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SPACE SHUTTLE MAIN ENGINE TURBO-PUMP BEARING ASSESSMENT PROGRAM

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ABSTRACT

This paper documents the work done on the bearing assessment program over the past two and a half years. The objective of the program is to develop a nondestructive evaluation system for the space shuttle main engine (SSME) high pressure oxidizer turbopumps (HPOTP's) which would be used to detect anomalies in installed bearings without component disassembly. Databases of various signatures are obtained by slowly turning the pump shafts before and after an engine firing. These signatures are then analyzed and compared to the original signatures to more accurately predict bearing wear.

I. INTRODUCTION

The SSME was the first reusable large liquid rocket engine in the world. With a planned design life of 55 starts, it promised to be the most cost effective and optimum engine for space travel. However, since its inception, it has had bearing problems which limit its reusability. Bearings within the engine's four high speed turbopumps must withstand a very harsh environment and operate at peak performance to avoid catastrophic engine failure. As a safety precaution, bearings within one of the SSME turbopumps are replaced every three flights, which is time-consuming, costly, and frequently appears to have been unnecessary.

Of the four turbopumps on an engine, the HPOTP by far has the most unpredictable and troublesome bearing wear problems. It contains two matched pairs of angular contact bearings. Two of these are located near the pump end and the other two near the turbine end. For easy reference, the bearings are numbered from one to four from the pump to the turbine end. Most wear is found on the pump end bearings, particularly bearing number two.

HPOTP bearings deteriorate quickly for many reasons. The balls wear the fastest of all the bearing components and, in the process, lose their preload. Liquid oxygen is their only lubricant and a poor one at that. It oxidizes all exterior surfaces, thus promoting metal to metal contact. Pump speeds in excess of 27,000 r/min and high temperatures in the contact stress areas are also significant contributing factors.

During flight, no internal instrumentation is allowed inside the turbopumps. Only externally mounted strain gages and accelerometers monitor bearing health. When an engine returns for post flight checkout, various methods are used to determine the condition of the bearings. The pump is disassembled if any bearing wear indicators are found in the flight data. However, by the time external instrumentation indicates a problem, significant wear has already occurred. If no indicators are found, inspection methods are used to better determine the actual degree of bearing wear.

Several diagnostic methods are used on all of the turbopumps. It is standard checkout procedure to perform manual torque tests on them to verify that their shafts are free to rotate. Another inspection method is the microwiggle test whereby the shaft is rotated and radial clearance is measured instead of travel. This test provides some HPOTP pump end bearing information as well as turbine end; however, it is still in the development stage.

Two inspection procedures are available for the HPOTP turbine end bearings. The first is called microshaft travel and involves a push and pull test of the turbopump whereby actual shaft displacement is measured. This diagnostic method reveals reliable data about the actual condition of the two bearings as a pair. Second, the number three bearing can be borescoped for evidence of visible damage to the bearing components (i.e., spalling, pitting, etc.).

Unlike the turbine end bearings, the HPOTP pump end bearings currently have no reliable inspection method or diagnostic tool. Consequently a conservative 2000-s limit is placed on these bearings to ensure mission safety. This amounts to a maximum of three flights before pump disassembly. If this limit could be replaced by a reliable inspection method, then the engine could possibly fly for a total of nine flights before it would have to be torn down. At an expense of $1.5 million per tear down, that would amount to a cost savings of $3 million per engine.

Recognizing the critical need for such a diagnostic tool, Marshall Space Flight Center (MSFC) engineers have developed the bearing assessment program. This research and development program has been in existence for almost 3 years and in that time, we have studied several different methods used to determine bearing wear. We have also developed a prototype unit called the automated torque sensor (ATS) and are in the process of qualifying it for service.

In this report we describe the program and methodology used to develop such a nondestructive evaluation (NDE) system . In sections III, IV, and V, the testing programs involving acoustic emission, vibration, and torque are discussed and their results are presented. The prototype diagnostic tool and its use are explained in sections VI and VII. In section VIII, an overall summary is given and our recommendations are presented. The report concludes with a discussion of our future program plans.

II. PROGRAM PLAN

The Support Equipment Branch, EP44, of MSFC's Propulsion Laboratory has been working on an innovative program to develop a bearing wear detection system for the SSME HPOTP's. This NDE system would be used to detect anomalies in bearings on assembled SSME's without component disassembly. The plan is to develop a database of various types of signatures obtained from slowly turning the HPOTP shafts before and after an engine firing. These signatures would in turn be analyzed and compared to the original signatures to more accurately predict bearing wear.

We began by conducting literature searches and researching past work done on similar projects. We investigated the current methods used to determine bearing wear and identified the areas we were most interested in pursuing. Then we laid the ground work by establishing a test facility, acquiring a test article, and forming a working group.

