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Drive System Enhancement in the NASA Lewis Research Center Supersonic Wind Tunnels

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DRIVE SYSTEM ENHANCEMENTS IN THE NASA LEWIS RESEARCH CENTER SUPERSONIC WIND TUNNELS

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Summary

An overview of NASA Lewis' Aeropropulsion Wind Tunnel Productivity Improvements was presented at the 19th AIAA Advanced Measurement & Ground Testing Technology Conference in New Orleans in June, 1996.[1] Since that time Lewis has implemented subsonic operation in their 10- by 10-Foot Supersonic Wind Tunnel as had been proven viable in the 8- by 6 and 9- by 15-Foot Wind Tunnel Complex and discussed at the aforementioned conference. In addition, two more years of data have been gathered to help quantify the true productivity increases in these facilities attributable to the drive system and operational improvements. This paper was invited for presentation at the 20th Advanced Measurement and Ground Testing Conference to discuss and quantify the productivity improvements in the 10- by 10 SWT since the implementation of less than full complement motor operation. An update on the increased productivity at the 8- by 6 and 9- by 15-Foot facility due to drive system enhancements will also be presented.

Introduction

Ever increasing labor hour and utilities costs coupled with downsized budgets in both research and institutional support areas have elevated improvements in productivity to a high level of managerial and operational concern. NASA has spent considerable time over the last four years developing, implementing and evaluating productivity improvements at each of their major Centers and in each of their major facilities. This paper focuses on productivity improvements in the drive systems of the two largest wind tunnel complexes at NASA Lewis. The drive systems in both the 8- by 6 SWT (Fig. 1) and the 10- by 10 (Fig. 2) consist of multiple induction motors driving large axial flow compressors. As highlighted in the 1996 paper,[1] the underlying philosophy at Lewis, with respect to wind tunnel productivity, is to "...reduce test cost, improve efficiency, and provide test operation flexibility." Three changes were made in these two facilities that address all three of these philosophical concerns. They are in order of their occurrence, the installation of a new in-house designed speed control system for the 8- by 6 and 9- by 15-Foot wind tunnel drive system, the implementation of one motor drive operation for the same facility and the enhanced subsonic operation of the 10- by 10-Foot main drive system on various combinations of drive motors.

Each of these productivity improvements will be explained with more specific detail than was presented in the 1996 productivity overview. Finally, the financial gains realized over the last two years will be quantified and discussed.

Improved Speed Control System

The topic of productivity can be approached from many angles besides the traditional and easily quantifiable energy savings or personnel hour reduction. The new speed control system project for the 8- by 6-Foot Supersonic Wind Tunnel (8- by 6 SWT) completed in late 1992 and checked out in early 1993 focused on some subtle applications of productivity improvement as well as the very obvious ones.

In September of 1991 planning for the large Construction of Facilities (CoF) upgrade at Lewis' 8- by 6 and 9- by 15-Foot wind tunnel was well underway. Every major area of the facility was undergoing some type of renovation, repair or upgrade. Many of these changes were productivity driven for ease of maintainability or improved tunnel response time. For years the facility's existing speed control system, last upgraded in 1983, had given operators and researchers difficulty when attempting to run at higher speeds and correspondingly higher electric power consumption. This system had been designed and recommended by the original equipment manufacturer that installed the tunnel drive system back in the mid 1940's. This very expensive system never quite reached performance expectations and three Lewis engineers (including this author) were convinced they could design and install a much simplified speed control system that would more closely match facility performance requirements and thus drastically improve facility productivity.

Figure 1 shows how the 8- by 6 and 9- by 15 test sections are actually contained in a common tunnel loop. While sharing the common tunnel loop and compressor drive system the historic method of operating each of the tunnels was significantly different in part because of the position of the compressor in the shared tunnel loop and because of the different speed ranges that the individual test sections were designed to operate. When operating the

8- by 6 facility subsonically, maintaining exact compressor speed over the historical 510 to 875 rpm range was imperative, since changes in compressor speed directly affect test section air speed. If operating supersonically, an unscheduled change in compressor speed could change the test section temperature causing a possible shift in the model force balance. Operation of the 9- by 15 was more robust, since the test section is located well away from the compressor. However, lower speeds could only be achieved by bleeding large quantities of compressor air flow out the Flow Control Doors 1 and 2 (see Fig. 1) even with the compressor running at its then minimum speed of 510 rpm. These requirements emphasized the need for an improved speed control system.

