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Modifications of the SR-30 Gas Turbine Experimental Apparatus to Improve Data Accuracy

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The SR-30 (LX4000) gas turbine engine manufactured by Turbine Technologies, Ltd. is used for teaching in a growing number of universities throughout North America. This system is a self-contained package that consists of the gas turbine and computer-aided data acquisition system. The base system provides data measurements for thrust, fuel consumption, engine speed, and various additional temperatures and pressures.

During testing, the measurement of thrust, fuel flow, and engine speed were found to be inadequate and the system had no airflow measurement capability. Several modifications were made to this system to make it viable for both classroom use and for research. This paper presents details of these modifications and the resulting data quality. All of these changes can be integrated into the existing computer data acquisition system, which is part of the base LX 4000 package.

Introduction

The base experimental apparatus is a LX4000 gas turbine engine, manufactured by TurbineTechnologies, Ltd. This system is shown in Figure 1. This engine is capable of producing about 22 lbs. of thrust. As shown in Figure 2, there is no bypass flow and the compressor and turbine are directly axially connected. This simple setup makes this unit ideal for experimental studies since it eliminates the need to account for other flows, transmission losses, etc.

This apparatus is used in a senior level mechanical engineering energy systems laboratory course [1]. In this class, students are asked to operate the engine at various speeds, while measuring various pressures and temperatures as well as fuel flow rate, airflow rate, engine emissions and engine thrust. The data is then used to calculate thrust specific fuel consumption (TSFC), component efficiencies, Brayton cycle efficiencies, system energy balance, and the A/F ratio. Further, using the linear momentum principle, engine thrust is calculated and compared with the measured value. Reference 1 provides further details of the experiments conducted by the students.

During testing, the measurement of thrust, fuel flow, and engine speed were found to be inadequate. Further, the system had no airflow measurement capability; the airflow was estimated using the compressor speed. The thrust measurement, in particular, was found to vary widely. The observed thrust measurement would lose its zero and impart an offset of as much as 10 lbs (worst case), or about 50% of the rated engine thrust! This caused considerable consternation among our students as they were being asked to theoretically determine the thrust using the momentum equation as shown below:

$$Thrust = [\dot{m}V]_{exhaust,exit} - [\dot{m}V_{air,inlet}] + [(p_{exhaust} - p_{inlet}) \cdot A], \qquad (1.1)$$

where the first term is the gross thrust produced at the exit nozzle, while the second term is the reverse thrust or ram drag of the inlet nozzle. The last term is the change in thrust due to the pressure differential across the gas turbine. As one might expect, the theoretically derived thrust value was not in close agreement with the measured value. Other universities have reported similar difficulties [2, 3].

These items have been addressed as discussed in the following sections. For more details regarding the base experimental apparatus, please see reference 4.

Figure 1. SR-30 System Overview (Courtesy of Turbine Technologies).

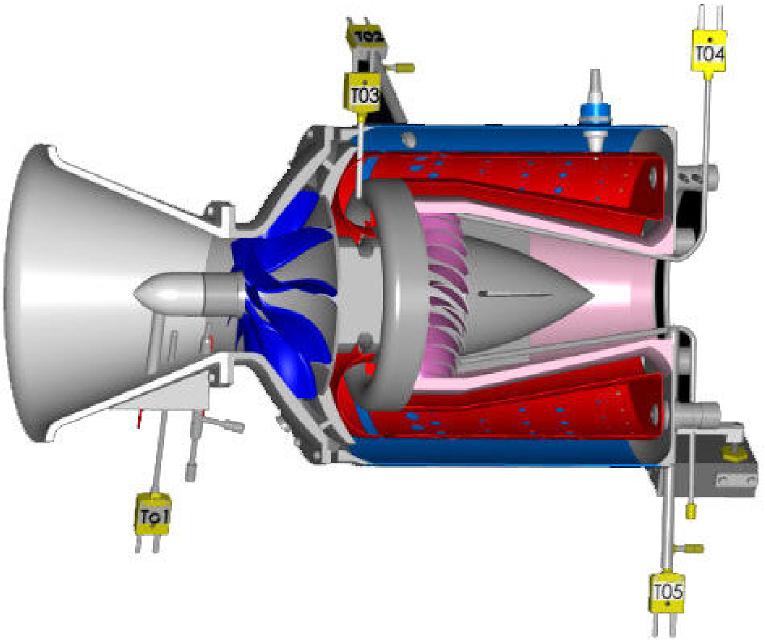

Figure 2. SR-30 Cut away Schematic (Courtesy of Turbine Technologies).

Thrust Measurement

The thrust measurement was limited by two factors: over-constrained jet engine support, and a primitive load transducer. Ideally, the load transducer should restrain all of the thrust produced by the jet engine. The jet engine was supported on two support “legs” as shown in Figure 3. The front leg was attached to the floor of the test stand, while the rear leg was not bolted to the floor. The load transducer was attached to the front support leg. This support design did not allow the jet engine to thrust directly against the load transducer.

Since the engine would normally produce thrust toward the front, the rear support leg should be free to lift so as not to interfere with the thrust measurement. Unfortunately, the rear leg, although it was not bolted, did not move freely with respect to the floor; thus it often interfered with the developed thrust. Additionally, the front support leg was bolted to the floor, thus it absorbed some of the thrust in bending. The fuel and oil lines were all rigid tubing, so that they, too, restrained the jet engine.

