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# THE NASA HIGH ACCURACY FUEL FLOWMETER (HAFF) DEVELOPMENT PROGRAM

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## ABSTRACT

The NASA-sponsored high accuracy fuel flowmeter development program is described. The goal is to develop a flightworthy meter that measures mass flowrate of aircraft fuels to within ±0.25% of reading over a 50:1 range of flow.

A study of measurement techniques to achieve this goal yielded three candidates: (1) a dual-turbine flowmeter with density and viscosity compensation; (2) an angular momentum flowmeter with a motor-driven, spring-restrained turbine and viscosity shroud; and (3) a vortex precession flowmeter with density and viscosity compensation. An experimental study of each technique was completed and the first two candidates were selected for prototype development. This work is currently under way.

The prototype meter with the best performance will be developed into a flightworthy meter. Initial flight testing is scheduled for 1985.

## INTRODUCTION

The overall objective of the high accuracy fuel flowmeter (HAFF) program is to develop a fuel flowmeter suitable for aircraft applications which is capable of measuring mass flowrate to within ±0.25 percent of reading. This paper will present the results to date of the development of a flowmeter capable of meeting the program objectives.

Precision flight-type fuel flowmeters are needed to make accurate measurements of engine fuel consumption under flight conditions. At the present time, much effort is being focused on improving engine and airframe components which have a direct effect on fuel consumption. Component improvements that result in fuel consumption improvements of only a few tenths of a percent, although costly to implement, have been shown to produce significant net savings over engine and/or airframe life cycles. However, the ability to accurately measure such small changes in fuel consumption during short duration flight tests is beyond the state of the art.

Precision fuel flowmeters also have application in computerized systems for minimizing fuel consumption during a given flight mission. In addition, future engine control systems can potentially be improved by the direct and precise measurement of fuel flowrate.

The work described in this paper is being performed by General Electric, Aircraft Instrument Department, Wilmington, Massachusetts, under contract to NASA Lewis Research Center (LeRC).

## THE HAFF PROGRAM

The HAFF program is a multi-year effort that is roughly divided into four phases.

The first phase, which has been completed, consisted of a study and selection of all potential methods for measuring fuel flowrate. This was followed by a preliminary analysis of the methods, including a relative rating of the methods, with selection of three of the most promising methods for further detailed analysis to define problem areas and to define experiments or development efforts to resolve these problem areas. Phase I concluded with the preparation of preliminary meter designs based on the selected methods.

The second phase of the HAFF program, which is now nearing completion, includes the formulation and execution of an experimental and analytical investigation plan to solve, eliminate or circumvent the problem areas previously identified. Based on the test results, two methods were chosen to be evaluated as prototype flowmeters. The two flowmeter concepts selected were the dual-turbine concept and the angular momentum concept. A detailed discussion of each concept will be presented in this paper.

During the early portion of the first phase work, it was recognized that state-of-the-art calibration systems do not have sufficient accuracy to verify the performance of the HAFF meter. As a result of the shortcomings in existing calibration facilities, an additional task was added to the second phase work to study this problem. This study included a survey of calibration service laboratories, a literature survey and an error analysis to determine the recommended method of mass flowrate calibration for use with the HAFF meter.

The second phase will conclude with an analysis of any remaining deficiencies in the two prototype flowmeter designs and a recommendation on how these deficiencies can be minimized or eliminated.

The third phase of the HAFF program is scheduled to begin in the fall of 1983. This work will encompass all of the activities required to design, procure, modify and operationally verify a high accuracy calibration system. This work will also include the design of electronics and software required to interface the HAFF meter and the test and calibration system. A full integration of the flowmeter and calibration system will be made for the purpose of proving the specifications.

The final phase of the program will consist of building a complete flight system based on the prototype with the best performance. This flight system will be tested at NASA LeRC on a ground-mounted engine test stand and finally on a research aircraft at NASA Dryden Flight Research Facility.