The 8- by 6/9- by 15 seven stage axial flow compressor is driven by three 29 000 hp wound rotor induction motors equipped with slip rings that allow for the insertion of external rotor resistance into the rotor circuit. Figure 3 shows the drive motor speed control schematic. The external resistance is supplied via liquid rheostat tanks filled with a conductive electrolyte solution. As the moveable electrodes, called "sticks," are raised out of the tanks more resistance in seen in the rotor circuit and the induction motor slows down. The sticks for all three motors move in virtual unison. However, power sharing among the motors is critical and this may cause slight variations in stick position due to uneven heating of the electrolyte solution, for example.

Productivity goals for the new system were established, requiring more accurate power sharing at high loads and compressor speeds, <1 percent variation in compressor speed with tunnel Mach number changes and the ability to make a continuous, stable step changes in compressor speed without the need for intermediate stopping points to be sure the speed control system remained stable (a key productivity issue during wide speed excursions).

The new control system design took several months, but since it was done in house and by engineers intimately familiar with the facility and its' required operation, much of the formality normally required for such a complex design effort was avoided in favor of weekly design meetings and informal communications among the participants. In reality the design was ready in about six months.

Demolition of the old speed control system and installation of the new system also employed subtle personnel productivity tactics. Specifically the tunnel drive system operators were accomplished electricians and mechanics that would have normally be re-deployed elsewhere or laid off during such an extended period of tunnel down time. Instead they were used for the electrical and mechanical demolition and installation phases of the actual hardware associated with the new speed control system. This proved a very wise and productive use of these personnel resources as evidenced by the fact the component and subsystem portions of the Integrated Systems Test (IST) were performed very smoothly and with an extreme minimum of delays to fix wiring, plumbing or other related problems. Productivity savings of this nature are very hard to quantify from a dollars and cents standpoint.

True productivity savings became evident during the final integrated system check out runs and the subsequent testing programs. While some 15 check out runs had been originally scheduled for tuning the new control system over its' entire speed range, the experience and accuracy that went into the design and installation as a whole, as well as the initial tuning parameters proved very worthwhile in that only three days of actual tuning were required to verify full readiness of the facility. It is estimated that this saved $175 000 in electrical power and personnel wages alone. This figure does not take into account the intangible benefit of having the facility available for testing several weeks earlier than had been anticipated.

The installed hardware cost of the new drive controls system was approximately $165 000. For comparison purposes the manufacturer supplied speed control upgrade installed in 1983 had cost $600 000 and taken nearly 6 months to optimize, with final performance never reaching expectations.

With the new speed control system the facility could now reach full speed Mach 2 test conditions from start up in only 17 min compared with 26 min previously. The speed control system balanced power between the motors to within 0.05 MW, allowing for maximum output shaft horsepower to be available to drive the compressor at higher power. Finally, the Power Hold feature, which never functioned properly in the 1983 design, allowed the tunnel operator to enter a power limit not to be exceeded by the drive system during the course of the tunnel run, thus avoiding potentially costly utility penalties normally incurred when research conditions inadvertently caused the tunnel to draw more than the ordered level of electrical power. The reader can see the subtle and obvious productivity impacts of such an in-house managed facility rehabilitation.

One Motor Drive Operation of the 8- by 6/9- by 15 Compressor

The drive train for the 8- by 6/9- by 15 wind tunnel complex consists of a seven stage axial flow compressor hard coupled to three 29 000 hp wound rotor induction motors also sharing this common shaft. The facility was originally designed with the 8- by 6 test section only (the 9- by 15 return leg was added in 1968), and was intended for supersonic operation up to Mach 2, thus the need for 87 000 shaft hp. The noise produced by diffusing the high speed air was a nuisance to NASA Lewis' neighbors so a

muffler leg and finally the Low Speed 9- by 15 leg were installed to close the tunnel loop (see Fig. 1). Transonic operation of the 8- by 6 was achieved by perforating the test section walls in 1957.

Historically the 8- by 6 Supersonic Wind Tunnel (SWT) complete with limited subsonic and full transonic testing capability could achieve testing speeds ranging from Mach 0.36 to Mach 2.0 for either aerodynamic (closed loop) or propulsion (open loop) tests based on customer needs. The 9- by 15 test section was equipped with noise suppression and slotted walls for low speed subsonic testing from zero to approximately 175 mph, depending on tunnel blockage.

The addition of the second test section (9- by 15 LSWT) has had a major impact on facility productivity over the last 30 years, while also filling a national need for sophisticated low speed acoustical testing.

