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Phillips Laboratory and its industrial partners have invested considerable resources into the development of hydrostatic bearings and their applications to turbopump technologies. The hydrostatic bearing has a thin film of high pressure fluid as a layer between the turbopump shaft ad the hydrostatic bearing. This concept decreases the weight and increases the lifetime of the turbopump by eliminating friction between bearing surfaces. The liquid hydrogen hydrostatic bearing program at the Phillips Laboratory is a materials program in which the best material combinations between bearing and shaft will be determined. To accomplish this task, an effective turbopump simulation is required. To achieve this simulation, high speed software couple with servomechanisms are used. This paper will demonstrate how an Allen Bradley Programmable Logic Controller (PLC), a hydraulically actuated valve, and a multiorifice digital valve can effectively simulate a turbopump environment.

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THE DIGITAL VALVE AND LIQUID HYDROGEN
HYDROSTATIC BEARINGS

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Abstract

Phillips Laboratory and its industrial partners have invested considerable resources into the development of hydrostatic bearings and their applications to turbopump technologies. The hydrostatic bearing uses a thin film of high pressure fluid as a layer between the turbopump shaft and the hydrostatic bearing. This concept decreases the weight and increases the lifetime of the turbopump by eliminating friction between bearing surfaces. The liquid hydrogen hydrostatic bearing program at the Phillips Laboratory is a materials program in which the best material combinations between bearing and shaft will be determined. To accomplish this task, an effective turbopump simulation is required. To achieve this simulation, high speed software coupled with servomechanisms are used. This paper will demonstrate how an Allen Bradley Programmable Logic Controller (PLC), a hydraulically actuated valve, and a multiorifice digital valve can effectively simulate a turbopump environment.

Introduction

The goal of the hydrostatic bearing program is to simulate the transient phases of a turbopump to determine the wear characteristics of material combinations for the next generation of turbopumps. The program will test five different material combinations between the shaft and the concentric bearing. The combination will vary between hard to hard and soft to hard. With hydrostatic bearings, during nominal operation, a thin high pressure layer of liquid hydrogen is present and no wear occurs on the bearing. However, during startup and shutdown phases, supply pressure is very low and the thin film cannot support the loads present, and a small amount of wear may occur.

This program will test five different materials to determine their feasibility. To achieve this goal, turbopump simulation is very important. To simulate the turbopump pressures, a multisized orifice control valve with a fast response time is necessary. This digital valve, in conjunction with a proportionally controlled hydraulic valve controlled by a PLC, will simulate the transient phase of the turbopump spinning up to 10,000 rpm at a ΔP across the test rig of 50 psid in the manner of a second.

Test Facility

The hydrostatic bearing evaluation will occur at Area 1-52 C+D Pad at Phillips Laboratory Operating Location at Edwards Air Force Base, California. To support the program, a modern cryogenic liquid hydrogen facility was constructed. The test stand included various liquid and gaseous propellants.

Liquid hydrogen is the liquid propellant used for the high pressure fluid in the hydrostatic bearing. Liquid propane is used for the flare stack system. Gaseous nitrogen is used for purges and for turbine supply pressures. Helium is also used for purges. Gaseous hydrogen is produced from the liquid hydrogen and used for a pressurant of the liquid hydrogen for the test rig.

The test stand (layout shown in Fig. 1) has the capability of 6000 psig in each of the three gaseous systems. The liquid hydrogen is stored in a 23,000-gal storage tank. The storage tank is connected to a liquid hydrogen cryogenic pump that pumps the liquid up in pressure at a rate of 10 psig a minute and then sends the liquid through a vaporizer where it is converted to gas and stored in the 600-ft^3 gaseous hydrogen storage tanks. The liquid hydrogen storage tank is also manifolded into a 300-ft transfer line which is connected to both the run line and the run tank. The run tank is a 1200-gal, 6000-psig

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tank that is pressurized from the gaseous hydrogen storage tanks. The run tank connects to the run line, which connects to the liquid bearing supply valve. This feeds into the hydrostatic bearing test rig. The hydrogen flows from the test rig into a flare stack for incineration.
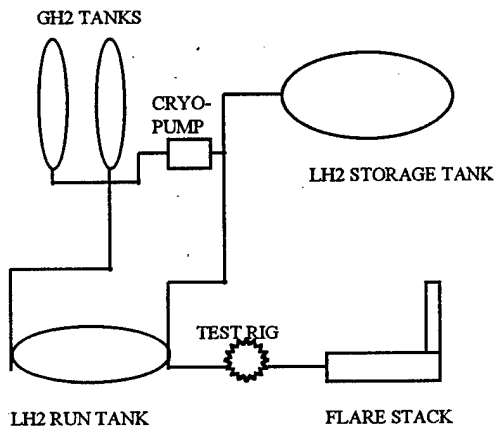