To expedite testing, we obtained a spare HPOTP for our test facility. This would enable us to determine concept feasibility more quickly and concisely. From the beginning, we were always cautious not to develop a technique that would work well in a laboratory setup but fail miserably in real life application. Every concept we consider must be capable of operating in a test stand environment.

The first pump we received was HPOTP unit 2315, which we had briefly before it was replaced with HPOTP unit 0810. Most all of our testing has been done with this pump. It is a phase II development pump with several configuration modifications. The pump end bearings have accumulated approximately 6,000 s of run time while the turbine end bearings have 10,000 s. Even though the bearings have much time on them, we still consider the pump to have good bearings. A microwiggle test was performed and no appreciable wear was found on any of the bearings. This only verified the predictions made from the internal isolator strain gage hot fire data which showed low amplitude cage frequency responses which can be correlated to uneven ball wear in the HPOTP pump end bearings.

The next logical step after preparing a test facility was to assemble a bearing assessment team. We composed this team of individuals from three different areas of expertise. The following disciplines were represented: mechanical, electrical, and data analysis.

Once a foundation was in place, our first task was to develop a system to dry-spin the turbopump. For this, we first used as much off-the-shelf hardware as possible and then eventually used the ATS itself to drive the pump. We designed and even fabricated the support and interface hardware.

With the ability to turn the pump came the question as to how fast we could rotate it dry without damaging the bearings or any other component. Rocketdyne, primary contractor for the SSME, has never given us a maximum speed limitation but advised us to turn as slowly as possible. To be conservative, we decided to limit our speed to a maximum of 8 r/min. With a functional test article in place, we were now ready to begin a comprehensive testing program.

III. ACOUSTIC EMISSION TESTING

One of the testing areas we have had little success with is acoustic emission (AE). AE's are stress waves that are produced when materials are stressed. A structure must be sufficiently loaded in order to produce stress waves. This method detects movement, not existing geometric discontinuities. Since MSFC government employees had limited experience with acoustic emission testing, the industry was surveyed.

Two independent contractors performed preliminary AE testing on HPOTP unit 0810. The results were inconclusive in one case and in the other the NDE method was deemed not viable at such low speeds. Turning at 0 to 8 r/min, the system did not generate enough energy to trigger the sensors. Even though the results were not promising, we still plan to continue testing in order to disprove or prove feasibility. With the required authorization, we will increase the speed of the turbopump up to 50 r/min and test again. Perhaps this will generate enough energy to excite the sensors.

IV. VIBRATION TESTING

The second testing area we explored involved conventional vibrational analysis. As bearings begin to wear, they demonstrate marked increases in vibration levels. Piezoelectric accelerometers are traditionally used to convert this vibratory motion into an electrical signal. These transducers are widely used in industry to determine bearing health and predict failure.

In our own vibration testing, we attached surface-mounted transducers to the pump housing, slowly rotated the shaft, and analyzed the output signal for bearing signature characteristics. We knew that the data analysis would be challenging because at speeds of 0 to 8 r/min, fundamental SSME bearing fault frequencies are all less than 1 Hz.

To begin, we had Physical Acoustics Corporation and Brüel and Kjær Instruments perform preliminary testing on HPOTP unit 0810. Both companies' tests were inconclusive since the background noise was indistinguishable from the pump noise. They did, however, recommend continued testing with seismic accelerometers.

Since those preliminary tests, we have conducted three significant test series. In our first series, we utilized a spare keel latch motor, which was developed for the Hubble Space Telescope maintenance mission, to rotate the pump. We designed the spool and internal spline to mate with the pump. The motor only ran at a constant speed of 8 r/min, which limited our testing, since throttle capability would have allowed us to better distinguish pump rotational driven spectral components from stationary background and electronic noise. The test series consisted of four 15-min runs at this constant speed. We used three different types of accelerometers: four miniature compression driven piezoelectric sensors with internal electronics, three seismic spring-mass type units sensitive in frequency to dc and four shear-type piezoelectric sensors driven by external charge amplifiers. These off-the-shelf transducers were mounted in three different tiers: the preburner pump flange, the HPOTP housing weld 3 region, and the G3 flange.

Our test objectives were to optimize the selection of acquisition equipment and the mounting locations of the transducers. To accomplish this, we classified the dynamic noise floor data prior to the pump rotation and then determined the external drive's influence on the data. The dynamic signals from the dry-spin testing were evaluated and the external environment influences on the dynamic data were identified.

It was obvious from our test results that there was not enough energy in the system. The miniature accelerometers had not functioned properly. We found that we needed to work on understanding the frequencies from external sources. As for identifying bearing defect frequencies, the overall results were inconclusive.

