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ROTATIONAL FLUID FLOW EXPERIMENT

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WORCESTER POLYTECHNIC INSTITUTE

This project, begun in 1986 as part of the WPI Advanced Space Design Program, focuses on the design and implementation of an electromechanical system for studying vortex behavior in a microgravity environment. Most of the existing equipment was revised and redesigned by this project team, as necessary. Emphasis was placed on documentation and integration of the electrical and mechanical subsystems. Project results include reconfiguration and thorough testing of all hardware subsystems, implementation of an infrared gas entrainment detector, new signal processing circuitry for the ultrasonic fluid circulation device, improved prototype interface circuits, and software for overall control of experiment operation.

INTRODUCTION

Many fluid mechanical phenomena involve dependance on more than one scaling parameter. A vortex is a good example of a practical concern when a design involves the flow of a liquid into an inlet. Understanding vortex formation is important, and involves three governing parameters. These parameters are the Reynolds number, the Froude number, and the Weber number, representing viscous, gravitational, and surface tension forces.

$$Re = \rho \frac{VD}{\mu}, \; Fr = \frac{V}{\sqrt{gD}}, \; We = \rho V^2 \frac{D}{s}$$

A vortex can be described as a rotational flow that forms a low pressure region at its center. Vortices are typically found in pump systems and, most commonly, in a bathtub or kitchen sink drain. The effects of vortices extend into the areas of hydrodynamics, aerodynamics, and hydraulics, playing important roles in determining the efficiencies of systems.

ADVANTAGE OF MICROGRAVITY

Pump performance can be altered significantly by designs that create an approach flow with large amounts of vorticity. For instance, a large vortex will cause a pump to pull air along with the fluid being pumped, which makes the pump less efficient and is characterized by surging of the pump system as vortices form and break. The result is unstable pump performance with undesirable accelerations and decelerations of the flow, and structural vibrations that lead to erosion of pump parts. Loss of pump efficiency due to vortices is estimated to be several percent.

Problems arise in scaling vortex flow from laboratory models to prototype dimensions, since experimenting with a full-size prototype is often not feasible. Results from models will be usable only if there are geometric, kinematic, and dynamic similitude. Geometric similarity requires the model and the prototype to be the same shape so all linear relationships between the model and the prototype are related by a constant scale factor. Kinematic similarity requires a constant scale factor between the velocities of the model and the prototype. Dynamic similarity indicates that all force relationships between the model and the prototype are related by a constant scale factor. Therefore, if two flows are dynamically similar, they are also geometrically and kinematically similar.

On Earth it is rarely possible to achieve a this dynamic similitude. A simple observation reveals that if D is increased, the Reynolds number increases by that factor, while the Froude number decreases by the square root of that number. This nonlinear relationship between the Reynolds and the Froude numbers preclude dynamic similitude between the model and the prototype. The way to maintain a linear relationship that will allow for a constant scale factor for different sizes of models (different D) is to vary gravity inversely with D. This cannot be achieved for gravities less than 1 *g* on Earth, but can be achieved in the GASCAN environment in the space shuttle.

The microgravity environment of space makes it possible to induce and vary gravity, which for this experiment, will be varied between micro-(10^{-6}) and 2-*g*. Both geometric and dynamic similitude between the model and the prototype may thus be achieved, and scale effects virtually eliminated.

PROPOSED EXPERIMENT

The Rotational Fluid Flow Experiment is designed to study the effects of varying conditions on the strength of a rotational fluid flow in a non-terrestrial environment. To accomplish this, several devices have been designed and built to alter the gravitational level of a swirling fluid and to gather data on the effects of such variations.

The apparatus uses a small container, about the size of a beverage can, with a 1/4-in-diameter hole in the bottom. Liquid that flows out of the hole is returned to the container by a pump. The entire apparatus is rotated about an axis perpendicular to the container axis producing centripetal acceleration. The liquid collects in the bottom of the container and flows out the hole. For high enough flow, a vortex, similar to a bathtub drain vortex, will form in the container. The vortex can be measured by optically recording the liquid surface shape. Air entrainment can be detected by sensing air bubbles in the outlet tube.