In 1989 another CoF project to modernize all of the tunnel controls was initiated. This CoF included the addition of the Distributed Control System (DCS) in the facility including a DCS drop in the drive control building that was used very little initially. The speed control upgrade in 1992 greatly simplified the hardwired controls for the drive system as well as drastically increased the role of the DCS drop in the tunnel drive control room. Historically, during many 9- by 15 runs the tunnel flow control doors 1 and 2 (see Fig. 1) would be open several feet exhausting tremendous amounts of excess air that was being produced by the compressor, even though it was running at its minimum speed, with the electrolyte sticks in their full up position. Surely this was not the most productive mode of operation for the low speed test section.

Large multiple motor drive systems of the type employed at this facility typically stagger the starts of the motors by as much as a minute for a variety of reasons. Many years ago these large drives represented a huge electrical burden on a then much smaller power grid. The staggered starts allowed for smoothing of the demand as well as easing the load on the distribution system. A drive start would never cause the current meters for these large motors to exceed 50 percent full load amps (FLA) during these start ups. It was specifically noted that the rotor current on a given motor would actually begin to decline before the 40 sec delay between motor starts on this drive had elapsed. Further study showed that the reason the inrush current stayed so low was attributed to the large amount of external rotor resistance present in the rotor circuits via the liquid rheostat tanks during start up (the drives are started with the sticks in the full up position).

The addition of the DCS operator display CRT's allowed much more drive information to be displayed in a simplified format which provided a valuable tool for studying the real dynamics of the tunnel drive system. Over time several key relationships became apparent. First, that the resistivity of the electrolyte solution was inversely proportional to temperature. Since the drive was originally designed to run a supersonic wind tunnel the electrolyte solution was designed to be kept warm (55 °C typically). This would allow for maximum separation of the electrodes at high power draws affording the previously inadequate stick positioning system physical separation of the electrodes to control the drive speed at these higher tunnel speeds. It soon became apparent that the opposite was desired for running the drive and thus the compressor slower, a fact that had apparently gone unnoticed all these years.

The second relationship discovered which has already been mentioned and was key. If the rotor current on the motor which was started first, and thus the input power to that motor (they are directly proportional), had begun to decay before the start of the next motor, and was doing so at drastically less then the motor's rated current, then one motor possessed the capability of safely running the compressor at some range of speeds even while it dragged along the weight and rotating resistance of the other two motors.

Finally there was the relationship between rotor current and rotor heat. It has always been held that running an induction motor at much less than its rated speed results in heating due to large losses normally attributed to this type of machine. However, these are not typical wound rotor induction machines since they possess external rotor resistance (in the liquid rheostat tanks) in an amount as high as 4 times that actually contained in the copper which makes up the rotor windings. Since the machines run at less than 50 percent of rated current and have the majority share of their rotor resistance outside the machine, they actually run cooler at lower speeds just like they do at higher speeds. In fact maximum heating of the rotor under unloaded motor conditions actually occurs at about 70 percent of rated speed as a result of the shape of the efficiency curves for this type of device. An almost amusing coincidence can be found in the fact that these 900 rpm rated devices were historically operated at around 600 to 630 rpm when the LSWT was being run to allow some control of stick position and thus compressor speed besides just using the tunnel flow control doors to control the test section speed in the 9- by 15. In others words this facility was historically run at near maximum inefficiency, by design, for 9- by 15 testing because it was never originally designed to have a low speed leg.

These relationships showed that One Motor Operation of this facility was surely feasible. Further it seemed an intuitive conclusion that one motor would use less electrical power than three motors operating at speeds less than the previous 510 rpm, and further, that lower compressor speeds would naturally equate to some lower

testing speeds than were previously attainable in either tunnel leg.[3]

The first One Motor Drive tests on the 8- by 6-Foot/ 9- by 15-Foot compressor drive system were performed in January of 1995. Analytical trending showed that the drive and compressor system reached a steady state speed of only 337 rpm in a little over 5 min. Not only was the drive train speed drastically reduced but the single motor was drawing only a little more than 6 MW of electrical power and the rotor current was only 25 percent of full rated load.

