Toward In-Flight Thrust Monitoring: Demonstration of an Acoustics-Based, Non-Intrusive Exhaust Thrust Sensor

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ABSTRACT

The ability to measure turbofan engine nozzle thrust in flight offers a number of advantages, from on-wing testing, to engine health monitoring. While many methods proposed for achieving in-flight thrust measurements involve complicated, sensitive and expense instruments, an acoustics-based approach is discussed which greatly simplifies the technology development pathway to in-flight applications. Results are provided for a minimum set of sensors applied in the exhaust of a research turbofan engine at Virginia Tech, showing the difference in acoustics-measured thrust and nozzle thrust found by integrating thermocouple and Kiel probe measurements to be less than 6% at the maximum fan speed examined.

1.0 INTRODUCTION

A non-intrusive acoustic method, as outlined by Otero et al. [1,2], is discussed for future in-flight measurement of engine exhaust properties. The proposed acoustic technique relies on the fundamentals of sonic anemometry and thermometry, which have been around for many years [3-9], but uses a new configuration to estimate higher subsonic Mach number flow characteristics simultaneously. While the first implementation of this acoustic technique was in a 50.8 mm, unheated uniform jet [1], the current work indicates that flow velocity and static temperature in non-uniform turbofan exhaust flows may be resolved. The primary objective of this work is to show that a minimal set of acoustics instrumentation, amenable to in-flight applications, can be used to monitor engine thrust.

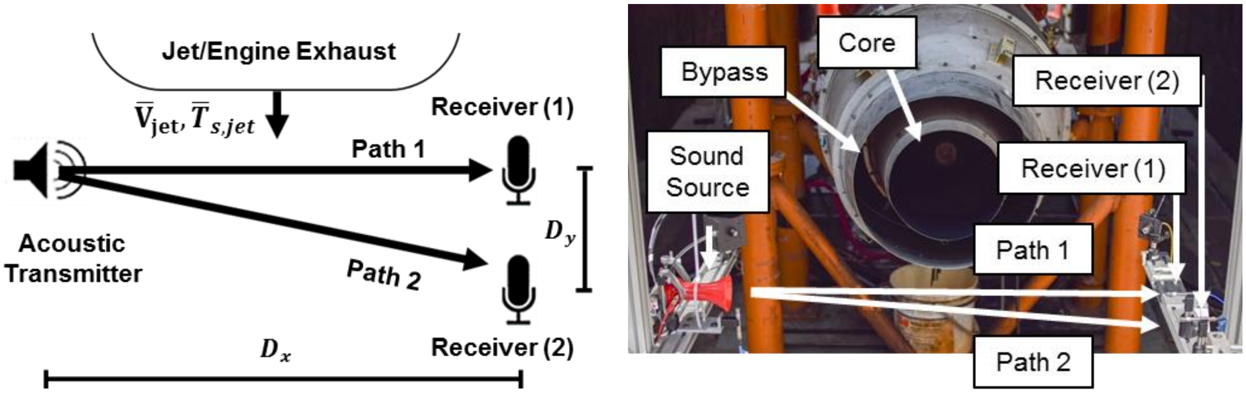
2.0 BACKGROUND

Building on the principles of sonic anemometry and sonic thermometry, the new acoustic technique used here allows for the measurement of integrated path velocity and static temperature in flows with transport-flight-relevant Mach numbers, i.e., approaching unity, using two stream-wise displaced acoustic path measurements as illustrated in Figure 2-1(a). The fundamental approach relies upon measurement of the acoustic time of flight for at least two rays,

$$\tau_n = \int \frac{ds}{(c\hat{n}+\vec{v})\cdot\widehat{t_n}} \tag{1}$$

Where c is the thermodynamic speed of sound, $\vec{v}$ is the vector flow velocity, $\widehat{t_n}$ is the unit vector tangent to the ray path, and the integral is taken along the ray path. The time of flight in equation (1) is sensitive to both temperature (via the thermodynamic sound speed) and the flow velocity along the ray path. To measure these flow variables, the concepts described by Otero et al. for jet experiments [1,2] may be used to obtain the path-integrated flow velocity and speed of sound. The procedure for obtaining path-integrated temperatures and velocities is outlined in Appendix A of Otero et al.'s work [1]. For special cases such as a uniform flow field, unique relationships may be derived for temperature and velocity based upon the relative placement of the acoustic transmitter, two receivers, and measured times of flight. For more general cases, iterative ray tracing is necessary, but measurements remain tractable [2].

In past work, a number of uncertainty drivers have been identified, quantified and mitigated where possible [1,2, 10]. These include signal-to-noise ratio, positioning uncertainty for sensors, and acoustic path reconstruction errors. Laboratory demonstrations of the technique yielded root-mean-square (RMS) static temperature errors of 1-3% and RMS velocity errors of 1-2.5% [2] over a wide range of free jet total temperatures (up to 700 K) and Mach number (up to 0.83). The laboratory successes led the authors to pursue a ground test application in the research engine at Virginia Tech in order to use simplified, two-path acoustic measurements for inferring engine thrust.



