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Isotropic Superfinishing of S-76C+ Main Transmission Gears

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TECHNICAL PAPER

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Abstract

Isotropic Superfinishing is a chemically accelerated vibratory finishing process that is capable of generating surface finishes with an Arithmetic Mean Roughness (R_a) < 3 μin. This process was applied to the third stage spur bull gear and mating pinions along with the second stage bevel gears of a Sikorsky S-76C+ main gearbox. The gearbox completed the standard Acceptance Test Procedure (ATP) and a 200-hour endurance test. During these tests noise, vibration, and operating temperatures were shown to be significantly reduced due to the lower friction. This technology has since been flight certified and integrated into the S-76C+ with several aircraft in commercial service. A description of the tests, performance data and a general description of the process will be presented.

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Introduction

Noise and vibration control is a primary concern for the transmission design engineer, and particularly so in the design of a helicopter main transmission. Excessive vibrations generated by transmissions typically result in undesirable noise levels in helicopter cockpits and/or cabins, which cause operator and/or passenger aural discomfort and/or damage to sensitive on-board instrumentation. Cabin and/or cockpit noise/vibration abatement is of particular concern in helicopters wherein the final stage of reduction gearing of the main transmission comprises one or more bull pinions interacting with a central bull gear.

For example, Sikorsky helicopters of the S-76 series, e.g., S-76A, S-76B, S-76C, have a main transmission that includes three stages of reduction gearing: a first stage for each engine output consisting of helical gearing, an intermediate stage consisting of spiral bevel gearing, and a final reduction stage comprising a central bull gear that intermeshes with right and left hand bull pinions (to combine the inputs of the two engines that provide the motive power for the helicopter). Research has shown that the cockpit and/or cabin noise levels of S-76 helicopters are primarily the result of vibrations originating in the main transmission.

Narrow band Fast Fourier Transform (FFT) analyses, A-weighted octave levels, and overall DBA levels recorded in the cockpits and/or cabins of S-76A, S-76B, and S-76C helicopters indicate that interior noise levels are predominately the result of vibrations occurring at the bull gearing meshing frequency of 778 Hz, as illustrated in Figure 1. The vibrations produced by the first and second reduction stages of S-76 main transmission gearboxes, i.e., the noise levels generated by the helical and spiral bevel gearing as illustrated in Figure 1, occur at higher frequencies and typically are not significant relative to the dominant noise levels produced by the fundamental and first few harmonics of the bull gearing meshing vibrations.

The gearbox vibrations resulting from bull gear meshing are transmitted to the helicopter airframe via the transmission housing. The resultant airframe vibrations generate noise in the helicopter cockpit and/or cabin. Abatement of such noise by acoustic treatment of the cockpit and/or cabin interior is generally inefficient, and therefore, effective noise control solutions must be implemented at the noise source, i.e., the main transmission.

To effectively abate such noise, it is necessary to identify the primary causal factor(s) of bull gearing vibrations. The vibrations generated by the helicopter main transmission may be aggravated by meshing between misaligned bull gearing, i.e., the central bull gear and bull pinion(s). Previous efforts to reduce the noise levels generated by intermeshing between misaligned bull pinions and the central bull gear included modifications to provide effective bull gear tip relief. While such modifications resulted in a modest reduction in bull gearing vibrations, the resultant reduced interior noise levels of S-76 helicopters were judged to still present an unacceptable level of aural discomfort.[1]

As a result, several avenues were explored to more fully identify the design and operating parameters that cause noise induced by the intermeshing gears of a drive train. One such avenue was the investigation of Superfinishing using Chemically Accelerated Vibratory Finishing. This process generates a very smooth surface on the flanks of gears and has proven its ability to reduce the coefficient of friction[2], and in laboratory testing, the frictional component of noise known as Vibro-Acoustic Noise.[3]

