Engineering Notes

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Fluidic Applications in Aerospace

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Introduction

THE purpose of this Note is to present examples of the successful use of fluidics in aerospace and, as an indication of the place of fluidics in aerospace, cite examples of research and development projects. A brief comment on the cost effectiveness of fluidics is also given.

Before presenting the applications, however, the meaning of fluidics might be helpful for those unfamiliar with it.

Definition of Fluidics

Fluidics is a technology that uses gases and liquids to perform amplification, logic, sensing, and control. Fluidics is, then, the general term used to denote a circuit or system utilizing fluid amplifiers or sensors. In some fluidic systems, the only fluidic devices may be a sensor and amplifier, while the remainder of the system is made up of interface devices, indicators, valves, regulators, and conventional electromechanical components.

Applications of Fluidics in Aerospace

The following applications of fluidics, while few in number, give a good indication of the proper use of fluidics. The first four applications are produced by AiResearch Manufacturing Company of Arizona.[1]

DC-10 Thrust Reverser Actuator Control

The first U.S. production aerospace fluidic application was for the thrust reverser actuator controls for the General Electric CF6 engine for the McDonnell Douglas DC-10. (This engine, with the same fluidic thrust reverser control, is also used on the European A300B Airbus.) The fluidic system reduces the thrust reverser actuator air motor speed after 90% stroke and limits torque at the end of stroke. A diagram of the fluidic circuit is shown in Fig. 1. A jet interrupted by a slotted wheel is the speed sensor, and the pressure difference across the air motor is the torque-limiting signal. After frequency-to-analog conversion (F/A), the speed signal is summed with the torque-limiting signal. The resulting signal is the input to an operational amplifier circuit with lead-lag compensation for system stability. The fluidic output controls the air motor actuator servocontrol valve to operate the brake and snubber valve on the air motor. The ambient temperature range is −40-177°C (−40-350°F) with bleed air supply at 316°C (600°F) and 5 bar (70 psig).

Concorde SST Thrust Reverser and Secondary Nozzle Actuator Control

On the Concorde SST, an air motor is used to drive a variable area nozzle on the exhaust of each engine, as well as actuate the thrust reversers. In addition to controlling thrust reversal, the fluidic circuit continuously modulates the variable area nozzle to optimize engine efficiency in response to altitude and Mach number signals. Ambient conditions range from −54-316°C (−65-600°F) and 0-24 km (80,000 ft). Bleed air supply is 260°C (500°F) at 2.4 bar (35 psig).

Lockheed S-3A Ram-Air Cooling Pressure Regulator

A fluidic three-stage amplifier gain block modulates a butterfly valve to maintain a pressure difference between a ram-air duct and an electronics compartment. The ram-air cooling augments and provides emergency backup for the normal environmental control system. Ambient conditions are −54-71°C (65-160°F) and 1500 m (5000 ft) altitude. Supply to the fluidics is 177°C (350°F) bleed air at 1.4 bar (20 psig).

B-1 Bomber Surge Control Valve

The auxiliary power unit (APU) for the North American Rockwell B-1 aircraft supplies compressor bleed air for main engine starting and for other ground power uses. A butterfly surge valve is modulated as a function of inlet temperature and total compressor airflow. The system schedules compressor bleed air during start, acceleration, steady-state, and transients to prevent compressor surge from compressor back pressure buildup. The electrical signal representing temperature is transduced to a fluidic signal, and summed with the pressure difference representing airflow. The summed signal is amplified with a fluidic three-stage gain block and controls the surge valve servo. Position feedback through a position-to-fluidic transducer improves accuracy and stability.

Pressure Ratio Sensor

Plessey Aerospace utilizes a fluidic pressure ratio sensor for the fluidic control and pneumatic ram system for variable guide vane actuation on the Rolls-Royce RB211−22 and −524 engines.[2] Fluidics has also been used in a fuel control

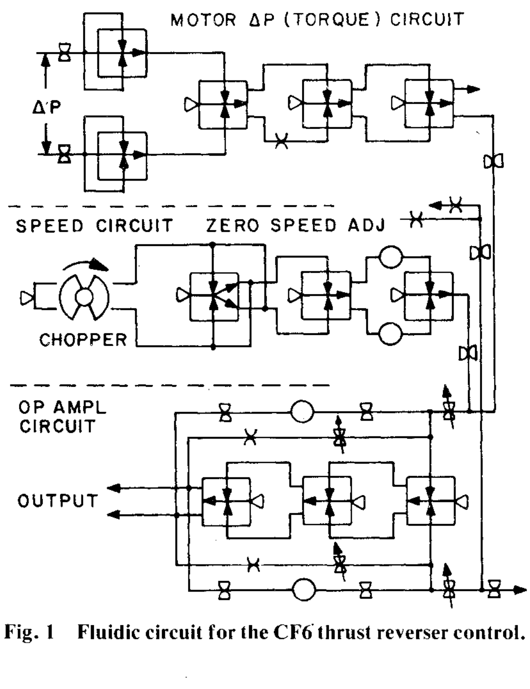

Fig. 1 Fluidic circuit for the CF6 thrust reverser control.