## FLOWMETER DESIGNS

### The Angular Momentum Flowmeter

The HAFF concept angular momentum flowmeter is an improved version of flowmeters currently being manufactured by General Electric. The HAFF flowmeter will utilize both established and new design concepts to eliminate or circumvent the majority of error sources which are inherent in current designs. Although high accuracy is the main goal, the design does not sacrifice other secondary parameters such as reliability, size and weight. The mass flowmeter described herein operates on the principle of rate of change of angular momentum. The design combines some of the most desirable features of flowmeters currently in production and microprocessor compensation techniques.

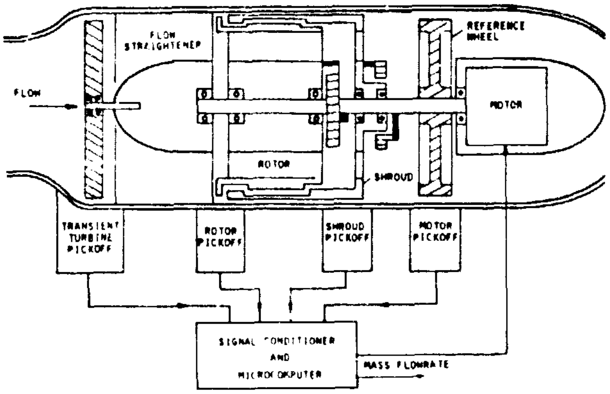

Figure 1 - Angular momentum flowmeter

The most important elements of the flowmeter as shown in fig. 1 are:

1. A free-spinning transient turbine wheel mounted on bearings and containing multiple short flow channels at a specified pitch angle. The main task of the transient turbine is to provide the fast response for the whole system since the typical angular momentum rotor has a relatively long response time. In order to achieve the high accuracy and fast responding output from the flowmeter, the transient turbine and rotor signals will pass through high-pass and low-pass filters having the same time constant, respectively, and these filtered outputs are summed to create the fast responding and accurate output signal.
2. A cylindrical, spinning rotor, mounted on bearings and containing multiple axial flow channels for passage of fluid.
3. A spiral spring between the rotor and the rotating shaft. The deflection of this spring is a measure of the fluid torque on the rotor.
4. A viscosity shroud mounted on bearings and having a large area with fluid in contact with the outer surface of the rotor and the inner surface of the housing.
5. A spiral spring between the viscosity shroud and the rotating shaft. The deflection of this spring is a measure of the viscous drag between the shroud and the inner surface of the housing.
6. A reference wheel fixed to the rotating shaft.
7. A synchronous motor generates constant angular speed for the rotor, viscosity shroud and reference wheel.
8. A modulated frequency pickoff measures the angular speed of the transient turbine.
9. A pickoff on the reference wheel generates an electrical signal when a magnet on the wheel passes a predetermined point on the main housing (reference pulse).
10. A rotor pickoff generates an electrical signal when a magnet on the rotor passes a predetermined point on the main housing (mass flow pulse).
11. A viscosity shroud pickoff generates an electrical signal when a magnet on the viscosity shroud passes a predetermined point on the main housing (viscosity pulse).
12. A signal conditioner houses the necessary electronics and microcomputer to provide the power input and signal compensation. Its output will indicate mass flowrate.

The viscosity measurement is particularly important to the high accuracy requirement. In most conventional flowmeter designs, there is no compensation for viscosity changes encountered at extreme temperatures. As a result of the varying velocity profile at different viscosities, expanded error limits are necessary at high (400K) and low (220K) temperatures. The viscosity shroud provides a measurement of the viscous drag in terms of the deflection of the spiral spring. The spring deflection, which is proportional to viscosity, is converted into a time base viscosity signal. This signal, when combined with the mass flowrate, will provide Reynolds Number information for the microcomputer to perform compensation. In addition, the viscosity shroud provides the function of shielding the rotor from the viscous drag.