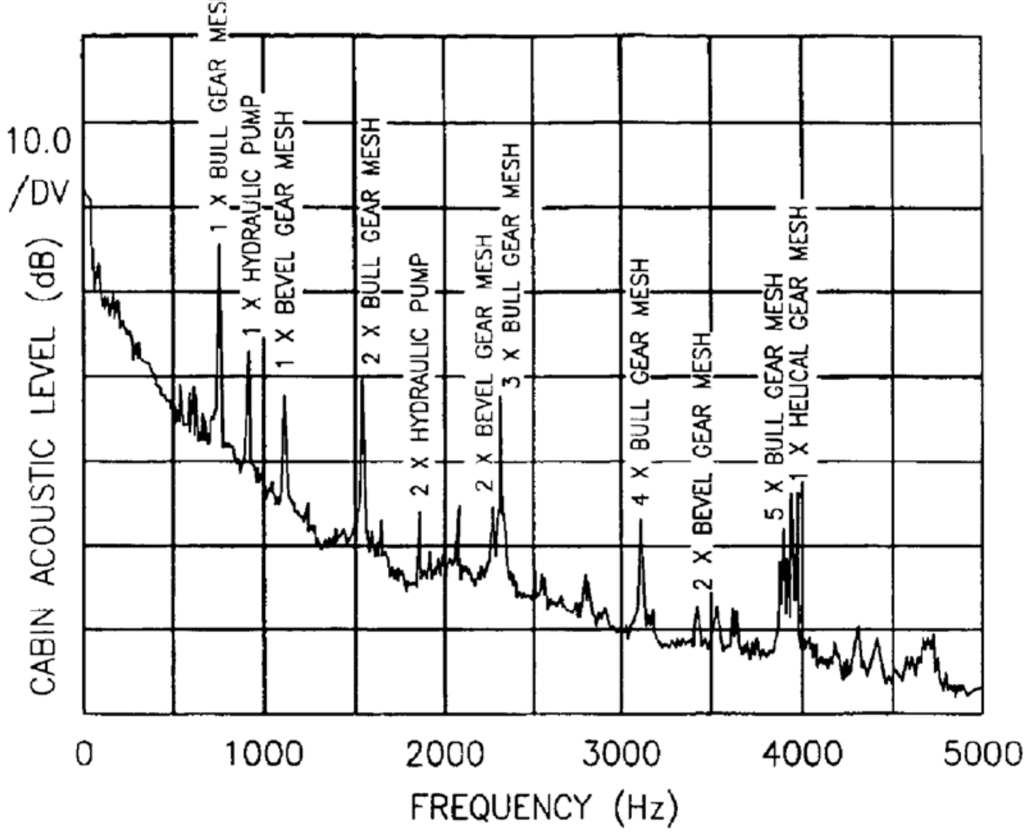

Figure 1: Chart showing that the predominant cabin noise is produced by the gearing meshing vibrations of the first few harmonics of the bull gear. Note that the highest cabin noise level is predominately the result of vibrations occurring at the first harmonic bull gearing meshing frequency of 778 Hz.

Vibro-acoustic noise

The gear meshing cycle consists of a large amount of sliding between the teeth making contact. At the pitch point, the gears experience pure rolling, however, the areas before and after the pitch point experience much more sliding motion. At this interface, the teeth experience high contact stresses which can result in low oil film thickness. When this happens, the result can be mixed or boundary lubrication conditions which lead to an increased coefficient of friction. At this point, the coefficient of friction is controlled either by the choice of lubricant or the surface finish of the teeth. This sliding and/or shearing of intermeshing teeth has been theorized as a significant contributor to the total noise signature of a gearbox and in the last few years, this theory has been proven in laboratory tests$^{\text{NO TAG}}$. As such, it will be appreciated that by Superfinishing, the friction coefficient on the gear teeth will be dramatically reduced, and so too, is the component of noise produced by the sliding action of the intermeshing gear teeth.

