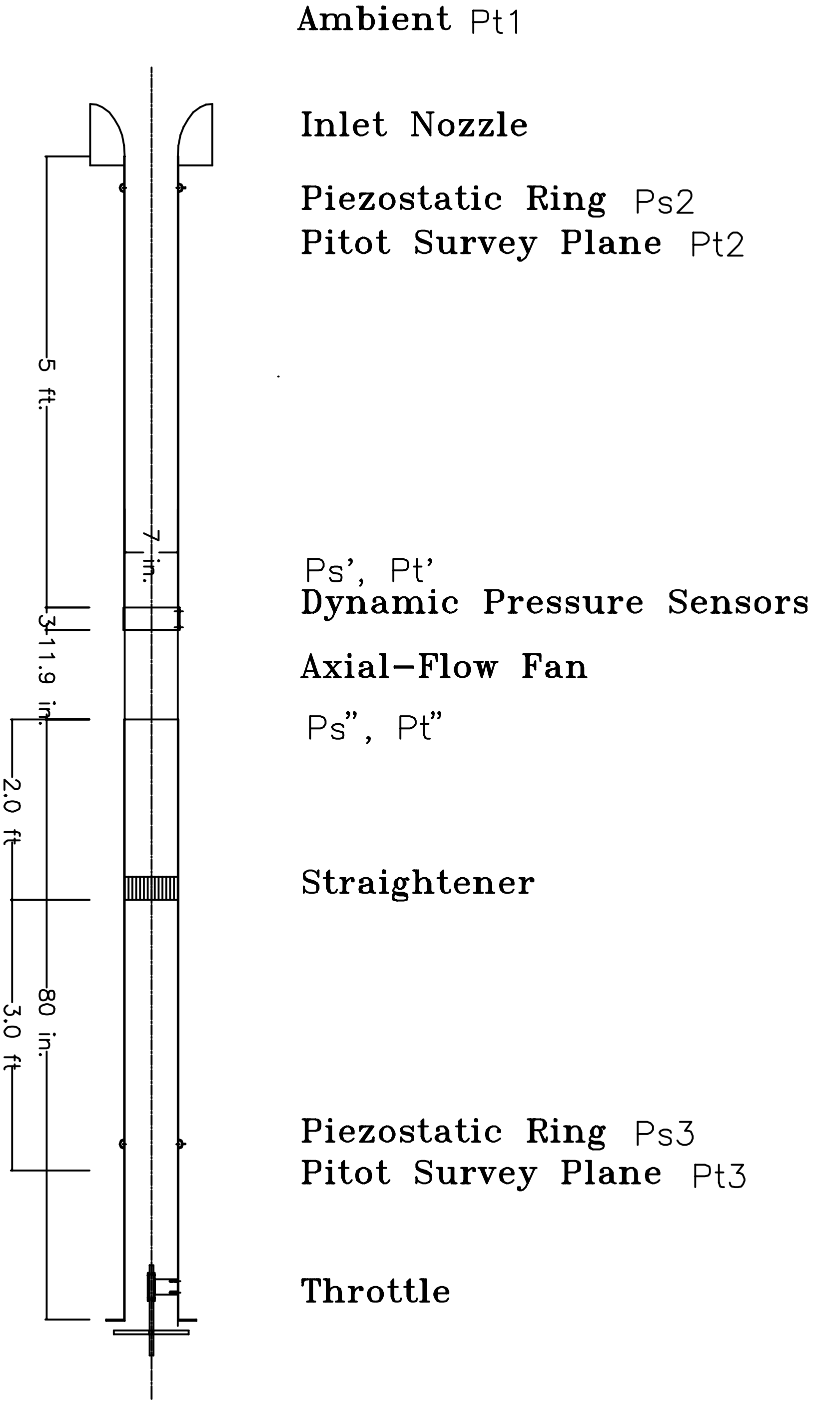
[3] A. Khalak, “Surge and Stall in an Axial-flow Compressor,” *SURF Report*, Oct. 1993.