APPARATUS

A rotating platform supports all mechanical and electrical equipment needed to conduct the experiment. In addition to the major flow components, including the pump and the vortex chamber, there is a photographic data collection system composed of a camera, mirror, and flash. The mechanical hardware is divided into three major groups: the flow system, the rotating platform system, and the photographic system.

Flow System

The major part of the experiment is the flow system. This system includes a positive displacement pump, the cylindrical chamber that will contain the vortex, aluminum tubing, and the bubble sensor (Fig. 1).

The vortex chamber is cylindrical and consists of an ultrasonic transducer mount, two cylindrical pieces of lucite (4-in ID × 1/4-in thick), a cap, and a base. The ultrasonic transducer mount is specifically designed to hold the transducers for the ultrasonic circulation meter. The mount does not have to be located at any particular height along the cylinder since the circulation of the vortex, once it has reached a steady state, is constant along the height of the cylinder. Presently, the transducer mount is located in the lower third of the cylinder so as not to obstruct the camera view of the vortex. Although the design of the base resembles that of the cap, the base has an 0.20-in diameter exit hole. To prevent fluid leakage from the cylinder, O-ring seals are used for all connections.

Another critical component of the flow system is the bubble sensor. On occasional experimental runs, it was observed that the vortex can gain such high vorticity that air bubbles begin to exit the cylinder and enter the pump. Since at low gravity levels it will be difficult to purge the flow system, a bubble sensor is used to detect the initial passage of bubbles. The bubble sensor is installed in the aluminum piping at the exit of the cylinder. If bubbles are detected, a feedback signal is generated.

The pump recycles the fluid exiting the vortex chamber back into the top of the chamber. Tangential injection creates a swirling mass of fluid that becomes a vortex. The drive motor for the pump is controlled using the onboard computer and a pulse-width modulated controller. The pump speed accurately determines flow rate so that independent measurement is not necessary. Based on results of extensive experiments conducted in the 1-*g* environment, the flow range for the pumping system was selected.

The cylinder is placed horizontally with the cap at the center of the platform and the base at the edge.