Finally, the load transducer was a simple strain gauge unit that is not commercially produced. This device had no temperature compensation and had a low output sensitivity. It was also attached to the front support leg, well below the centerline of the thrust.

The net effect of these design issues was that the load measurement did not maintain zero and the resolution was inadequate. In fact, the zero load condition could be shifted by several pounds just by tapping the rear support leg. In order to improve the thrust measurement; both the engine support system and the load transducer were replaced.

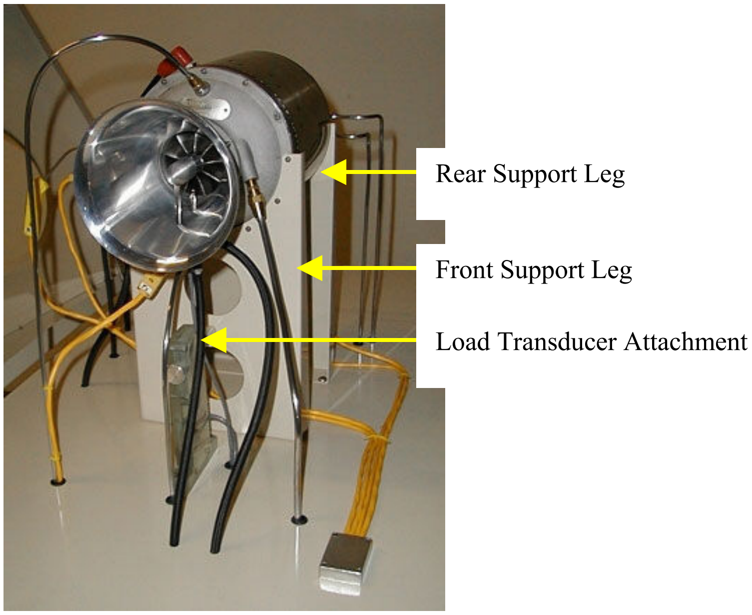

Figure 3. View of the Jet engine (inlet side).

To provide for freer engine response to thrust, the engine was hung from an external frame using four straps made from 0.05” thick stainless steel shim stock. Aluminum Unistrut beams (1” x 1-5/8”) are mounted to the ceiling of the test stand. The stainless steel bands are fastened to the Unistrut beams via steel clamps. The new configuration is shown in Figures 4 - 7. The support legs were retained in order to provide a convenient mount for the hanging supports; however, the unit has been raised up about ½ inch off the floor so that the legs do not touch the floor. The straps provide little resistance to axial thrust, while preventing the system from twisting or moving laterally.

In order to further improve the thrust response, all of the rigid tubing connections were replaced with flexible couplings. The flexible tubing used in this conversion is Teflon Polytetrafluoroethylene (PTFE). PTFE features the best flexibility of all Teflon formulations: low permeability, and smooth friction-resistant surfaces. The temperature range for Teflon PTFE tubing is –400 to 500°F, which is in the acceptable range for use inside the turbine test cell. The maximum line pressure that the Teflon PTFE tubing can withstand is 168 psi, which is greater than the max line pressure of 150 psi used for the fuel supply and return lines. An added bonus to using Teflon PTFE tubing is it is translucent allowing the operator to see physical flow of the fluids. Figure 8 shows a photograph of the rear of the turbine after the flexible PTFE lines were installed.

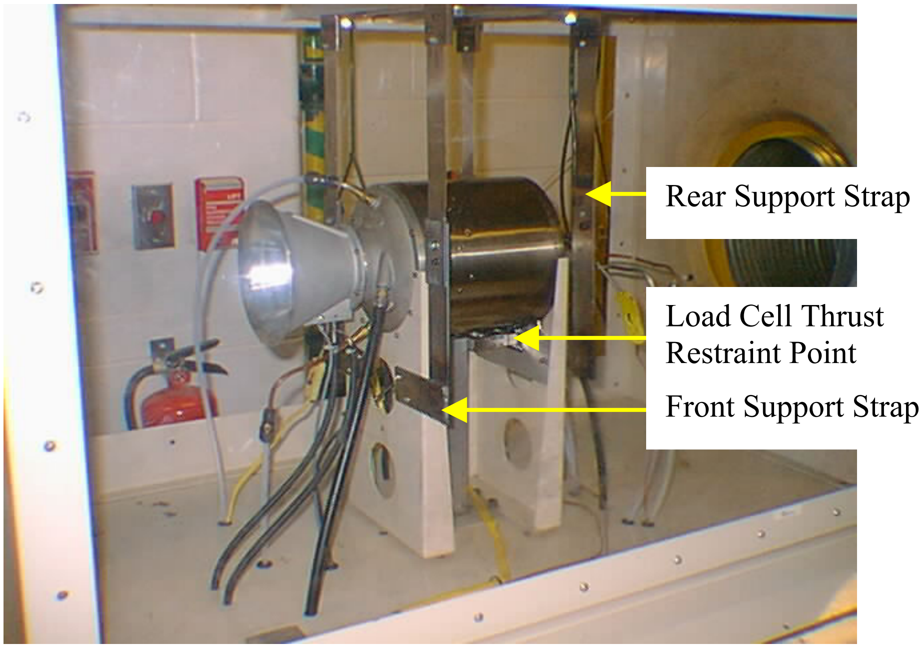

Figure 4. Modified Support System, Front view.