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system for the BS360/GEM engine for the Lynx helicopter. The pressure ratio device is said to be precise and reliable at operation to 14 km (45,000 ft).

Stability Augmentation System for Helicopters

Honeywell, Inc. has been directing their fluidics effort to the use of hydraulic oil as the working fluid. The primary application is for helicopter stability augmentation systems (SAS), which assist the pilot in performing the majority of control functions. Successful SAS flight tests have been conducted on the OH58 Jet Ranger, CH-54 Flying Crane, a prototype utility tactical transport system (UTTAS) helicopter, and an autopilot for the UH-1M.

Future Aerospace Applications of Fluidics

To avoid the purely speculative aspect of predicting future applications for fluidics in aerospace, a few examples of research and development projects will be cited. The majority of these projects are government funded and reflect the objectives of the fluidics community; however, these projects involve invested money and provide a reasonable indication of future use.

Ejection Seats

Fluidic systems are being investigated for sequencing[3] and two-axis control of ejection seats. Timing for chute deployment depends on altitude and speed. Sequencing is accomplished with a fluidic oscillator and counter circuit. Chute deployment squibs are initiated with the output of the fluidic counter by directing a jet of gas on a resonant tube. Gas in the resonant tube becomes hot enough to fire a detonator.

Pitch and yaw control of the seat is attained with vortex rate sensors and amplifiers to provide the signals for thrust vector control of a ball and gimbal nozzle.

Engine Controls

Gas turbine engine fuel controls with fluidic speed, temperature, and pressure-sensing circuits have been developed. The circuit output is interfaced with the fuel shutoff valve for control of startup, steady-state, and transient load operations. In APU and gas turbine missile applications,[1] the compressor discharge pressure is also an input to the fuel control system. A fluidic speed-sensing fuel shutoff system for free-turbine overspeed protection has operated in a 430°C (800°F) environment.[1] A low-pressure fuel flow distributor for jet engine combustors[4] is designed to give a logarithmic pressure-flow relation by using vortex valves.

Aircraft Environmental Control System (ECS)

Feasibility has been demonstrated for fluidically controlled ECS for high performance aircraft.[5] The F-4 aircraft air conditioning system was used as the model for the design. The system provides temperature control in the cabin and also protective functions, such as compressor inlet temperature, turbine overspeed, and water separator anti-ice control.

Compressor Surge

A research investigation on compressor-blade surge sensing[6] utilizes taps on a stator blade and a pitot tube between the rotor and stator blades. From tests on a particular compressor, the pressure-flow characteristics of the probes at the onset of surge can be used to switch a passive fluidic device.

Brake Control

Fluidic implementation of the existing electronic antiskid system for the Boeing 737 was found to be feasible.[7] In this system, the wheel speed is differentiated and compared to a pilot-selected brake-pressure level. Full brake pressure is available until the selected level is reached.

Flight Control Systems and Sensors

In the area of flight control systems, research and development programs have been funded for fly-by-tube as a backup, and dissimilar redundant systems for electronic fly-by-wire, low-cost inertial grade gyros,[8] an approach power compensator for carrier-based aircraft, and missile seeker torquing.

General Aviation

Feasibility studies on low-cost and low-maintenance autopilots and stall warning devices for general aviation light aircraft are being conducted. The studies are aimed at providing increased capabilities for the relatively inexperienced pilot without significantly affecting his workload, particularly under adverse weather conditions.

Cost Effectiveness of Fluidics

In the preceding applications, the overall cost effectiveness of the fluidic systems is the reason for using them. Weight reduction (or addition) has not been a factor in any instance. Initial and replacement costs for the fluidics may be comparable or less than conventional systems; however, the most significant savings are realized from the reliability of the fluidics. The data from the fluidic systems on the McDonnell Douglas DC-10, European A300B Airbus, Concorde SST, Lockheed S-3A, Boeing E-3A, and the North American Rockwell B-1 substantiate the reliability of fluidics.[9] Total aircraft operating time through June 1976 was approximately 5.5 Mh. During this period, there were 11 failures (nine from contamination and two from mechanical). The mean time between unscheduled removals (MTBUR) for the DC-10 thrust reverser is approximately 9500 h. This is over twice the 4000-h MTBUR for the conventional pneumatics on the 747 thrust reverser.

Summary

Fluidic systems are being used or considered for speed, temperature, pressure, angular rate sensing, and amplification in aerospace applications.

Fluidic systems are being used on operational aircraft in ambient conditions of −54-315°C (−65-600°F) and altitudes from 0-24 km (0-80,000 ft). Bleed air supply to fluidic systems can be as high as 177-315°C (350-600°F) at pressures of 1.4-6 bar (20-90 psig).

Fluidic systems are usually competitive in cost and performance with conventional systems, but the higher reliability and resulting lower maintenance of fluidic systems are a major consideration in the total cost effectiveness of the application.