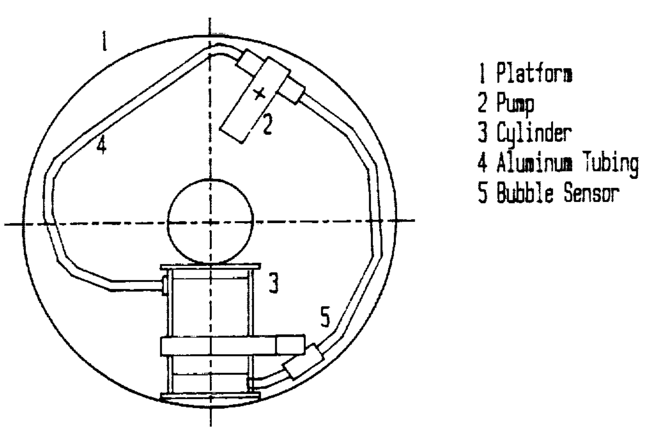

Fig. 1. Flow System

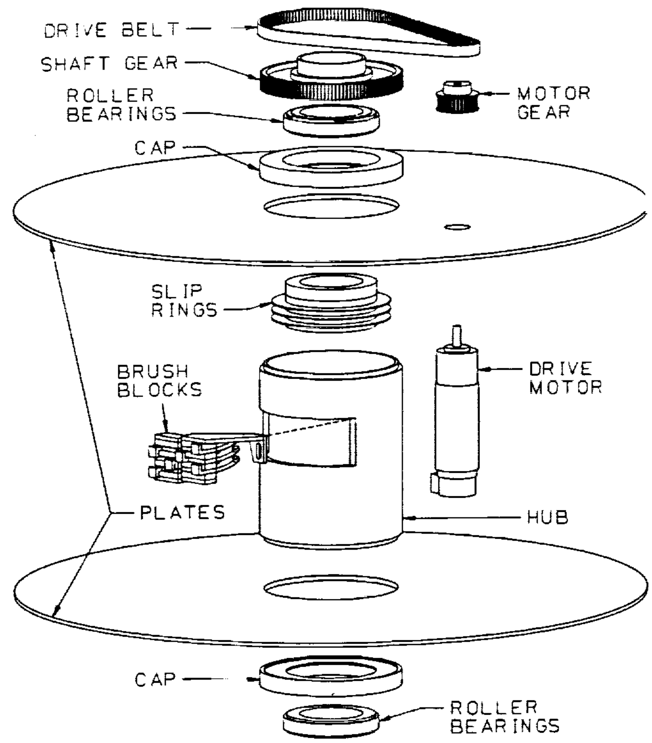

Fig. 2. Rotational Drive Equipment

Rotating Platform System

All equipment, both mechanical and electrical, is mounted on the platform (Fig. 2). This rotating platform is made from aluminum and consists of a hollow cylinder with two large, circular mounting plates, one at either end. The cylinder portion of the platform houses the mechanism by which the experiment is connected to the GASCAN mounting shaft, which forms the platform axle. The cylinder also houses the slip rings that carry electrical power to the experiment. The circular plates on the ends of the cylinder provide the surface to mount the experiment components and insure structural stability, including maintenance of a sufficiently high frequency for the first vibrational mode.

The central shaft of the structure is made of aluminum and is 2 in. It is hollow to allow the power cables to be run from the battery box to the other experiments, and for routing cables to the NASA interface. Since the Rotational Fluid Flow Experiment is located at the bottom of the GASCAN, its installation is facilitated.

The slip rings are part of the power supply delivery system that are attached to the mounting shaft. The brushes are connected to the cylindrical portion of the platform. As the platform rotates, the brushes keep in constant contact with the slip rings, thus providing electrical power to the experiment. The input side of the slip rings is connected to the battery supply and the output side to the equipment in the experiment needing electrical power. Three different voltages are provided and all are switched on by a signal from crew.

An electric motor is used to rotate the experiment package. It is mounted to the top mounting plate of the rotating platform. The shaft of the motor protrudes far enough through the plate to allow for a small, toothed pulley to be attached to it. The pulley is essential to insure that the motor shaft and drive belt are positively connected. The pulley also has top and bottom edges to insure that the drive belt does not slide off the shaft.

The drive pulley is mounted onto the shaft just above the platform. The pulley serves a twofold purpose. First, it is fixed to the shaft, which enables the platform to rotate. The drive belt connects the pulley and the motor gear. Secondly, the collar used to attach the pulley to the shaft also serves as the top mounting bushing for the platform. The canister plate underneath and the pulley above prevent the platform from moving up and down on the shaft. The collar of the pulley is made of aluminum; the pulley itself is plastic. The pulley is fixed to the shaft with set screws.

The drive belt is a reinforced rubber belt. It is smooth on the outer side; the inner surface is notched to mate with the teeth of the pulleys. Since the notched surface of the belt exactly matches the teeth of the drive pulley, slipping of the belt is avoided.

The drive motor is controlled using a pulse-width modulated system to conserve electrical power. Signals to the controller come from the onboard computer system.

Photographic System

The camera and flash provide a visual record of vortex formation. From the photographs, it will be possible to see vortex shape as a function of the *g*-levels being experienced (Fig.3).

The camera experiment is a commercial unit that was modified for electronic activation. The camera selected was required to operate under expected environmental conditions, and to have features such as autowind, short focusing distance, flash capability, and the ability to be triggered by an electrical impulse. The greatest environmental concern is the low temperature that the camera and film will be exposed to when operating in orbit. The worst-case scenario, in which the space shuttle bay would be facing space for long periods of time, would result in a temperature as low as -30° C. The camera must be able to operate at that temperature without experiencing mechanical and/or electrical failures in any of its components.

To evaluate the effects of temperature, tests were conducted on a 400 ASA black & white film. Pictures were taken immediately after the film was taken out of the freezer and then developed after refreezing the film. The film was virtually unaffected by the low temperature environment and the pictures developed well. The only remaining concern is that when the film becomes brittle at these low temperatures, breakage might occur while the camera is winding to the next frame.