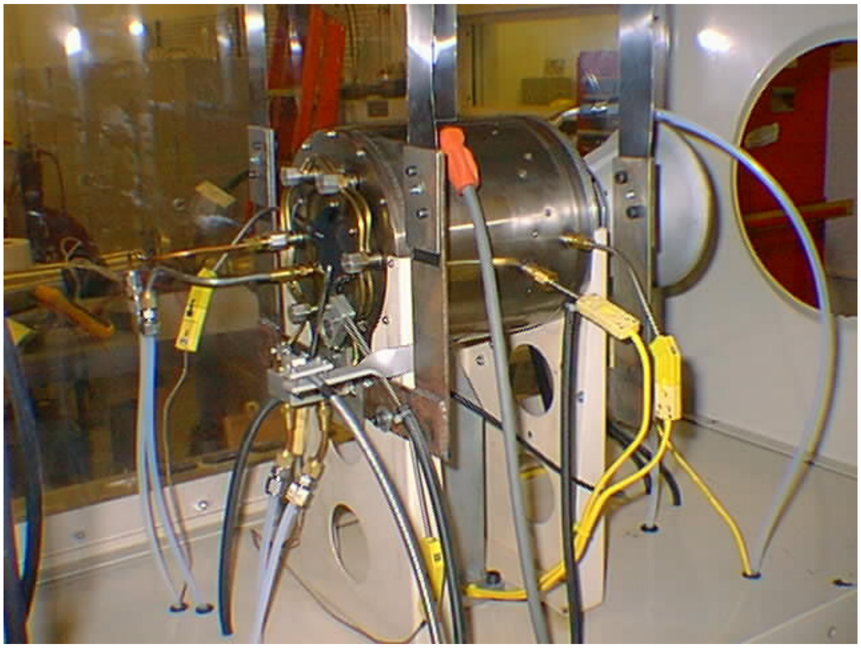

Figure 5. Modified Support System, Rear view.

Figure 6 Turbine Mounting Configuration as Seen Looking Up.

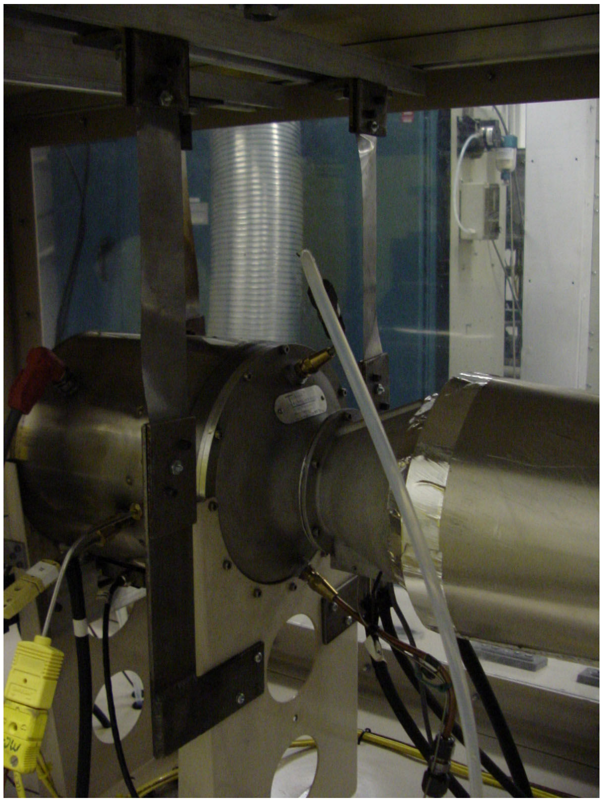

Figure 7 Jet Mounting Configuration Showing Steel "L" Bracket Attachments to the Existing Support Structure.