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Deployment Forces in Towing Systems

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Introduction

THE equilibrium shape and tension of flexible towing cables have been investigated extensively in the past.[1-4] However, the cables must withstand much higher loads. Usually the towing airplane climbs with the towed system undeployed to a certain prescribed altitude where deployment takes place. When the cable is fully extended, it experiences a sudden stretch, due to the velocity difference between the airplane and the towed vehicle. This stretch generates tension forces in the attachment point to the airplane that are much higher than in equilibrium flight. This phenomenon is similar to the snatch force generated in parachute deployment.[5] The aim of the present Note is to develop an approximate solution to the deployment forces in towing systems.

Analysis

The exact treatment of the deployment process should take account of the sinking rate of the towed vehicle and the transverse dynamics of the cable. However, this has only a minor effect on the peak deployment forces. In the present model the whole process is assumed to occur in a horizontal plane. The cable is assumed to be uniform, having linear elasticity and negligible tangential drag forces.

The deployment starts with the release of the towed vehicle from the airplane, usually in constant-speed horizontal flight. As the vehicle decelerates behind the airplane, it pulls out the cable. At the end of the deployment process the extended cable has the same velocity v_f as the decelerated vehicle. It then suddenly obtains the velocity v_0 of the towing airplane. This generates a downstream running stress wave, originating at the point attached to the airplane. The magnitude of the stress wavefront is known from the theory of elasticity to be

$$\sigma = E(v_0 - v_f)/C \tag{1}$$

where C is the wave propagation velocity and E is Young's modulus.

When treating the problem of waves in a finite solid, one has to consider also the effect of reflected waves. However, towing cables are usually very long, so that even a small amount of internal damping is enough to attenuate the stress wave, causing it to almost vanish before returning upstream. The peak stress in the cable during deployment is thus given by Eq. (1), where only the final velocity v_f is unknown.

Using the notations of Fig. 1, one obtains the rate of cable pullout and equation of motion of the towed body, respectively.

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$$\frac{\mathrm{d}x}{\mathrm{d}t} = v_0 - v \tag{2}$$

$$T - D = m\frac{\mathrm{d}v}{\mathrm{d}t} \tag{3}$$

The cable equation of motion may be deduced by equating its change of momentum to the impulse exerted by the towed body

$$-T\Delta t = \mu(x+\Delta x)(v+\Delta v) - (\mu x v + \mu \Delta x v_0) \tag{4a}$$

where μ is the cable mass per unit length. This yields

$$-T = \mu\frac{\mathrm{d}(vx)}{\mathrm{d}t} - \mu v_0\frac{\mathrm{d}x}{\mathrm{d}t} \tag{4b}$$

By adding Eqs. (3) and (4b), writing the drag of the towed body explicitly, and dividing by Eq. (2), we get

$$\frac{\mathrm{d}}{\mathrm{d}x}[-\mu(v_0-v)x + mv] = -\frac{\rho S C_D v^2}{2(v_0-v)}$$

where S and C_D are the area and drag coefficient of the towed body, respectively. Performing the differentiation on the lefthand side, separating the variables and defining

$$\alpha^2 = \frac{\rho S C_D}{2\mu} \tag{5}$$

one gets

$$\int_{v_0}^{v_f}\frac{(v_0-v)\,\mathrm{d}v}{(v_0-v)^2-\alpha^2 v^2} = \frac{\mu}{m}\int_0^{\ell}\frac{\mathrm{d}x}{1+\mu/mx}$$

The integration is straightforward, yielding an expression relating the final velocity to the parameter α and the mass ratio $\mu\ell/m$

$$\tfrac{1}{2}\left(\frac{v_f}{v_0}-1\right) - \tfrac{1}{4}\ln\left(2\frac{v_f}{v_0}-1\right) = \ln\left(1+\frac{\mu\ell}{m}\right) \qquad (\alpha = 1) \tag{6a}$$

$$\frac{\alpha^2}{\alpha^2(v_f/v_0)^2-(1-v_f/v_0)^2}\left[\frac{(1+\alpha)v_f/v_0-1}{1-(1-\alpha)v_f/v_0}\right]^{\alpha} = \left(1+\frac{\mu\ell}{m}\right)^{2(1-\alpha^2)} \qquad (\alpha \neq 1) \tag{6b}$$

In both cases, if the mass of the cable is much greater than the mass of the towed vehicle, the final velocity tends asymptotically to

$$\frac{v_f}{v_0} = \frac{1}{1+\alpha} \tag{7}$$

which determines an upper bound to the peak deployment stress

$$\sigma_{\max} = E\frac{v_0}{C}\frac{\alpha}{1+\alpha} \tag{8}$$

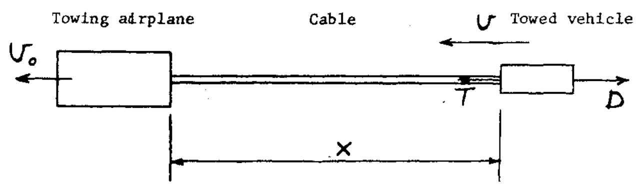

Fig. 1 Schematic diagram of towing system.