Fig. 1. Test Stand Layout

The test rig was designed by Pratt & Whitney and contained three bearings. The top bearing, the reaction bearing, and the bottom bearing (the slave bearing) are all fixed bearings. The middle bearing is the test bearing and is forced by loader arms to apply a load of 50 lb_f to the shaft. By forcing the shaft against the bearing during the simulated transient phases of the turbopump, wear characteristics of five different material combinations can be determined.

The turbopump simulation is achieved through the combination of the gaseous nitrogen digital valve and the proportionally controlled hydraulic liquid bearing supply valve.

Test Apparatus

The test rig (as seen in Fig. 2) was designed to withstand 5000 psig. The entire rig is constructed of AMS 5664, a dimensionally stable heat treat of Inconel 718. By using one material for the rig, fits and clearance changes due to various operating temperatures are minimized.[1] The maximum operating speed is a function of the bearing; therefore it is not DN limited. The maximum operating speed of the
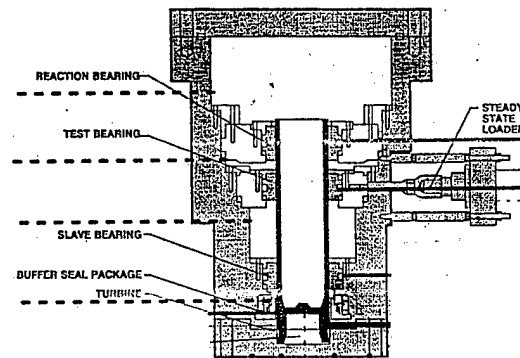
baseline configuration is 83,500 rpm.[1]

Fig. 2. Cross-sectional View of Test Rig

The rpm of the shaft is set by using the gaseous digital valve. This valve was designed by Engineering Measurements Company (EMCO) and is multiorificed. The 11-bit digital valve is used to simulate the turbine drive pressure, which imparts at least a 10,000-rpm rotation to the shaft. Each orifice has a different orifice sizing. This 11-bit system can provide a total of 2047 possibilities to impart the 10,000 rpm.

Although transfer of information can be accomplished through the use of bits, it was determined that it would be more successful to translate commands through a word. By definition, a word consists of 16 bits. By masking out the five most significant bits of the word, through non-electrical hookup, a word can now be commanded with 11 bits. The gaseous digital valve contains 11 elements, enabling the multi-orifice position to be encoded through the use of a word. The binary signal for all 11 elements open would be:

(binary) 0000011111111111=2048 (decimal) (1)

The equation for the total number of possibilities to achieve a desired speed is:

$$2\wedge n-1 \qquad (2)$$

Therefore, the total number of possibilities to impart any given speed is 2047. The digital valve is a binary system and speaks the same language as a computer. Therefore, no time is lost in translation from analog to digital conversion. The valve can be operated in either a manual mode, where each element can be individually opened or closed, or in an

automatic mode where the desired turbopump rpm ramp can be simulated using a proportional integral derivative (PID) loop through the PLC. A cross-sectional view of the valve is shown in Figure 3.
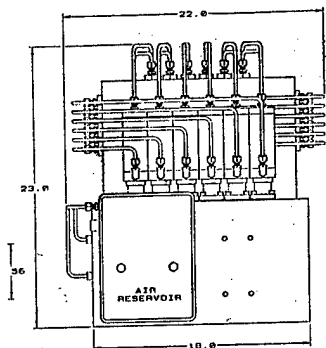

Fig. 3. Cross-sectional View of Gaseous Digital Valve

The use of proportionally controlled valves is exercised to the fullest extent in the hydrostatic bearing program. During operations, the test rig is maintained at 200 psig. This is accomplished by using a bearing back pressure valve that is downstream of the bearing vent lines. This valve is a hydraulically operated PID-controlled valve using the PLC touch screens as a user interface. To maintain 200 psig in the test rig, the bearing back pressure valve needs to be set at 185 psig. The valve is operated through a pressure transducer and sets itself to a position where 185 psig can be obtained downstream of the test rig. It will open or close slightly to maintain this pressure. It is a Y-body stainless steel valve that is rated at liquid hydrogen temperatures of -423°F. A cross-sectional view of the valve is shown in Figure 4.
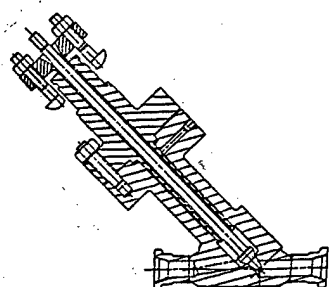