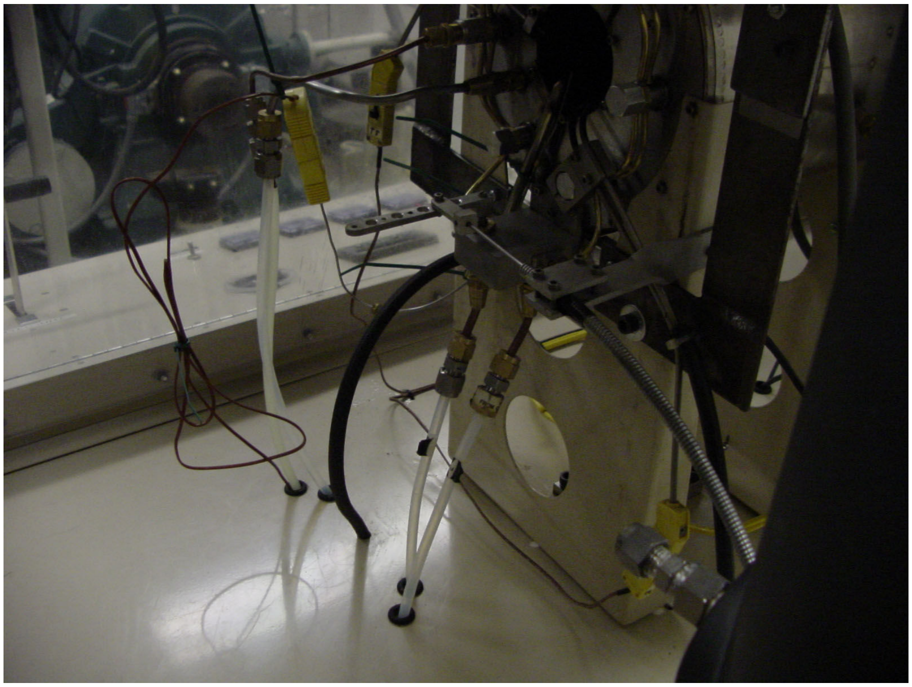

Figure 8 Fuel/Oil Delivery & Return System Showing Flexible Connections

In the new configuration, the jet engine is axially restrained by the load cell. If the load cell were removed, the engine would freely move forward under thrust, with the support straps acting as pendulum supports. The load cell is mounted so that it resists the thrust, in compression, as near to the thrust centerline as is practical. The new location of the load cell is directly underneath the turbine engine. A support tower was manufactured from 1" x 3" aluminum stock, to position the load cell. The tower is fastened to the floor of the test stand to reduce any flex as a result of the thrust. An aluminum plate is located on the inside of the manufacturer's mounting bracket directly in front of the fuel rail. The turbine engine thrust is translated to the load cell through this plate rather than locating the load cell directly behind the fuel rail. This eliminates any stress that would be applied to the fuel rail that could have negative long-term effects on the operation of the fuel delivery system. The new load cell mounting system is shown in Figure 9.

The original load transducer was replaced with a commercially available load cell rated to 25 lbs. The specifications of this device are presented in the Specifications section. This unit was selected because of its high sensitivity response to excitation voltage (3 mV/V; typical load cell sensitivity is 2 mV/V). Further, it is temperature compensated and has good accuracy and linearity.

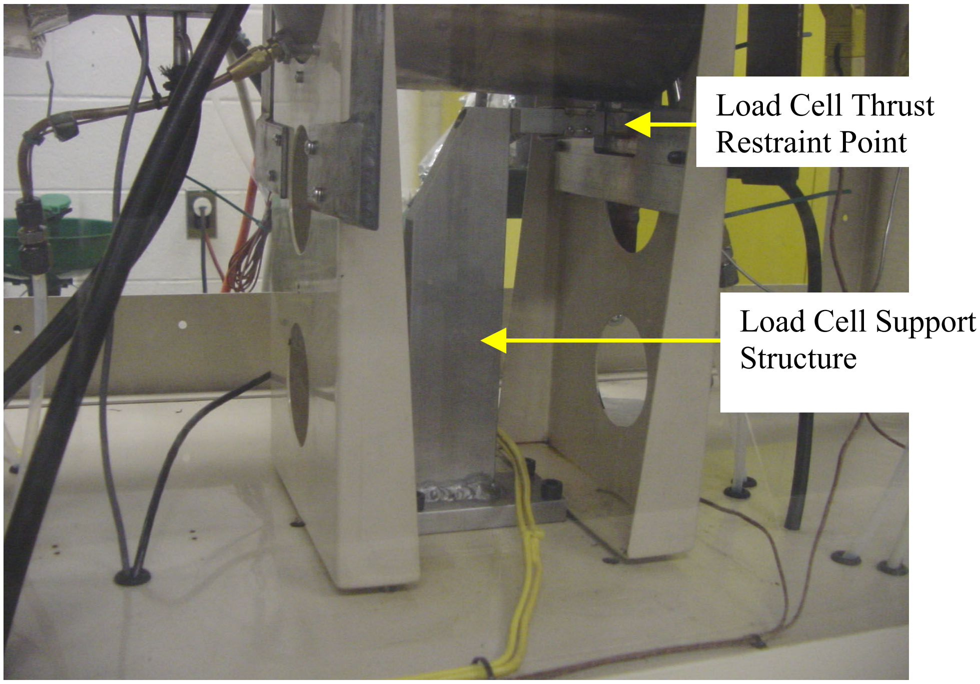

Figure 9 Load Cell Mounting System

In order to calibrate the thrust measurement, a cable-pulley system was devised so that calibrated weights could be hung from the centerline of the jet engine. This was accomplished by attaching lightweight cable to the front of the intake nozzle. This cable then extends forward in a horizontal direction until it contacts the pulley. The cable then rotates to the vertical position in order to hang calibration weights as shown in Figure 10. The system is now calibrated to a resolution of better than 0.1 lbs. The thrust measurement system also maintains zero and is repeatable with load increases or decreases. We have found after extensive operation that it is still good practice to manually push the jet engine back off of the load cell button and let it return to rest on the load cell button before taking measurements to ensure that the unit has not twisted. This ensures that the measurements will be repeatable.