After several other short tests a full load test was scheduled in March of 1995 where the single motor was permitted to be loaded to 90 percent of rated load. The speed range for the compressor obtainable for One Motor Operation was remarkably broad (337 to 600 rpm). However, it was soon observed that at roughly 540 rpm (a speed attainable with three motors one line) the single motor was drawing power similar to what the drive would be drawing with all three motors running. Some two motor testing was evaluated but proved of little benefit simply because of the dynamics of the system. It was therefore determined that for prolonged One Motor Operation, 560 rpm or 15 MW of input power was not to be exceeded for more than one hour. Three motors would not use any more electrical power at 560 rpm than would the single motor, yet with three motors sharing that load their individual current draws were drastically lower and the chances for rotor heating greatly reduced. This decision had no impact on the new productivity capability of the drive but made perfect sense from a wear and tear standpoint.

One Motor Operation was a huge success. Testing in the 9- by 15 was now being accomplished using 60 percent less power for the majority of tests. Only at speeds higher than about Mach 0.14 were three motors required to run the facility. Depending on the time of day the facility was to be run this electrical savings alone was amounting to over $500/hr.

As One Motor Operation grew in popularity it was discovered that many tests required speeds where One Motor Operation and the traditional three motor operation would be necessary. Since One Motor Operation effectively interrupted the old starting sequence (now mostly software controlled since the speed control upgrade) the drive system had to be shut down in order to be restarted on three motors. This procedure had about a 20 min impact on productivity every time it was necessary to go from one motor to three or from three motors to one.

Since two of the engineers who helped design the speed control system were still very much involved with the operations of the facility they were able to quickly devise a safe way to modify the software logic to allow for "on-line" changes in the number of motors running within limits that kept the overall operation of the facility safe. These changes allowed researchers to change drive states twice (1-3-1 or 3-1-3) during a given run without shutting down. The only requirement is a quick trip through about 400 rpm to be sure the rheostat electrodes were in their full up positions before motors were electrically added or subtracted from the drive train. This would insure proper load balancing during these transitions, and typically took only a few minutes to accomplish. This software productivity change further enhanced the capabilities for facility "On" time.

Run hour meters were eventually added to the motors once it was determined that One Motor Operation was a proven productivity mode of operation. After the first full year of quantifiable operation it was found that motor number one was being used roughly twice as much as motors two and three (492 versus 258 hr). This equated to an electrical power savings of at least $127 000. The reader should note that besides the electrical savings the facility run time was up nearly 50 percent as well (492 hr versus a previous 7 year average of 337 hr).

The results of the second full year just completed in March of 1998 were even more encouraging. Over the last year motor number one was used nearly three to one (731 versus 240) over motors two and three. Amazingly facility run time was now up an additional 50 percent over the previous year and much more than twice what it had been in the 7 years preceding the introduction of One Motor Operation. Clearly the idea of One Motor Operation has had a more intangible productivity benefit as well, namely, the facility is now much busier than before and attracting more business in great part because it is now much cheaper to test in both the 8- by 6 or the 9- by 15 test facilities from an electrical power standpoint. Even the 8- by 6 is now attracting more subsonic business as the testing envelope has expanded downward from the previous Mach 0.36 to Mach 0.25 while under compressor and drive power.

Enhanced Subsonic Operation of the 10- by 10- Foot Supersonic Wind Tunnel

The 10- by 10- Foot supersonic wind tunnel is NASA Lewis' largest wind tunnel. It was designed in the late 1940's and underwent construction in the early 1950's.[4] Figure 2 shows the general layout of the facility and the presence of two separate drive trains in this single tunnel loop. The Main Drive system consists of 4 motors as seen in the upper left of the figure. The Secondary Drive, consisting of three drive motors identical to those in the Main Drive, is needed in order to achieve test section speeds higher than Mach 2.5 and does so by increasing the pressure ratio in the test section. With all seven motors running supersonic test section speeds in excess of Mach 3.5 are possible.

In the early 1980's a series of testing was undertaken to use the Main Drive in an effort to perform subsonic testing in the test section. The 10- by 10- Foot SWT was designed with "By-Pass" switches in the motor start and stop sequencing logic for both the Main and Secondary drive systems. These switches functioned essentially to "skip" a motor in the normal starting sequence. Original copies of the manufacturer's operations manuals indicate that individual motors my be "By-Passed" if is desired to do so. The text makes no reference as to why one might wish to by-pass a particular motor but maintenance or servicing reasons are implied.

After verifying the success of One Motor Operation at the 8- by 6/9- by 15- Foot facility an effort was undertaken to investigate what possibilities might lie in the operation of the 10- by 10- SWT on less than its' full compliment of drive motors.