(a) (b)

Figure 2-1. Experimental configurations: a) Acoustic thrust sensor concept b) Instrument installed in the exhaust of the JT15D-1A research engine.

3.0 EXPERIMENTAL SETUP AND PROCEDURES

To assess the performance of the proposed acoustic method in engine exhaust flows, Otero et al. [10] conducted total temperature/total pressure probe and non-intrusive (acoustic) measurements at the Virginia Tech JT15D-1A engine research facility, 0.58 m (2.3 core diameters) downstream of the core exhaust plane. Figure 2-1(b) illustrates the acoustic instrumentation layout at the exhaust of the turbofan engine.

Throughout the experiment, data were first collected using the traversing probe configuration and later using the acoustic configuration. A linear traverse was oriented to collect data at various radial positions using a 1/8 inch combination Kiel pressure and K-type thermocouple probe. Probe measurements would ultimately serve as the benchmark for acoustic measurement error quantification, though the variability in the engine conditions were likely greater than instrumentation errors encountered. In the acoustic measurement configuration, a spark sound source was used to generate an acoustic impulse signal, and three microphones were used to collect acoustic data.

4.0 GROUND TEST RESULTS

An engine ground test application intended to demonstrate the applicability of the acoustic time-of-flight technique for plume momentum measurements was conducted. As a first step, the path-integrated temperature and velocity found from acoustics measurements were compared to the integrated values determined from a traversed probe. Using a numerical ray tracing approach, implementing Snell's Law for convected flows [9,11] and Fermat's principle of least time modeling [11-13], the probe measurements were temporally integrated for comparison with the acoustic measurements. The RMS differences were 3.8 m/s and 2.3 K for flow velocity and temperature, respectively. Given these results, a calibrated method for measuring the engine mass flow rate and thrust variation with corrected fan speed was developed, described further to follow.

Single-constant calibration functions were developed for exhaust mass flow and nozzle thrust based upon a defined reference mass flow and reference thrust term. The forms of the mass flow and thrust equations are, respectively,

$$\dot{m} = K_1 \left(\frac{p_s}{RT_{acoustic}} v_{acoustic} \right) \tag{2}$$

$$\mathcal{T} = K_2 \left(\frac{p_s}{RT_{acoustic}} v_{acoustic}^2 \right) \tag{3}$$

Where K_1, K_2 are the two calibration constants, p_s is the atmospheric static pressure, R is the gas constant for the exhaust gas, $T_{acoustic}$ and $v_{acoustic}$ are the acoustics-derived average temperature and velocity, respectively. All terms are measurements except for K_1 and K_2, which may be determined by calibration based upon flow temperature and velocity profile, which was shown to vary little in a normalized sense (see Figure 4-1).

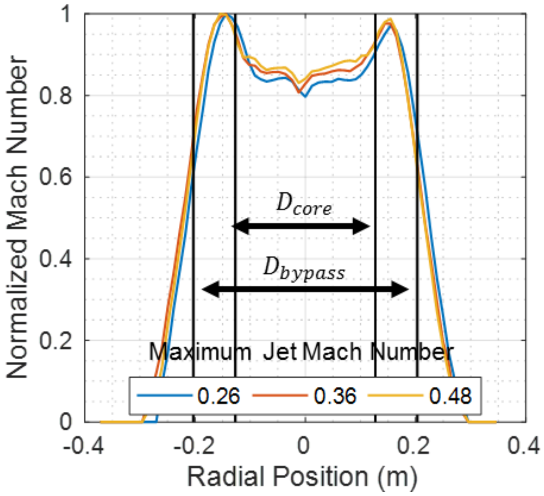
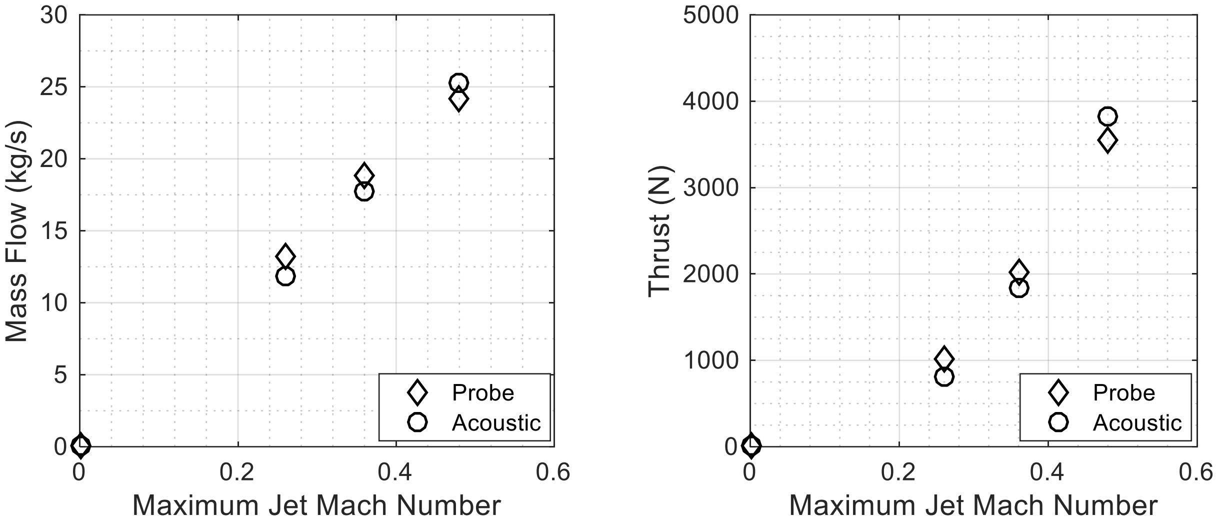