Fig. 4. Cross-sectional View of Y-body Valve

In addition to the bearing back pressure valve, the test bearing supply valve is also a proportionally controlled hydraulic valve. This valve supplies the liquid hydrogen to the test bearing and applies the thin viscous layer of hydrogen between the shaft and the bearing. Similar to the bearing back pressure valve, the test bearing supply valve is also controlled through a PID loop. The valve can also be operated through manual control in which it is opened in 5% increments. It simulates the turbopump pressure ramps and is the equivalent of the gaseous digital valve except that it simulates pressure by controlling the ΔP across the test rig. It is a Y-body valve made out of 316 stainless steel and operates at liquid hydrogen temperatures of -423°F.

In addition, there are other valves used for the chilldown process. By opening or closing this set of valves, the rig is chilled down through the vent or supply lines. Figure 5 shows the layout of the valves connected to the test rig.
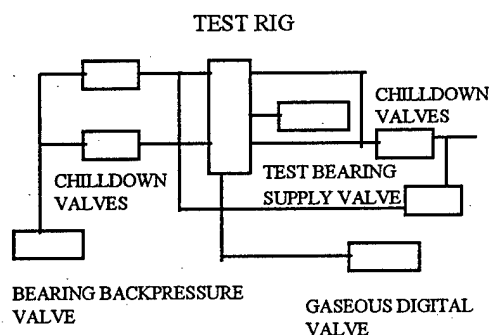

Fig. 5. Layout of Test Rig and Valves

Turbopump Operations

A typical operation using the test rig includes purging of the rig with low pressure helium and nitrogen. Gaseous helium is used for those sections operating with liquid hydrogen for the purpose of evacuating contaminants from the lines. The next step is to start chilling down the rig with the low temperature cryogen. The buffer seal supply line is then pressurized to prevent the liquid hydrogen from entering into the turbine area. The chilldown is accomplished through the bearing vent lines. This is done to prevent high velocity gas flow from entering

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into the bearings, which induce a pneumatic hammer instability.[1] Once the bearing vent temperatures indicate that the rig is chilled down, the chilldown is completed by sending the liquid hydrogen through the proportionally controlled hydraulic bearing supply valve and the bearing supply lines until test rig temperatures indicate liquid hydrogen is present in the test apparatus.

The test rig pressure is increased to 200 psig from chilldown pressures through the slave bearing supply lines, and the buffer seal pressure is increased. The shaft, supported radially by the slave bearings, is being pushed down onto the thrust bearing, and the rig is maintained at 200 psig.

The bearing supply valve is then opened, supplying liquid hydrogen to the test bearing. The valve is also tested to the point at which vibration occurs in the rig. This point is determined, and the valve will not be opened farther than that for the desired transient ramps of the test rig.

The thrust bearing back pressure is pressurized to 185 psig with gaseous nitrogen. This flow will leak around the turbine, venting out the turbine exhaust. The gas thrust bearing is then pressurized to 1550 psig, which levitates the thrust bearing.

The turbine supply pressure is increased to 400 psig and, using the gaseous digital valve, the desired rpm can be reached.

Simultaneous ramps of the gaseous digital valve and the bearing supply valve will simulate the pressures and speed ramps of the turbopump. While this is occurring, forced loads of up to 50 pounds will be applied to the shaft by pulling the test bearing to one side of the test rig or the other.

Electronic Hardware

To achieve the proper turbopump simulation, different instrumentation hardware configurations are used. The major components consist of the PLC, a CYBER Systems Incorporated Data Acquisition System (DAS), and a plethora of transducers.

The PLC is a multiprocessor configuration with a dedicated 5/15 processor to achieve maximum response on all turbopump ramp related control algorithms. By using two processors, one processor is able to concentrate on high speed ramps while a 5/60 manages facility controls. Facility controls consist of a cornucopia of discretely controlled valves, liquid level indicators, facility lighting, camera controls, and remotely controlled pressure regulators that govern the operation of the test stand.