[4] A. Khalak, “Operating Caltech’s Axial-flow Fan Testing Facility for ME 96”, Jan. 1994.

6 Appendix

- Test set-up schematic
- Operating the System
- Precautions

6.1 Test set-up schematic



6.2 Operating the System

There are several details concerning the actual operation of the fan facility which require attention before actually attempting to operate the system.

The axial fan, an Able 29680, is driven by an electric motor. It is designed to run continuously at 11700 rpm, to draw 2700 Watts of power, and 10 Amps of current. Its commercial use is in the cooling of the avionics (the control circuitry) of an MD-11 Aircraft.

In the ME 96 Experiment, you will be running the fan at speeds at or below 10,500 rpm (350 Hz)(when running full speed, the fan produces a great deal of noise). The power supply, since it is variable frequency, can run the fan at most any speed. This is done by changing the frequency of the input power, which (since the fan uses an induction motor) will change the rotor speed. In fact, the fan impeller will run at a speed half the speed of the input power frequency. Standard airplane power frequency is 400 Hz, which corresponds to a fan speed of 12000 rpm (nominal) which is 200 Hz. The power supply outputs power up to 400 Hz.

To operate the system, follow these steps:

1. Turn on the LARGE wall switch to allow current to flow to the power supply (motor controller). Then turn on the power toggle switch on the tethered remote control box mounted to the same table as the axial fan.
2. Use the switch on the side of the remote control box to select manual or BNC (remote) control of the fan speed. Under manual (knob) control turn the potentiometer knob until the desired frequency appears on the LED readout on the power supply (motor controller). Under BNC control, a voltage (0–8 Vdc) is supplied to the BNC connector (usually from a D/A channel of the data acquisition system) to set the drive frequency in the range of 0 to 350 Hz.
3. Turn off the power toggle switch on the tethered remote control to shut down the fan. This will signal the power supply to automatically ramp down the drive frequency.
4. Be sure to turn the LARGE wall switch off only AFTER the fan has come to a complete stop.

Note that the fan speed may be changed while the fan is running by simply following steps 2 and 3. The power supply will automatically ramp the voltage in the appropriate way. Please see the precautions section for cautionary information.

6.3 Precautions

The fan facility uses a significant amount of power and includes some very high speed rotating machinery. Therefore it is very important to handle the entire system with care to avoid damaging the setup and, more importantly, to ensure operator safety. There are several precautions to take whenever using the setup which are described in the following list.

1. Do not let anything come close to the inlet of the nozzle. Loose items could be sucked into the impeller, damaging it. A flow straightener is located just inside the nozzle to prevent large items from entering, but these large items may become lodged in the inlet. Items small enough to fit through an 8 mm square hole could pass through the straightener and damage the impeller.
2. Do not turn off the LARGE switch on the wall that provides power to the power supply (motor controller) before shutting the fan off from the tethered remote control. Turning off the power switch on the tethered remote control causes the power supply to ramp down and safely shut off the fan.
3. There are several wires and hoses which run from the facility to the power supply, monometer, and computer. Use caution when moving around the rig to avoid disturbing these connections.
4. Do not run the fan with the throttle closed for any significant amount of time. The fan requires flow through it to expel the generated heat. Running with the throttle closed can cause the fan to overheat.
5. Avoid running the fan at too low a speed (say lower than 66 Hz drive frequency or 2000 rpm). This may not produce enough flow for the fan to cool properly.
6. Do not start the fan in a throttled condition. Starting up with high losses in the system (e.g. a closed throttle) can cause undue stress.
7. Avoid leaning on, sitting on, or manipulating the fan. This may cause misalignment of the assembly.
8. When adjusting the throttle plate, be sure to avoid positioning your head (especially your eyes) in the flow. The flow velocity is high and the potential for injury exists.