We did learn that we needed the ability to vary the motor speed. This would make it much easier to distinguish bearing related spectral components from environmental and instrumentation noise. A slow throttling capability would also prove beneficial. Prior to the actual test, we should have performed decoupled testing in order to isolate the feed through from the drive mechanism to the HPOTP data. Also we needed to record a shaft rotational speed data channel, i.e., key phaser information, to better enable us to locate bearing related frequencies.

V. TORQUE TESTING

In addition to the standard NDE methods of AE and vibration, we also investigated a new approach - dynamic torque analysis. Little if any work has ever been done investigating SSME torque signatures for bearing signature content. Since torque checks must be performed on all pumps, it seemed logical to tap into this available resource.

Currently torque tests are routinely performed on turbopumps during checkout to determine breakaway and running torque. The test consists of a technician with a Snap-on torque wrench hand turning the pump while a quality inspector reads the dial indicator upside down. Needless to say the test is rather crude, and a more sophisticated test could possibly produce useful data. Since the test must be performed any way, it seemed reasonable to have it automated so that the data could be stored and analyzed for later use. Because the unit is hard mounted to the pump, the tests are more accurate and consistent. No human error is involved, and no side loads are induced into the pump. The automated test is definitely more precise in measuring static torque, since the accuracy of a hand held torque wrench is only plus or minus 2 percent within the upper 80 percent of the scale. Moreover, the dynamic content of the available torque signature could prove useful in determining bearing health.

VI. AUTOMATED TORQUE SENSOR

The ATS was envisioned from the very beginning of the bearing assessment program. The prototype was planned as an engineering unit for development purposes. Its requirements gradually evolved over time. The finished product is fully functional and reliable.

The ATS is battery powered, computer controlled, and easy to use. It was designed to be portable and durable for operation on test stands. The complete ATS system is composed mainly of two parts, a torque test head and a data acquisition system. The entire unit fits in two cases which have a combined weight of less than 40 lb.

The torque test head contains a 100 in-lb torque transducer, a motor with a speed reducer, an optical encoder, various couplings, a ball bearing, and a torque sensor motor control printed wiring assembly. All of these components are encased in a container with a removable lid to protect them from the elements. The test head mates with an interface rod via a $\frac{3}{8}$ in square drive at the container's open end and hard mounts to the pump by way of a flange.

The data acquisition system consists of a 486SLC-25 notebook PC and a docking station. The laptop is configured with an 80-megabyte hard drive, 4 megabytes of RAM, a 3.5-in floppy disk drive, an ac-dc adaptor, and an Ni-Cad rechargeable battery pack.

Other important hardware included with the system are the ATS battery pack and its accompanying battery charger, an interface cable, and a Bayonet Neil-Concelman (BNC) breakout box. This box serves as an interface between the laptop and a data recorder. The ATS has a BNC output of the unfiltered analog torque signal for recording to high-frequency analog tape. From the beginning, the bearing assessment team felt that the ATS should have a BNC connector in order to record the analog signal before the A/D conversion process. The analog data would be used to verify the ATS's proper operation and expand our high frequency data processing options.

The accompanying software program was written especially for the ATS and controls its entire operation. The program is menu driven and very user-friendly. It offers two levels of security with both an operator and a supervisor password. All activity is recorded in a log that can only be accessed by the supervisor. In order not to damage a pump by accidentally exceeded its maximum torque limit, the value can be preset. The entire unit will shutdown if this maximum torque is exceeded.

To run a test, the operator can either select a previously loaded test set or select new parameters via pull down menus. Many options are available and can be set in any sequence. The speed at which the pump turns can be set anywhere from 0 to 4 r/min. The duration of the test can be established by either selecting the number of revolutions or the number of seconds. One to four data points can be recorded per degree of rotation. It is also possible to always start a test in a designated zero position. If this option is selected, the unit will rotate to the start position before the test begins.

Once all the parameters have been chosen, the operator must verify his selections before the test can begin. During an actual test, the torque, angular position, and r/min levels are dynamically displayed. Upon completion, the results can be viewed along with the average values for the running and breakaway torque. Data can be stored in ASCII on either the hard disk or on a diskette.

VII. COMBINATION TESTING

After the first test series, we were eager to begin recording torque and vibration data simultaneously. The team configured an off-the-shelf torque sensor, motor, and tachometer into a workable unit. We also designed and fabricated the support and interface structure ourselves to expedite testing.

Before the test began, we performed a manual torque check on the pump. Data from the torque sensor, the tachometer, and the accelerometers was simultaneously recorded. The same transducers were mounted in similar locations to the previous test series. During our test, we gradually increased the pump's speed to a maximum of 4 r/min during a 30-min time interval. We slowly ramped up to 4 r/min, held this speed for 15 min, and then slowly ramped back down. The results of this successful test will be mentioned later.