As the 10- by 10 facility has a larger 8 stage axial flow compressor of considerably larger diameter and drive motors that individually have nearly 50 percent more horsepower (40 000 plus versus 29 000 hp) than those at the 8- by 6, it was understandable that there would be some differences in the way this facility would respond to running on less than the full complement of drive motors. However, it was encouraging that this facility had a start and stop sequence and a shared electrolyte system that were both very similar to that of the smaller 8- by 6 facility. Additionally, the presence of the motor "By-pass" switches would make arguing the safety of less than 4 motor operation a much simpler matter. Exactly what compressor (and thus test section) speeds could be achieved on various combinations of less than all four drive motors was all that remained to be determined.

One area of potential concern was that the 10- by 10 facility was equipped with dedicated facility exhausters that were historically used to pump the tunnel down to as low as 200 psf in order to provide high altitude testing and to reduce the load on the model when passing the shock across the test section on start-up to supersonic operation. This raised two concerns relative to the investigation of subsonic operation of this facility. First, was it necessary to pump the tunnel down in order to start the drive motors. In other words, did pumping the tunnel down drastically reduce the load on the drive motors and thus "soften" the drive start. Second, would the 20 to 30 min of time it took to pump the tunnel down (based on ambient outside test conditions) remain a significant productivity issue as it currently was for supersonic testing, if it remained necessary to pump the tunnel down below a certain level for subsonic testing. It was made an early test goal of the subsonic testing evaluation process to determine if the need for a pump down existed.

Before attempting to run such a large compressor at speeds slower than ever before attempted, it was decided for compressor safety reasons (the fear of stall, etc.) to instrument the compressor with pressure transducers in order to monitor for precursors to stall. Additionally, vibration monitoring equipment was mounted on the main compressor's air flow by-pass line (shown as the dashed line on Fig. 2) to watch for high vibrations that had evidenced themselves back in the early 1980's when subsonic testing was attempted using all four drive motors. It bears noting here as a subtle but critical productivity issue that the skills and trust of colleagues among the members of the subsonic test evaluation team allowed for this managerial mandate to be met within one week so as not to miss an open window for the evaluation of subsonic operation. The efforts of all involved were the epitome of productivity. Had this window been missed, it would have meant six months of waiting before subsonic testing could be revisited.

Initial testing commenced in February of 1996 and the test results quickly proved that one motor could indeed run the compressor against atmosphere. The speed range seemed somewhat limited compared to that achieved at the other wind tunnel with the electrolyte temperature limit being the constraining factor. An investigation into this matter showed the flow rates of cooled electrolyte to the individual motors in the main drive train at the 10- by 10 to be out of balance significantly. The flow rates were balanced using ultra-sonic flow meters and the speed range drastically improved. The first series of tests also showed that the motor "By-Pass" switches indeed functioned as anticipated and that the starting sequence for anything less than all four motors could be manipulated quite easily using these switches.

Initial testing on one motor with the electrolyte cooling system in balance allowed test section speeds between 32 and 100 kn (0.152 Mach) to be achieved; quite remarkable for a Supersonic wind tunnel.

Various combinations of one, two and three motors were attempted as the team worked through the test matrix. Table I summarizes the results of the subsonic testing.

Results of this new facility capability were immediately announced to Lewis customers and as a result of hitting the Spring '96 subsonic testing validation window, facility management was able to schedule a subsonic test entry for late Fall of 1996.

Official subsonic testing at the 10- by 10 resumed in November of 1996 during which the cooperative nature of the customer and the Lewis operations engineers allowed the subsonic testing process to be further refined. It was determined that again, as at the 8- by 6 facility, the drive motors could be turned off "on-line" assuming all of the moveable electrodes were in their respective full up positions thus, guaranteeing load sharing between the motors. Since the speed control system at the 10- by 10 is not as

refined as that at the 8- by 6, it is not yet possible to cycle up and down in the number of motors "on-line." By not having to shut down and re-start the drive for different motor configurations 20 to 30 min of delay time is avoided for each such change. This simply requires that the test matrix be designed to start the subsonic testing at the higher subsonic speeds first and then drop motors off line as the slower test section speeds are required.

By the end of this initial subsonic testing program the facility had logged over 146 hr of subsonic testing on 1, 2, 3 and 4 motors and consumed 6421 MW of electrical power. This 44 MW/hr average power usage is drastically lower than the 70 to 80 MW/hr draw shown for the subsonic operation attempted in the early 1980's on all four motors only[4]. The estimated electrical power savings for this one test alone was approximately $282 000.