### The Dual-Turbine Flowmeter

The principal advantages of the standard turbine flowmeter are:

1. Proven reliability.
2. Excellent repeatability (within 0.1%).
3. Good accuracy (within 0.5% when viscosity is known).
4. Pulse output, readily digitized.
5. Fast response (10 ms).

Disadvantages are:

1. Volumetric type.
2. Susceptible to swirl.
3. Affected by velocity profile variation.
4. Susceptible to viscosity changes.
5. Affected by bearing friction.

The high accuracy dual-turbine concept either eliminates or significantly reduces the disadvantages listed for the standard type turbine flowmeter.

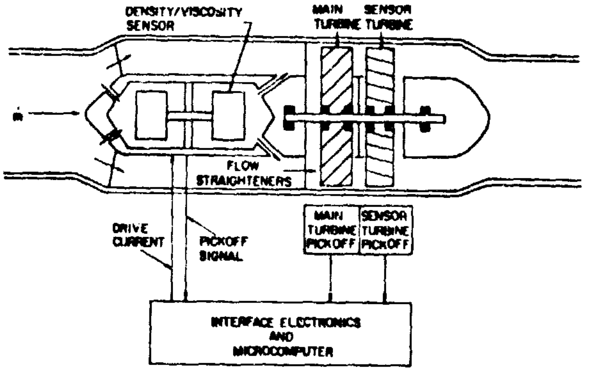

Figure 2 - Dual-turbine flowmeter

The HAFF turbine meter is shown conceptually in fig. 2. Its unique features are the addition of a density/viscosity sensor, and a second, reduced speed, counter-rotating sensor turbine. Volumetric flowrate is a constant times the sum of the main and sensor turbine pickoff frequencies as detailed in ref. 1. The sensor turbine has been added to provide accurate compensation for swirl which may be present in the incoming flow stream. The sensor turbine rotates in the direction opposite to that of the main turbine so that swirl will speed up one and slow down the other; then the frequency sum undergoes no change with swirl. Both turbines have six blades, but the sensor blade angle is less than the angle in the main turbine in order to increase overall linearity with laminar flow, as discussed in ref. 1. Furthermore, by monitoring the ratio of the turbine frequencies, the dual turbine concept provides a continuous self-check of bearing health.

### Densitometer-Viscometer

The dual-turbine flowmeter is a volumetric device and requires precise density and approximate viscosity data to perform as a mass flowmeter. General Electric currently produces a densitometer that oscillates at a frequency determined by fluid density. Fig. 3 shows a conceptual drawing of the densitometer being considered for use in the HAFF meter.

The two couplers joined via a spring vibrate in torsion 180 degrees out of phase. Piezoelectric crystals sandwiched between spring ends and each coupler act to either drive the system into oscillation or to pickoff torsional stress. Natural frequency decreases as coupler moment of inertia increases with increased fluid density. It is supported at the central nodal point so that no energy is transmitted to the three mounting tabs. Operational frequency is well above the normal range of environmental vibration (greater than 2 kHz). Ceramic couplers and a Ni-Span-C spring, carefully heat treated, reduce temperature sensitivity to less than 1/2 percent over the temperature range.

The effect which viscosity has on the frequency response of the spring-mass system can be measured and used to determine fluid viscosity. To do this, the mechanical resonator of the densitometer is retained and the simple loop-closing electronics of the baseline densitometer are replaced by more sophisticated driving and phase control circuits that provide a signal from which viscosity and density are calculated in the microcomputer.

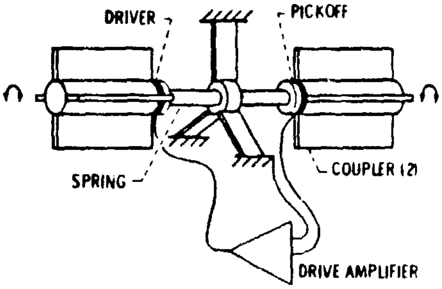

Figure 3. - Densitometer concept

A temperature sensor is provided to compensate for thermoelastic coefficient of the spring material and coefficient of thermal expansion of the coupler material. Although the spring and coupler materials are carefully selected and heat treated to minimize temperature sensitivity, the high accuracy requirement dictates that any temperature sensitivity be nullified.