Figure 4-1. Normalized Mach number distributions at measured engine power levels.

Given the nozzle mass flow and thrust measurements obtained from the total temperature/total pressure probe data to correlate the temporally integrated acoustic measurements at 35% corrected fan speed, the constants K_1 and K_2 were found to be 0.298 and 0.453. Multiplying these constants by the acoustically-determined flux terms, the exhaust mass flow and thrust of the JT15D-1A engine could be approximated at higher engine power levels (Figure 4-2).



(a) **(b)**

Figure 4-2. Comparison of acoustic and probe measurements: a) Mass Flow Rate b) Thrust.

The results presented in Figures 4-2 indicate that the technique is promising as a calibrated approach for measuring engine mass flow rates and thrust. Mass flow and thrust root mean square errors were shown to be 1.1 kg/s and 200 N, respectively. The differences in Figure 4-2 are likely dominated by differences in engine operating conditions associated with the different times at which probe and acoustic data acquisition were acquired. Future experiments are planned using a thrust stand facility so that acoustically determined values can be compared in real-time with intrusive measurements.

5.0 COMMENTS ON FLIGHT SCALING

The acoustic technique developed to date holds promise for flight scaling due to the simplicity of the sensors, but has challenges associated with the physics of the technique. An obvious limitation for effective measurements is sufficient signal-to-noise ratio of the acoustics signal over hydrodynamic pressure fluctuations in flight systems. The ground test application avoids this complication by placing all sensors and sources outside of the flow-path, but flight measurements will require flow-mounted sensors. This aspect can be mitigated by (1) designing sensor tubes to dampen hydrodynamic fluctuations and (2) taking advantage of statistics to pick out correlated acoustic signals from decorrelated turbulence. Physics limits the applicability of the approach to subsonic portions of the flow path, such that any application in supersonic exhaust engines must be done in the subsonic portion of the nozzle. In nozzle systems close to the turbine outlet, local temperatures must be considered due to limitations of acoustic sensors. Although an electrical spark source was mentioned above, pneumatic sources are available, and are likely more attractive for flight operation. These sources can operate on small quantities of available compressor bleed air and are robust to harsh environments.

In addition to the direct measurement capability discussed, the availability of acoustic measurements in exhaust systems could be attractive for other uses such as monitoring acoustic spectra to identify changes to the system. Furthermore, additional work conducted at Virginia Tech seeks to extend the capability for spatially-resolved temperature/velocity field measurements using tomography [14] and inlet applications.

6.0 CONCLUSIONS

This study tested the performance of a non-intrusive acoustic flow characterization system, thought to be feasible for in-flight gas-turbine engine exhaust measurements. A proof-of-concept, ground-based experiment was performed on a modified JT15D-1A turbofan research engine operating up to a maximum non-uniform jet Mach number of 0.48. Probe and non-intrusive acoustic measurements were collected at three different engine operating conditions for comparison.

Assuming linear propagation between acoustic equipment, the equations outlined by Otero et al. [1] were used to approximate the integrated path velocity and static temperature of the turbofan engine exhaust. The integrated path velocity and static temperature root mean square errors were found to be 3.8 m/s and 2.3 K, respectively. In order to estimate the mass flow rate and thrust of the engine, a novel calibration was performed to relate the acoustic measurements to engine exhaust mass flow and thrust measured using the total temperature/total pressure probe. Using only a single calibration constant, engine mass flow rate and thrust root mean square errors were found to be 1.1 kg/s and 200 N, respectively.

Overall, these results indicate that the acoustic technique may be used to measure and monitor gas turbine engine performance. This sort of instrument could be used to reduce engine down-time due to catastrophic failure or performance checks and improve cost efficiency. Future work will seek to reduce uncertainty and assess measurement accuracy for more advanced engine cycles. To the authors’ knowledge, this is the only acoustics-based technique used to characterize engine flows with Mach numbers greater than 0.3, offering a low cost, non-intrusive, direct monitoring approach for exhaust applications.

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