It bears noting here that the four motor subsonic operation of the 1980's produced damaging vibrations in the compressor air flow by-pass line since so much mass flow was by-passing the compressor in an effort to minimize the test section speed. This new method of operation eliminated these vibrations over a very wide subsonic speed range because the mass flow itself was reduced by running less motors. It should also be noted, however, that it is still the vibration in the by-pass line that provides the upper limit for subsonic testing while using four motors as opposed to the electrolyte cooling capability when using one, two or three motors.

Calendar year 1997 saw limited use of subsonic testing in the 10- by 10. However, in each case the subsonic testing was added to the test matrix as part of a single tunnel entry because it was possible to do so. This represents an intangible productivity benefit as had been mentioned before. Clearly, this is not a benefit that should be taken lightly. How much additional expense and trouble would these customers have had to endure in order to gather this thirty plus hours of subsonic testing information. A potentially much larger testing matrix would have had to been proposed in order to secure a facility perhaps or in order to get management approval for such an undertaking. Clearly our customers were more productive by just piggybacking this testing onto their existing matrixes and productively killing two birds with one stone.

The 10- by 10 is not an efficient stand alone subsonic testing facility. However, the productivity enhancements achieved through drive system operation modifications make it unique in its' ability to offer customers the opportunity to include take-off and landing speed information along with their supersonic data.

Summary and Conclusions

Installing a new and simple speed control system that had been designed in-house drastically improved the productivity of the existing 8- by 6/9- by 15 wind tunnel facility by improving its' supersonic performance and reliability. Having engineers most familiar with the operations of the entire facility design the system, ultimately proved a very productive approach from both a time management and integrity of design standpoint. Further, utilizing technicians intimately familiar with the wiring and other support systems in the facility and possessing a vested interest in the success of the project, proved productive as well. Never before in this author's tenure had a project this complex been completed in such a short amount of time.

Enhancing subsonic operation of the Lewis wind tunnels has brought more research business to Lewis and drastically reduced costs for the internal research programs. Some of the productivity savings resulting from these efforts are easily quantifiable, and, where possible, this has been done. Indeed hundreds of thousands of dollars in electrical power alone has been saved in the two short years since the first productivity overview was presented.[1] NASA Lewis takes the concept of improved productivity very seriously and we look forward to presenting additional successes in the future.

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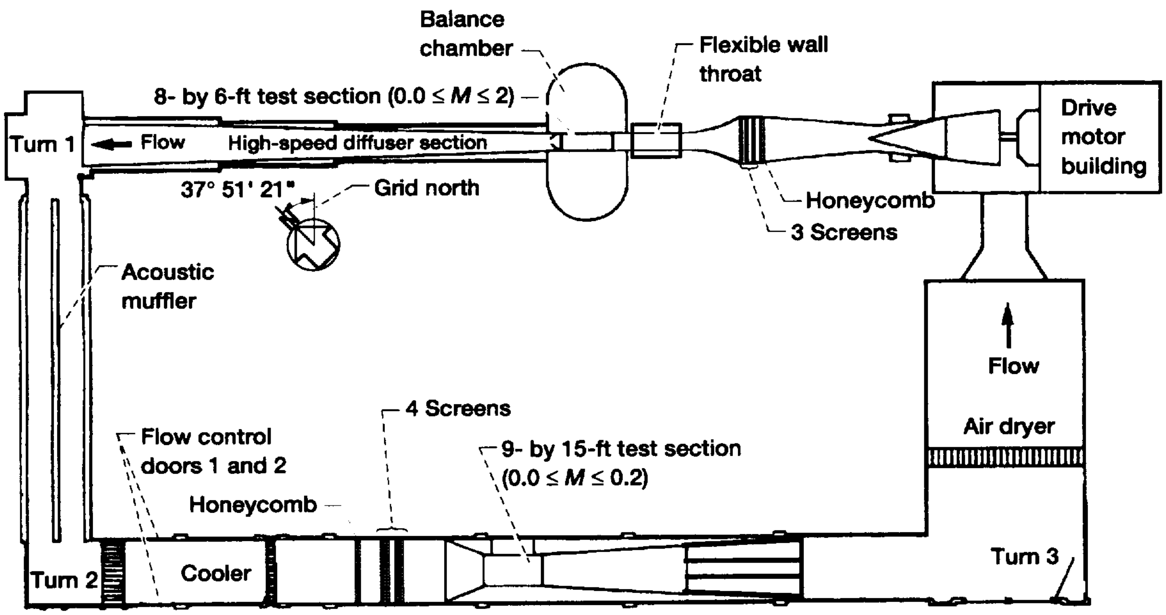

Figure 1.—Layout of 8- by 6-Foot Supersonic/9- by 15-Foot Low-Speed Wind Tunnel complex.