## DATA ACQUISITION AND PROCESSING

The angular momentum prototype has a total of four electrical signal outputs. These include the transient turbine frequency, mass flowrate pulse, viscosity pulse and the reference pulse. The dual-turbine prototype has electrical signal outputs for the main and sensor turbines, density, viscosity and temperature. In either prototype, the conversion of these signals to mass flowrate through the various known calibration functions requires a dedicated computer to obtain meaningful results in real time.

A digital 16 bit microcomputer will perform these tasks in the production flowmeter system, but for the prototype evaluation, these computations will be performed by a laboratory data acquisition and processing system. In the laboratory system, frequency signals are routed to digital counters which send measurements to a digital bus and which are controlled or synchronized by the bus. The temperature information will be another input to the digital bus via a digital multimeter. Tests in the laboratory will be performed at steady state flow conditions with a data sample rate of 0.3 samples/second. The production flowmeter with its fast response time will require data sample rates at much higher rates, on the order of 6 to 30 samples/second.

The laboratory system uses a HP86A computer to control the data flow and it is programmed in Basic to compute mass flow. A monitor, disk storage, and printer/plotter complete the system.

## DESIGN SPECIFICATIONS AND PROTOTYPE TEST PLANS

Some of the salient specifications of the HAFF meter are listed below.

1. Measurand - Flowmeter output to be mass flow (both rate and total accumulated) measured either directly or as a combination of volume flow and density).
2. Accuracy - The program goal is an uncertainty not to exceed ±0.25 percent of reading.
3. Flow range - The fuel flow range of interest is 50:1 with a nominal full scale of 2.5 kg/s.
4. Pressure - Maximum operating pressure is 7000 kPa.
5. Pressure drop - At maximum flow, pressure drop is not to exceed 70 kPa.
6. Temperature - The fuel temperature span covers the range from 220K to 400K.
7. Response - Time constant not to exceed 25 ms.
8. Fuels - Aircraft fuels of interest include JP3, JP4, JP5, A-1 and Type A.

There are many additional requirements the HAFF meter must meet with respect to both safety and being able to operate in an aircraft engine environment. These requirements are too numerous to mention here and are not unique to the HAFF meter.

The test plan for the dual-turbine prototype involves several tests. The effects of inlet swirl on the angular velocity of both turbines and on the summed frequency will be determined. A second test will check on repeatability of the turbines with emphasis on the lower end of the flow range. Calibrations will be performed with fluids having different viscosities and over a wide range of temperatures to establish calibration factor vs. Reynolds Number. The densitometer/viscometer portion of the dual-turbine meter will be calibrated over the density, viscosity and temperature range of interest using various fluids and in-house precision standards.

Angular momentum prototype tests will begin with determining the output characteristic of the rotor in terms of time period vs. mass flowrate and the viscosity shroud output characteristics in terms of time period vs. absolute viscosity. A test to determine any thermal effect on the output will be performed.

Following these tests, the complete flowmeter systems for both prototypes will be tested for accuracy, repeatability, sensitivity to vibration and attitude, pressure drop, response time and alternate fuel capability.

## CONCLUDING REMARKS

The HAFF flowmeter development program has progressed to the point where two flowmeter concepts have been identified as having the potential for meeting the design goals. A prototype of the dual-turbine meter has been fabricated and testing has been started. The fabrication of the angular momentum meter is under way. Test results of the two prototypes will be used to select the best concept for building a complete flight-qualified flowmeter system.

## REFERENCE

1. Mayer, C., Rose, L., Chan, A., Chin, B., and Gregory, W., "High Accuracy Fuel Flowmeter," NASA CR 167893, March 1983.