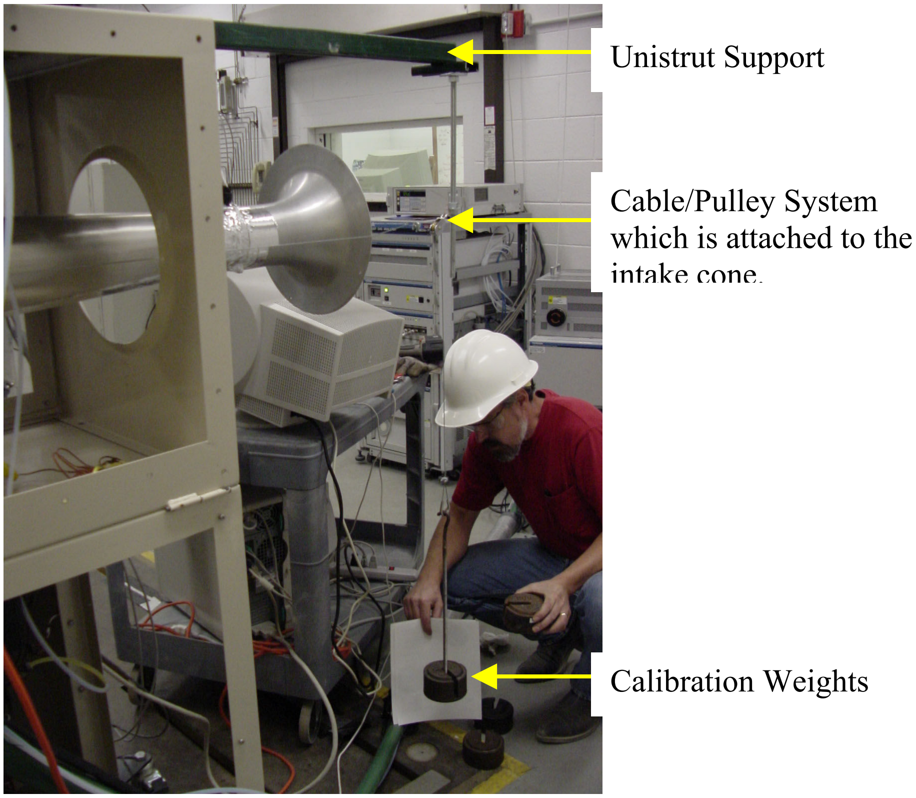

Figure 10 Load Cell Calibration System

Fuel Measurement

The fuel measurement was not accurate as it was based on an indirect approach. This approach relies on the return line pressure and factory calibration to estimate the actual flow rates. We have found that using different fuels and operating at different temperatures can impact the accuracy of this measurement. Further, over time, one would not expect this measurement to remain static; thus it would require us to devise a way to recalibrate the signal. In order to achieve the highest accuracy measurement at the lowest cost, the fuel is now directly measured as it is consumed using a scale. This gravimetric approach is simple and gives very good accuracy for steady state operation; however, it would be inadequate for any dynamic measurements. In practice, we generally, set the engine to an operating point and consume a known weight of fuel while timing the operation. Figure 11 shows a view of the fuel tank as it sits upon the scale; note that the fuel filter was also moved to this location.

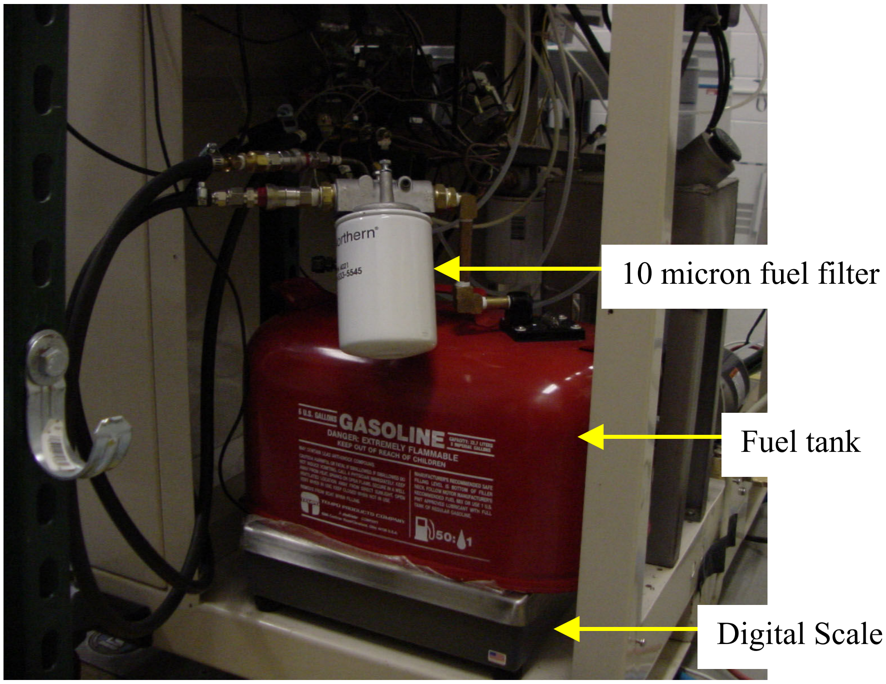

Figure 11 Fuel Tank & Scale

Jet Engine Speed Measurement

The original system used a frequency to voltage custom circuit to convert the engine speed to an analog voltage. To increase accuracy, it was decided to replace this with a direct frequency counter which outputs both a digital display and analog voltage. Serendipitously, it was found that the panel meter supplied with the base system already has this capability, so it was used. The speed pulses are now directly wired to the panel meter, bypassing the custom circuit.

Air flow Measurement

The base system does not include the ability to directly measure the airflow. To overcome this, we designed a system that allowed us to use a direct massflow transducer to measure the inlet airflow. This transducer is based upon hot-film/wire technology. This unit compensates for humidity, temperature, and pressure changes in the flow. Unfortunately, the diameter of the unit used is smaller than that of the intake nozzle used on the jet engine. In order to overcome this difficulty without making major changes to the jet engine itself, we designed a transition nozzle and a new intake nozzle to match the diameter of the mass airflow sensor. This system is shown in Figure 12.