Superfinishing using chemically accelerated vibratory finishing

Chemically accelerated vibratory finishing incorporating high density non-abrasive ceramic media enhances the performance of components that are subjected to metal-to-metal contact or bending fatigue. The isotropic surface generated is unique when compared to even the finest honing and lapping in that it has no directionality and is capable of producing a final surface roughness of < 4 μin. (0.1 μm) R_a. It has a texture which consists of only random scratches and shallow dents. When the resultant surface has an R_a of approximately 4.0 μin. (0.1 μm) or less and a non-directional surface pattern, it is referred to as an Isotropic Superfinish (ISF$^{\circledR}$), however, for this document Superfinish will be used to denote this process and surface topography. Figure 2 shows an SEM image at 1000X of a typical ground surface with an R_a of approximately 10 μin. (0.25 μm) ((top image) and a Superfinished surface with an $R_a < 2$ μin. (0.05 μm) (bottom image) for reference. Note the directional asperities on the ground surface and the lack of directional asperities on the Superfinished surface. Only light scratches and tiny dents are visible amongst smooth, plateaued areas of the Superfinished surface. It is theorized that these tiny dents facilitate lubricant retention during operation.[4] Such surfaces are unique in their remarkable ability to reduce friction[2], wear[5], operating temperature[6], and noise[3], as well as contact[7] and dynamic fatigue[8] when compared to similar surface finishes produced by other techniques. There has been increasing interest over the years in applying this process to aerospace gears since the industry is being driven to produce higher cycle life gears at increased power densities while still allowing for large safety margins.

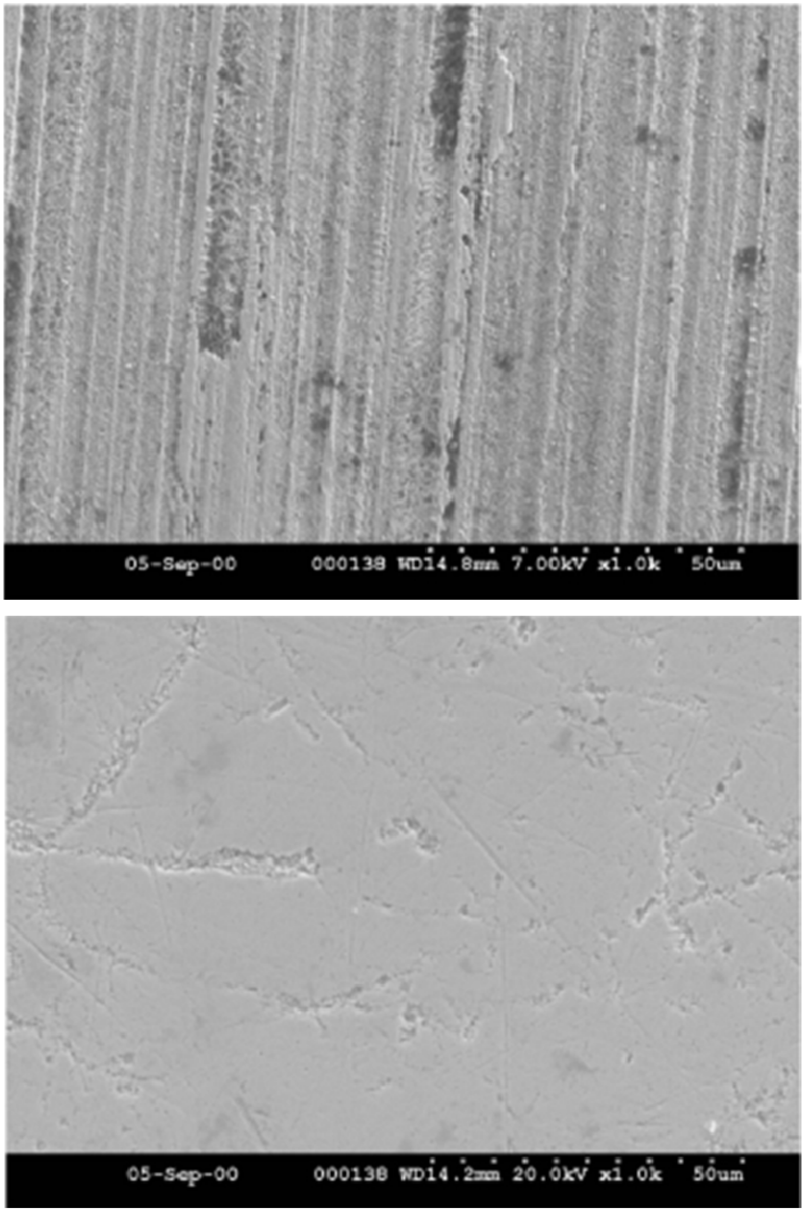

Figure 2: Scanning Electron Micrograph (SEM) at 1000X of a typical ground surface with an Ra approximately 10 μin. (0.25 μm) (top) and a Superfinished surface with an Ra < 2 μin. (0.05 μm) (bottom). Note the isotropic (non-directional) surface texture on the Superfinished surface versus the directional asperities on the ground surface.