When the ATS was delivered, we were again enthusiastic to begin a third test series. In this test, we could achieve a twofold objective. We wanted to baseline our pump with good bearings and verify that the ATS was recording torque data accurately. In order to do this, the team used state-of-the-art accelerometers and seismic transducers. The ATS drove the pump at a constant speed of 4 r/min. Three different types of data were recorded which included high frequency torque data, key-phaser data, and acceleration data. The actual test ran for 10 min, with 9 min at maximum speed and 30 s at the beginning and end at zero speed.

In the data reduction, two different frequency regions were explored, those below 100 Hz and those below 20 kHz. In the low frequency analysis, the acquired torque signatures were examined for fundamental bearing defects. In the high frequency analysis, bearing diagnostic information was searched for using envelope detection techniques.

In the time and waveform analysis, the results looked promising. As expected the accelerometers registered very low energy levels. However, the general shape of the torque signature was consistent with those previously taken in test series one and two. This showed that the torque signature from the pump was repeatable using totally different sensors and data acquisition systems.

The frequency analysis also demonstrated favorable results. In the 0 to 100-Hz spectrum, no distinguishable components were found in the accelerometer data. However, some discrete low frequency activity was noted in the torque data. The 0 to 20 Hz spectrum taken from the ATS was remarkably similar to that taken in a previous test series.

The high frequency torque data looked very promising since the signature content was repeatable from test to test with different transducers. No obvious bearing defect frequencies were found as we had expected with good bearings. However, some unidentified spectral components were noticed which provide merit for further study. In conclusion, the team decided that a HPCTP with severely worn bearings was needed as a test article to unequivocally prove concept feasibility.

VIII. CONCLUSION

To date, the bearing assessment team has made important strides. Of the three different NDE methods that were considered, we have enjoyed the most success with torque. AE and vibration still need much more work for their verification. Our accomplishments are many. We have baselined a HPOTP which to the best of our knowledge has good bearings, and thus have excellent reference data to be used for later comparisons. The very development of a prototype torque device was significant in itself. We have verified that the ATS can record Rocketdyne HPOTP static torque data accurately and consistently.

Thus, it is our recommendation that the ATS be incorporated into the standard turbopump checkout procedures to replace the manual torque checks for both the Rocketdyne and Pratt and Whitney HPOTP's. There is no doubt that this automated method is better than the currently used manual one. In addition, the data taken can be stored and later retrieved for study and analysis. The data has the potential of one day being used to determine the amount of HPOTP pump end bearing wear. Additional systems could be developed for use at Stennis Space Center, Kennedy Space Center, and Rocketdyne.

Mission safety has always been a primary goal of the space shuttle program This ATS would only enhance the SSME's performance and reliability. It would greatly improve bearing diagnostics and thus provide another degree of confidence to ensure shuttle safety. The savings in time and money are secondary but are still worth serious consideration during these times of severe budget cuts.

XI. FUTURE PLANS

Although much has been accomplished, much more work is left. The program is by no means finished. Our research with acoustic emission and vibration sensors will still continue but with a new angle. The team is in the process of designing an advanced ATS that will be capable of turning the turbopump a maximum of 50 r/min. Faster rotational speeds will increase energy levels in the system and hopefully better excite the monitoring sensors. This advanced ATS will also have an increased motor and torque capacity to handle the alternate Pratt and Whitney HPOTP which breaks at a much higher torque level of 370 in-lb.

Our ultimate goal to determine the relationship between torque signatures and bearing wear is still foremost in our minds. Since the likelihood of obtaining a turbopump to test with severely worn bearings is not favorable, the bearing and seal materials tester will be used. This unit is conveniently located at MSFC and runs a set of bearings until they are worn. Our objective will be to establish a torque signature for the unit with new bearings and then acquire the torque signature at the end of the bearing test when there is likely substantial bearing distress. Upon disassembly the bearings will be analyzed and the wear correlated to our data observations. This approach will give us fast results and enable us to familiarize ourselves with data and to develop data analysis criteria.

As a parallel effort we will test the ATS on an assembled SSME. However in order to accomplish this, precision interface hardware must be designed to mount the unit to an installed HPOTP. A support bracket will hold the test head in place and guide the interface rod to mate with the pump through the preburner pump inlet duct. Since attachment involves a blind installation through a duct, this guide is needed so the ATS will not induce any additional loads into the HPOTP. Once it is demonstrated that we can take successful measurements on both Rocketdyne and Pratt and Whitney HPOTP's, a fairly extensive database of flight and developmental HPOTP's can be established. Then our formidable task of data analysis will begin.

The ATS itself will be optimized by making the unit lighter and shorter for ease of handling and installation. The software package will be enhanced to accommodate more user-defined parameters and to enable the operator to manipulate the data immediately following the test. Finally, this system may one day be adapted for industrial use to perform quick and reliable bearing checks and thus provide another level of quality assurance.