To improve user interface, five touch screens are used. Three of the screens, which are based from the 5/60 controller, control the operation of the three major propellants – nitrogen, helium, and hydrogen. The fourth screen controls facility items such as cameras, lighting system, flame detection notification, and recording rates of the data acquisition system. The fifth screen governs the turbopump simulation. Through PID loops, the gaseous digital valve and the test bearing supply valve simulate turbopump operations. This screen is attached to the 5/15 controller.

A Very High Speed Counter Module (1771-VHSC) reads the rpm signal at a response rate of 1 MHz. Originally, a standard PLC counter module was used, but the rpm frequency of the turboshaft superseded the capability of this device. The 1771-VHSC far exceeds the maximum frequency expected from the rpm sensor.

The DAS is a UNIX-based system with a 100k samples per second (sps) aggregate throughput capability, real time and replay x-y plots, strip charts, and tabular displays. The DAS has 104 channels at a 512-sps record rate. Thanks to in-house software modifications and a parallel port, strip chart and x-y plot data can be printed into a hard copy format in a manner of seconds. This greatly improves on the previous serially encoded 15-min hard copy production. It also allows faster data analysis, enabling quick modifications to control algorithms in a minimum amount of time for quicker repeat of tests and large propellant cost savings.

Data is communicated to the DAS through a vast array of pressure and temperature transducers. There are 69 Teledyne Taber pressure transducers with a ±0.1% repeatability. The output voltage of these devices is 3 mV per every volt of excitation. In addition to the pressure transducers, there are two 4-20 mA transducers used for automated tank venting. The 29 temperature transducers have an accuracy of ±4°F.

In addition to the transducers, there are six eddy current transducers (probes). Eddy current

probes measure the displacement movements (distance) of a shaft within a bearing.[2] Four of the probes are used for axial displacement and one is used for radial. The sixth probe is used for an rpm reading based on the notches on the bottom of the shaft. As the shaft spins, the notches machined into the bottom of the shaft cause the eddy probe to generate a frequency one-fifth of the rpm. A simple algorithm built into the PLC converts this number into a displayable rpm reading.

An Uninterrupted Power Supply (UPS) system can supply power for approximately 1 hr to the 110 and 28V test stand hardware. In addition, the control room has a UPS that can supply power for all control room operations for up to 7 hrs.

Computer Software

In the PLC programming there are two different modes of operation – manual and automatic. These modes are selected via touch screen, dictating which subroutine path the PLC will follow. Both the programming of the gaseous digital valve and the test bearing supply valve use this algorithm.

The gaseous digital valve regulates the speed of the turbo shaft. In the manual mode, each element can be opened uniquely or in combination to produce any given speed. In the automatic mode, there is a sequencer that reads a set point rpm from a data file for each given point in time. Therefore, one word at a time is fed into the PID loop for that set point rpm. The digital valve, in return, will achieve that rpm by matching the binary word value for the corresponding opening and closing of elements in the digital valve.

The test bearing supply valve regulates the pressure differential across the test bearing. As in the digital valve, but opposed to opening discrete elements, the hydraulic valve is actuated in 5% increments. In the manual mode, this is used to determine the maximum opening of the valve before hammer of the test article occurs. In the same manner that the gaseous digital valve attains its desired rpm set point, the test bearing supply valve achieves its maximum ΔP.

A red line condition exists in the PID programming loop. If a minimum rpm is not reached by the third set point in time, the ramp process is shut down and a status window alerts the user of an impending problem. This problem could be the binding of the turboshaft, which would damage the test article.

In addition, the programming adds the versatility of allowing both control valves to operate independent of each other. In essence, the gaseous digital valve can be in the automatic mode while the test bearing supply valve is in the manual mode and vice versa.

Transients

The transient phases, otherwise known as the start and stop transients of the turbopump, are the primary purpose for this materials testing program. When the thin high pressure layer of hydrogen is present, very little wear occurs on the bearing. But during the start and stop transient phases, when supply pressure is very low and the thin film cannot support the loads present, a very small amount of wear may occur.

Choosing the correct material combination will provide the least wear. Achieving this goal requires proper simulation of the turbopump transients. Through the combination of the aforementioned valve elements, this simulation can be accomplished.