The new intake cone is a bellmouth design similar to the original intake nozzle. The transition nozzle was constructed using 0.10-inch thick stainless steel sheet metal. In order to construct it easily, the exit angle was fixed at the optimum angle of 7°. This angle leads to the minimum head loss and turbulence [5]. In order to match the diameter of the original intake nozzle to that of the mass airflow sensor, the length of the transition nozzle was found to be 18.0 inches long.

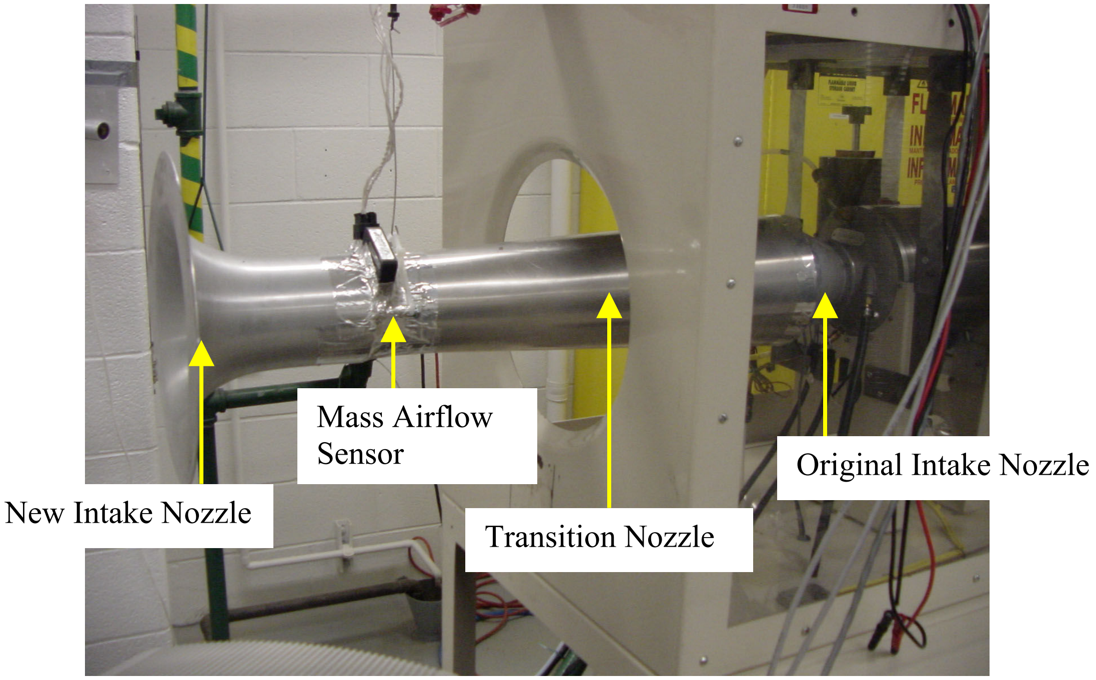

Figure 12 Mass Airflow Measurement System Installed on the Jet Engine

We use two different mass airflow transducers. The most accurate transducer is a research grade device manufactured by Sierra Technologies. This system is used as the airflow measurement standard in our laboratories due to its extremely stable calibration. Unfortunately, this unit is also quite heavy, which hurts our ability to measure the jet engine thrust since the unit must be hung with the jet engine. Further, this system is also quite expensive; thus making it difficult for general use. To minimize cost and to protect our calibration standard, we are currently using automotive mass airflow sensors in our system. These units are relatively inexpensive and lightweight. Weight is important as the mass airflow device is supported directly by the jet engine as is shown in Figure 12.

The automotive mass airflow sensors output a frequency in response to massflow. Unfortunately, the manufacturer does not provide the output response; therefore these sensors must first be calibrated against a known device. We developed a system to calibrate directly against our Sierra transducer. This setup is depicted in Figure 13. The laboratory ventilation duct is used to draw air through both the Sierra and the automotive mass airflow (MAF) sensor for calibration. Once this calibration is accomplished the automotive MAF, works extremely well for this application. We have found these units to be quite linear and stable as shown in Figure 14.

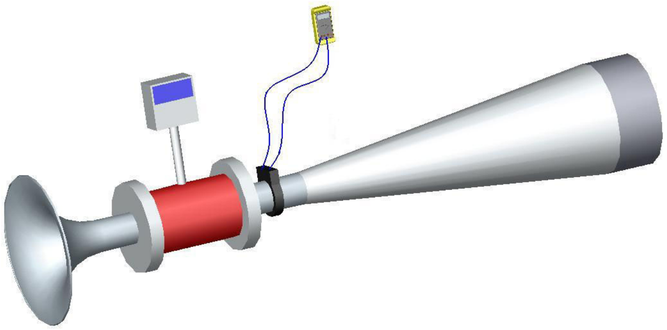

Figure 13 Mass Airflow Sensor Calibration Schematic.