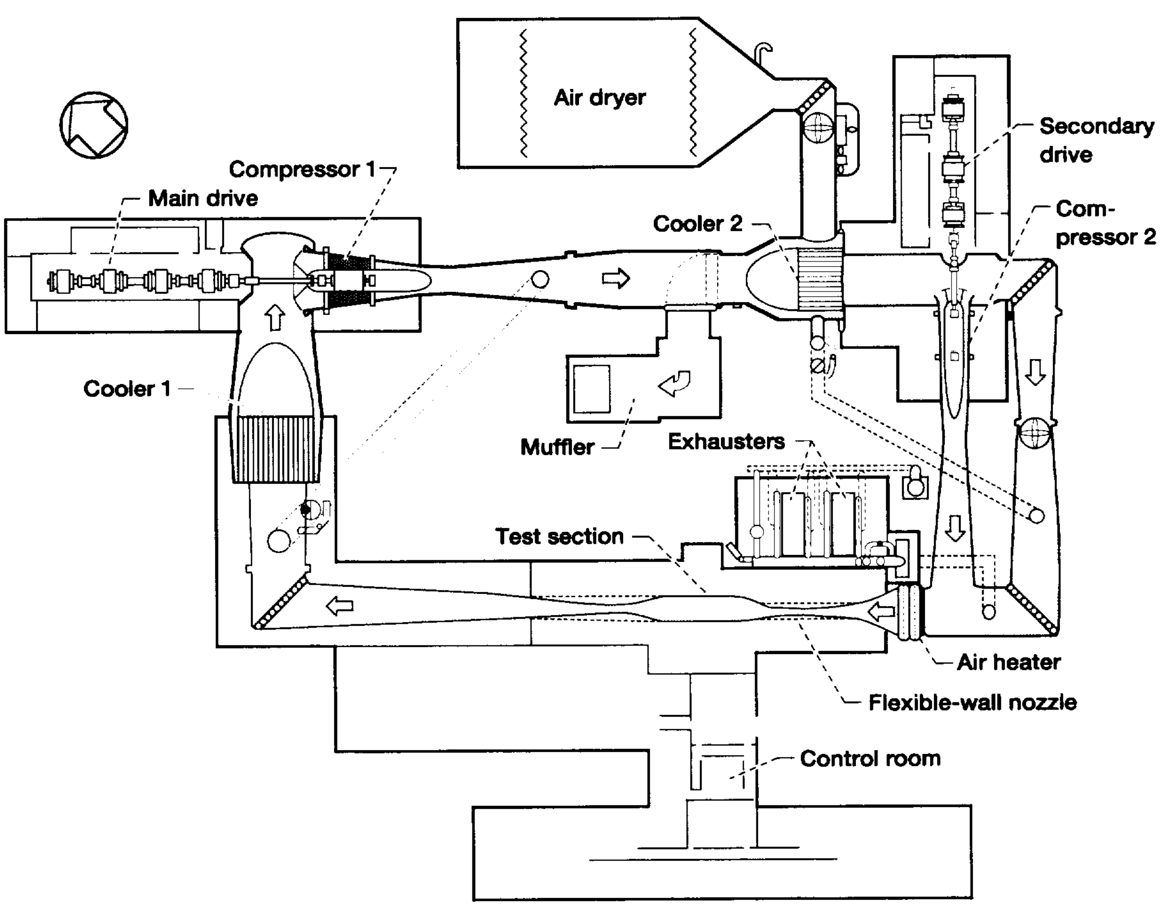

Figure 2.—Layout of 10- by 10-Foot Supersonic Wind Tunnel.