The PID loop is used to ramp the turboshaft to a desired speed. Basically, a tabular data sheet is input into the PLC. For a given time period, the set point value for the rpm and ΔP across the test rig is listed. Therefore, the slope, or given speed or pressure ramp, is predetermined. This part of the system uses the PLC automatic mode. There is also a manual mode in which the elements of the digital valve are opened by hand using the touch screen. The manual mode is important, because it can lock the shaft at a certain speed, thus making the test assembly more stable.

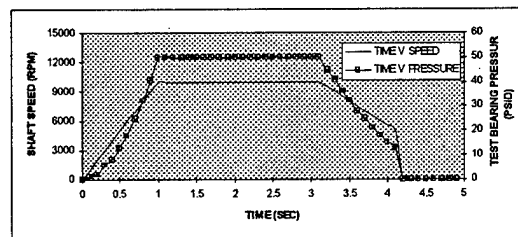Figure 6 shows an example speed and pressure ramp profile in tabular and graphical form.

Fig. 6. Graphical Display of Turbopump Ramp

Time (sec)	Speed (rpm)	Pressure (psid)
0	0	0
0.1	1000	1
0.2	2000	2
0.3	3000	6
0.4	4000	8
0.5	5000	13
0.6	6000	18
0.7	7000	25
0.8	8000	32
0.9	9000	41
1	10000	50
1.1-3.1	10000	50
3.2	9500	45
3.3	9000	41
3.4	8500	36
3.5	8000	32
3.6	7500	28
3.7	7000	25
3.8	6500	21
3.9	6000	18
4	5500	15
4.1	5000	13
4.2	0	0

Fig. 7. Turbopump Ramp

In Figure 7, the proposed ramp of the shaft uses a combination of the automatic and manual modes. The shaft speed increases from a standstill to 10,000 rpm in 1 sec. This occurs in the automatic mode using a PID loop.

$$\Delta P = 5.0e-7 * RPM^2 \qquad (3)$$

Test bearing inlet pressure is controlled, providing a bearing ΔP (bearing inlet pressure minus sump pressure) that increases with speed squared ($\pm 10\%$) and provides a bearing ΔP of 50 psid at 10,000 rpm.[3] Test bearing lift-off occurs anywhere between 2000 and 5000 rpm.

For the following 2 sec, which is pictorially described as the section with zero slope (dwell or plateau), the speed remains constant. This step is accomplished with a predetermined value from the manual mode. The predetermined value is preferred to the automatic mode, because in that mode the computer will try to maintain the PID loop set point, which would allow the speed to fluctuate back and forth around the designated speed. By setting the valve into a set position, a speed is locked in and the searching is removed. This also makes the test assembly more stable. In the next second, the turbopump ramps down to 5000 rpm. This part also uses a PID loop to maintain a predetermined slope. Below 5000 rpm, there is no turbine control required. All elements of the digital valve, along with the test bearing supply valve, are automatically closed, allowing the shaft to coast down to 0 rpm on its own.

Ladder Logic

The PLC coding that achieves the above pressure and ramp profiles is inherently simple. PLC programming is accomplished through ladder logic.

For the given profile, a time constant of 0.1 sec is set. For the entire ramp, the automatic subroutine programming is used. During previous testing, the decimal number for the speed and pressure constant for t=1.1 - 3.1 were determined. The PLC programmer inputs this number into a copy command. At t=1.1 sec, the copy command dictates the position of these control valves to maintain a locked position to allow stability at the plateau of the ramp. When t=3.2 sec, the programming reverts back to the sequencer subroutine for the spinning down of the shaft. At t=4.2 sec, both valves are closed and the shaft is left to spin down without control. This ladder logic is pictorially described in Figure 6.

The definitive advantage of this type of programming logic is repeatability. Using the previously described control method, the system will automatically compensate for changing conditions in the apparatus.

Conclusions

Due to the nature of testing, modifications of an experiment are usually required. Using the combination of the manual and automatic modes, any variety of speeds and ramps can be accomplished. Therefore, if, during a test, a modification is necessary to achieve the new objectives, the instrumentation operator can quickly modify a PID loop or manual actuation without hampering test continuity. Through the use of computers and valving technology,

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versatility of testing can now be accomplished without aborting a test.

References

[1]Pratt & Whitney, "Turbopump Design and Fabrication Support," FR-23726, February 1995.

[2]SKF Condition Monitoring, "Eddy Probe Systems," Technical Manual: Part Number 31075800, 1992.

[3]Leclaire, Richard, Engineering request, 1995.

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