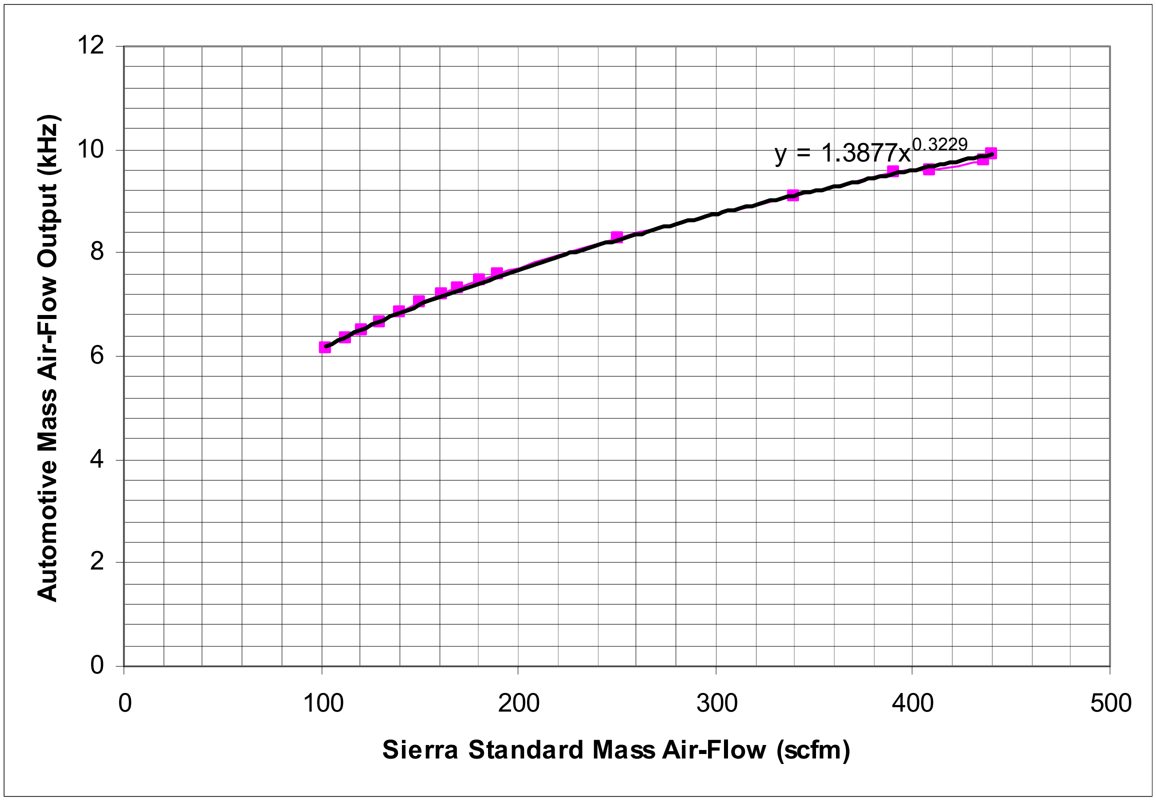

Figure 14 Typical Calibration Curve for the Automotive Mass Airflow Sensor Output (GM part)

Results

A comparison was made between the measured thrust and that as predicted using the momentum equation. This comparison now shows reasonable agreement, generally less than 10% difference, between the two values. It is interesting to note that the measured thrust was consistently higher than that predicted using equation 1.1. This is probably indicative of an error in the measurement of either one of the velocities or the pressure values used in t he momentum equation. Still, there is very good agreement. This comparison is shown in figure 15.

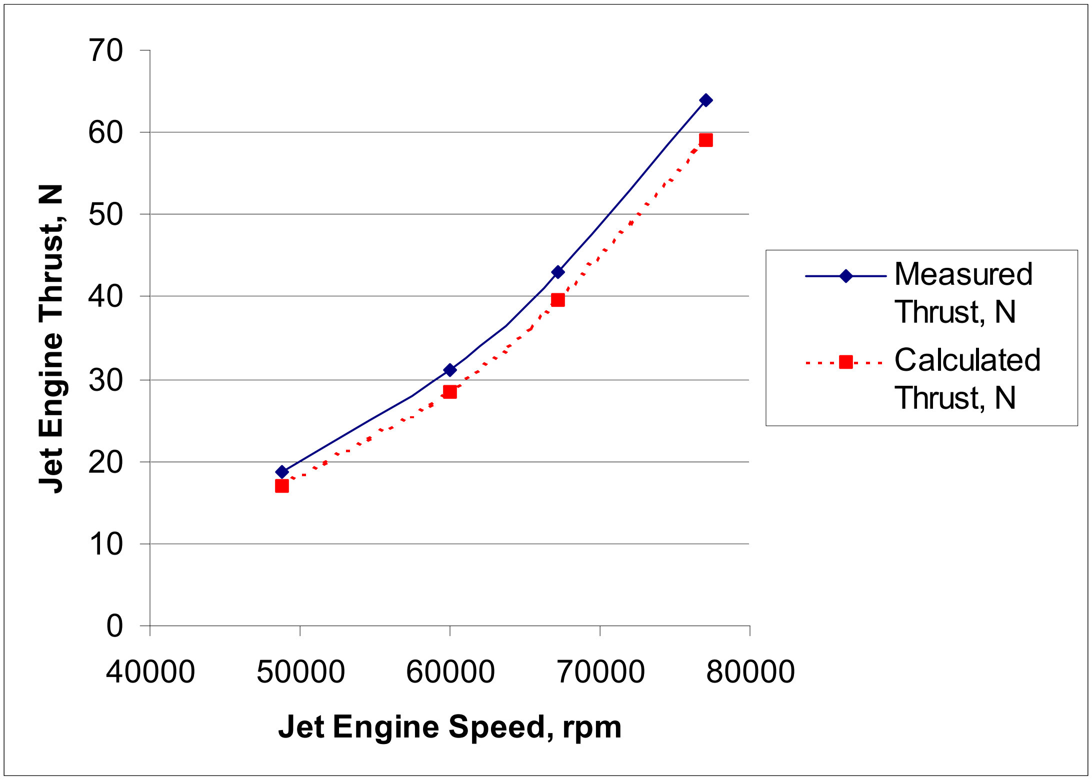

Figure 15 Comparison of Measured and Calculated Thrust Using the Modified Experimental Apparatus (Data taken from reference 1)