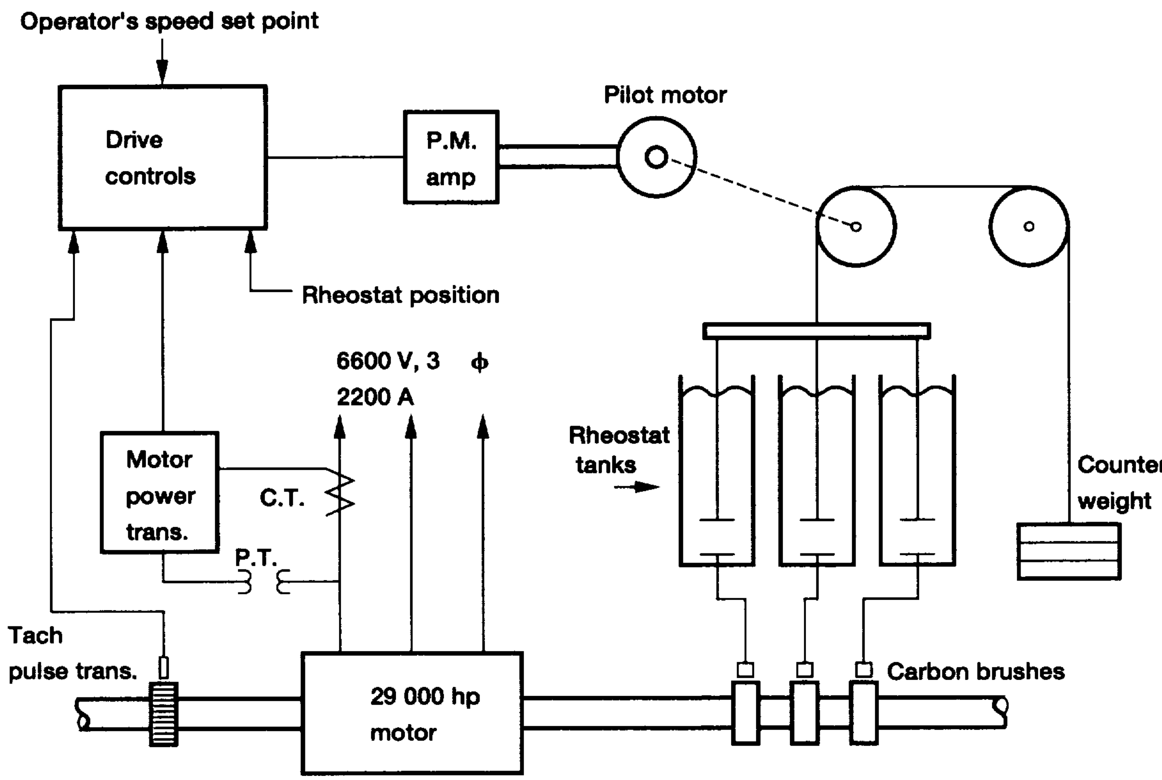

Figure 3.—Drive motor speed control schematic.

TABLE I.—10x10 SWT SUBSCONIC PERFORMANCE SUMMARY

Drive motors running	Motor, #1 only		Two motors, 1&4[a]		Three motors, 1,4 & 2[a]		Wing blowers running	Test section speed, kn	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum		Minimum	Maximum
RPM	190	290	257	420	310	450	1	6	10
Test section speed, kn	32	100	90	173	110	150	2	9	12
Motor rotor current, A	1450	3197	1150	3200	1050	2300	3	9.5	15.5
Motor rotor voltage	3100	2583	3000	2150	2700	2000	4	12.7	16
Total power in, MW's	10	22	18.2	22.6	8.5	17.3	5	16	27
Total rotor power, heat MW	7.2	14.5	6	11.5	4.8	8	6	16	30
Electrolyte temperature, °C	46	66	42	64	44	51	7	16	33
							8	16.5	33

[a]Data for 2 and 3 motor runs are per motor unless indicated.
Maximum power usage for all 8 wing blowers on line <1.5 MW.
Test section speeds do not correlate directly to drive RPM.

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13. ABSTRACT ***(Maximum 200 words)***

An overview of NASA Lewis' Aeropropulsion Wind Tunnel Productivity Improvements was presented at the 19th AIAA Advanced Measurement & Ground Testing Technology Conference in New Orleans in June, 1996. Since that time Lewis has implemented subsonic operation in their 10– by 10–Foot Supersonic Wind Tunnel as had been proven viable in the 8– by 6 and 9– by 15–Foot Wind Tunnel Complex and discussed at the aforementioned conference. In addition, two more years of data have been gathered to help quantify the true productivity increases in these facilities attributable to the drive system and operational improvements. This paper was invited for presentation at the 20th Advanced Measurement and Ground Testing Conference to discuss and quantify the productivity improvements in the 10– by 10 SWT since the implementation of less than full complement motor operation. An update on the increased productivity at the 8– by 6 and 9– by 15–Foot facility due to drive system enhancements will also be presented.

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