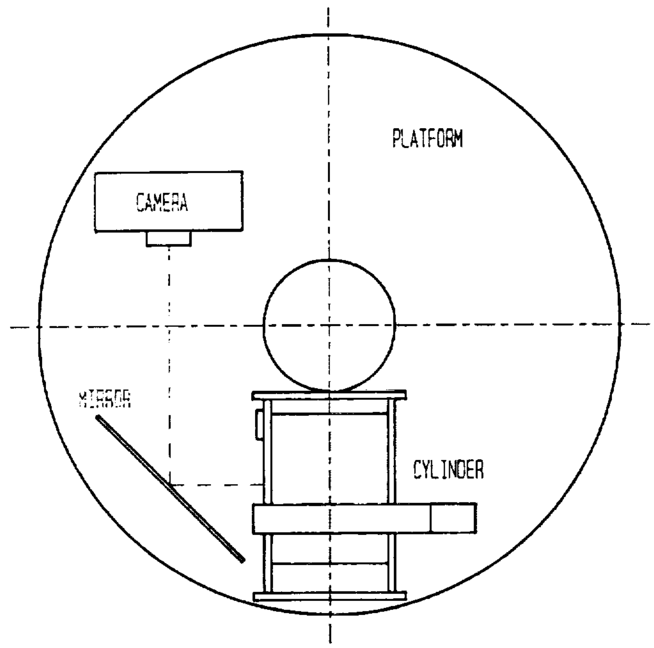

Fig. 3. Camera Arrangement

The camera that was chosen is a 35mm Pentax A4000 model, which can not only be electrically triggered, but has an autowind system built into the body. The camera must be capable of using alkaline batteries, since the use of lithium batteries is prohibited by NASA gas safety regulations.

The camera is controlled by the CPU, or Central Processing Unit, which also sends the signals to the pump and platform drive. The CPU first sends a signal to supply power to the camera and then a trigger signal to take a picture. After the picture is taken, the CPU sends another signal to disconnect the camera from the power source. This process is be repeated every time the CPU sends a signal to the pump at the start of a new experimental run.

HISTORY OF EXPERIMENT DEVELOPMENT

The Rotational Fluid Flow Experiment, begun in 1986 as part of the Worcester Polytechnic Institute's Advanced Space Design Program, required an investigation of design for experimental hardware, determination of significant parameters to be measured, and examination of a variety of measuring devices and controlling systems. In the five years that the experiment has been under development, many ideas for construction of different subsystems have been designed, constructed, tested, and, if not feasible, changed completely.

Developments during early years of the project included choosing the offset injection method over the rotating screen method to induce a vortex in the vortex chamber, as well as laying out the schematics of the fluid-flow subsystem (pump, flowmeter, and piping, Fig. 4). The fluid-flow subsystem is the most important subsystem in the experiment since it produces the vortex. The pump recycles the water from the chamber back into the piping and across the flowmeter. The flowmeter's main function was to measure the volumetric flow rate of the fluid. As part of the electrical subsystems, work was begun on the different circuits that would monitor volumetric flow rate, flow circulation, core and dimple depth, effective gravity induced by the rotation of the platform, air entrainment within the piping layout, pressure and atmosphere conditions within the vortex chamber, as well as electrically activating and deactivating all the mechanical equipment to start and stop experimental runs. The measurements allow the calculation of the Reynolds, Froude, and Weber dimensionless parameters that describe the vortex flow at varying gravities. The scaling effects associated with vortex modeling can then be eliminated.

Other developments included determination of the working fluid and actual hardware procurement. The first piece of hardware developed was the rotating platform, that was designed as a modular component is independent of the rest of the experiment and can be used for other research in the future (Fig. 5). Once the hardware was manufactured, the drive motor and slip rings used to control the platform rotation were obtained. Another part of the experiment developed and built previously was the vortex formation cylinder. The cylinder is made of clear lucite and consists of three basic parts, the cylinder itself and the two end caps. The pump for the working fluid was also obtained with some aluminum tubing and steel fixtures to be used as piping for the flow system. Another major accomplishment of the previous groups was determination of the working fluid. The two major constraints of the working fluid are that the fluid maintain a constant viscosity in the extreme temperature differences experienced in the GASCAN and that the fluid be able to support vortices at a wide range of flow rates.