Summary

The SR-30 (LX4000) gas turbine engine manufactured by Turbine Technologies, Ltd. is an excellent teaching tool that is used in a growing number of universities throughout North America. This system is a self-contained package that consists of the gas turbine and computer-aided data acquisition system. The base system provides data measurements for thrust, fuel consumption, engine speed, and various additional temperatures and pressures.

During testing, the measurement of thrust, fuel flow, and engine speed were found to be inadequate and the system had no airflow measurement capability. Several modifications have been described which will enable SR-30 users to greatly improve data measurement precision and accuracy. These changes make the SR-30 experimental apparatus useful for both classroom use and for research. Further, they have been made in a modular fashion so that the user can select which areas to modify to suit their particular needs. For example, some users may not need a measurement of airflow, so this change can simply be eliminated. Finally, all of these changes can be integrated into the existing computer data acquisition system, which is part of the base LX 4000 package.

Acknowledgements

Work on this projected has been conducted with the help of many faculty, staff and students. The author would particularly like to express his gratitude to the following individuals: Mr. Ray Rust, Senior Engineering Technician; Mr. Geoffrey Lindberg, Undergraduate Student; and Dr. Homayun Navaz, Associate Professor of Mechanical Engineering. Further, some of this work was accomplished with the financial support provided by Nasa under an STTR grant, NAS3-02044, "Study of NOx Production for A New Fuel in a Small Jet Engine."

System Specifications

The following sensors and transducers are used to measure data during engine operation:

Pressure Sensors:

Compressor inlet pitot (P1): Setra 265 Differential Pressure transducer, rated to 10 psi, ±1% FSO accuracy, ±0.98% FSO non-linearity, 0.1% FSO hysteresis, 0.05% FSO repeatability, temperature compensated range 0 – 150 F, 0.033 shift %FSO/degF

The following pressures are found using a Setra 209 P. Transducer, rated to 50 psig, ±0.25% FSO accuracy, ±0.22% FSO non-linearity, 0.1% FSO hysteresis, 0.05% FSO repeatability, temperature compensated range 4 – 212 F, <2 %FSO/100degF:

Compressor exit stage stagnation pressure (P02)
Combustion chamber pressure (P3)
Turbine exit stagnation pressure (P04)
Thrust nozzle exit stagnation pressure (P05)

Temperature Sensors: All Thermocouples Are K-Type:

Compressor inlet static thermocouple (T1)
Compressor exit stagnation thermocouple (T02)
Turbine stage inlet stagnation thermocouple (T03)
Turbine stage exit stagnation thermocouple (T04)
Thrust nozzle exit stagnation thermocouple (T05)

Fuel Flow:

The fuel flow is determined by using a direct gravimetric approach. The weight change of fuel used is measured using the following scale:

Weigh-Tronix WI-125sst, 810,000 counts at 3mV/V resolution, 0.0001 to 20000 increments programmable, 8VDC excitation, -0.14 to 3.5 mV/V analog output, operating temp. 14 to 104 F, 10-90%RH

Air Flow:

Research Grade Apparatus: Sierra 780S Flat-Trak Mass Air Meter

Calibrated Ranges: 600 scfm, 200 scfm

Accuracy: ± 2% of reading from 10 to 100% of calibrated range, ± 0.5 % of full scale below 10% of calibrated range

Repeatability: ± 0.2% of full scale

Temperature Coefficient:

± 0.02% of reading per °F within ± 50° F of 80° F
± 0.03% of reading per °F within ± 50° F to 100° F of 80° F
± 0.04% of reading per °C within ± 25° C of 26.7° C
± 0.06% of reading per °C within ± 25° C to 50° C of 26.7° C

Pressure Coefficient: .02% per psi for air

Response Time: One second to 63% of final velocity value

Standard Apparatus: General Motors Mass Airflow Sensor

Thrust Force:

The engine thrust is measured using a standard load cell:

Omega LC101-25

Rated to 25 lbf, 3mV/V ±0.0075 mV/V sensitivity, excitation voltage 10-15 Vdc, ±0.03% FSO accuracy, ±0.03% FSO linearity, ±0.02% hysteresis, ±1% zero balance, FM/CFA approved

As installed, the load accuracy is better than 0.1 lbs.

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Biographical Information

DR. GREG DAVIS is a Professor of Mechanical Engineering at Kettering University, formerly known as GMI Engineering & Management Institute. Acting in this capacity, he teaches courses in the Automotive and Thermal Science disciplines. He also serves a Director of the Advanced Engine Research Laboratory, where he conducts research in alternative fuels and engines. Currently, Greg serves as the faculty advisor for the world's largest Student Chapter of the Society of Automotive Engineers (SAE) and the Clean Snowmobile Challenge Project. Greg is also active on the professional level of SAE, serving as Chair of the Student Activities Committee and Chair of the Engineering Education Board. Dr. Davis is a registered Professional Engineer in the State of Michigan.