After studying the mechanics of the microgravity experiment, it was determined that an experiment based on Earth would be of significant value. The most persuasive reason for the on-Earth experiment was the feasibility of vortex formation even

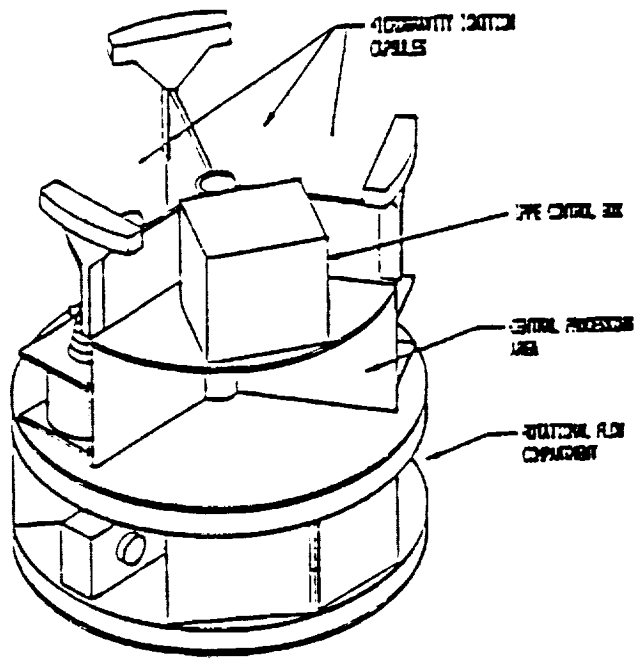

Fig. 5. GASCAN II Layout

with the unusual forces being placed on the fluid. It was unclear from static tests whether the data gathered by the microgravity test would be of use, or if a vortex would form at all. The on-Earth test is a slightly modified and simplified version of the space-based experiment. The most important modification is to suspend the cylinder from the edge of the rotating platform so that it can swing freely to the proper orientation for the speed of rotation In this way, the resultant force vector is as close as possible to that which would be experienced in space.

Other testing determined the best placement for the camera and flash on the platform to avoid too much glare or too little light when the picture is taken.

During this project year several modifications were made to the existing electrical equipment, and some new components were added. Programs were written to test the functioning of the 8088 CPU, DS-64, MOR-800 boards, and 8155 and 8255 chips. The programs ran successfully and proved that those components operated properly. Also, each subcircuit in the gas entrainment detector was tested for proper operation once the design was completed and built. These tests also proved successful. Once all the electrical components were tested and their operation verified, they were interconnected and mounted. A complete software program was developed to control the function and timing requirements of the entire electromechanical system. After the program was written, a final, general test was run on the entire integrated system.

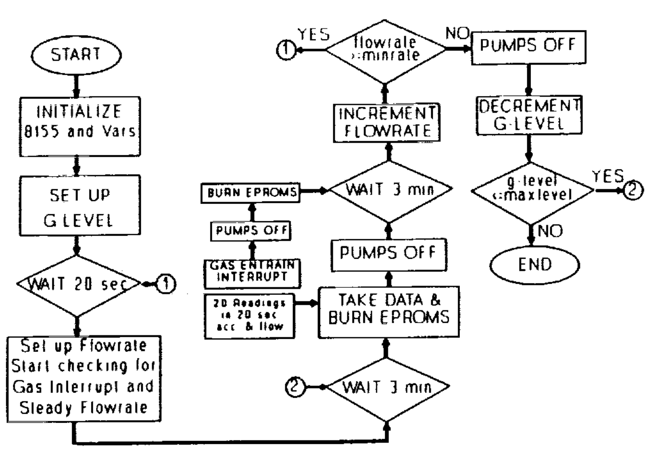

Fig. 4. Flow Chart Timing Diagram