The Superfinish process is discussed in detail elsewhere[7], but the following is a brief summary of the process. Superfinish is produced in vibratory finishing bowls or tubs. A proprietary active chemistry is used in the vibratory machine in conjunction with high-density, non-abrasive ceramic media. When introduced into the machine, this active chemistry produces a stable, soft conversion coating on the surface of the gear(s) being processed. The rubbing motion across the gear(s) developed by the machine and media effectively wipes the conversion coating off the "peaks" of the gear's surfaces, but leaves the "valleys" untouched. (No finishing occurs where media is unable to contact or rub.) The conversion coating is continually re-formed and rubbed off during this stage producing a surface smoothing mechanism. This process is continued in the vibratory machine until the surfaces of the gear(s) are free of asperities. At this point, the active chemistry is rinsed from the machine with a neutral soap. The conversion coating is rubbed off the gear(s) one final time to produce the Superfinished surface. In this final step, commonly referred to as burnishing, no metal is removed.

The Superfinish process is a mass finishing operation whereby tens or hundreds of gears can be simultaneously processed in the same machine. If all of the raw gears placed in the vibratory machine are identical at the start, then they are all identically finished at the end of the process. Every gear tooth will have the same surface finish and geometry since the parts continually and randomly move through the vibratory machine and statistically experience the same chemical and media exposure. If one tooth on a gear has its tooth thickness reduced by 0.0003 inches (0.0076 mm), then every tooth on that gear and every gear in the finishing machine will have its tooth thickness reduced by the same amount. Therefore, there is no need for costly final inspection of each and every gear as must be done after grinding or honing.

In addition, the simplicity of the Superfinish process yields a very robust manufacturing method. Vibratory machines are run for years without any maintenance except for minor lubrication. The media is non-abrasive so it retains its shape and size for long periods of time. The important parameters that control the surface finishing operation are the number of gears in the finishing machine, the concentration of the active chemistry, the flow rate of active chemistry, and the processing time. All of these parameters are easily controlled. The process lends itself to automation, and has been commercially used over the past 19 years.

S-76C+ Main Transmission Testing

Origin of the test gears

Sikorsky Aircraft Corporation supplied off the shelf S-76C+ main transmission gears to REM Chemicals, Inc. for Superfinishing. This process was applied to the third stage spur bull gear and mating pinions along with the second stage bevel gears. See Figure 3 for a schematic of the S-76C+ drive train and the gears processed. These gears were manufactured from AMS 6308 steel, carburized to existing Sikorsky Aircraft Corporation specifications and precision ground. The goal was to Superfinish these production gears to a $R_a < 4$ μin. (0.1 μm) across the active profile area of the teeth.

Starting condition of the test gears

The five gears were accepted production gears and were in typical aerospace precision ground condition. The surface roughness of the gears was measured by REM Chemicals, Inc. upon receipt and prior to processing using a Hommel T1000 profilometer fitted with a 5 micron radius stylus and following the ISO 4288 specification for the measurement of surface roughness. For easy comparison to the finished surface, a Tracing Length (Lt) of 1.5 mm and a Wavelength Cut-off (Lc) of 0.25 mm was used in the measurement of the as-received gears since this is the specification for a non-periodic surface pattern and R_a between 0.8 μin (0.02 μm) and 4.0 μin (0.1 μm). The surface roughness results of the as-received, or starting condition, gears prior to Superfinishing is listed in Table 1. A typical surface roughness profile and data printout for an as-received gear is shown in Figure 4. This printout is from a third stage spur pinion gear.

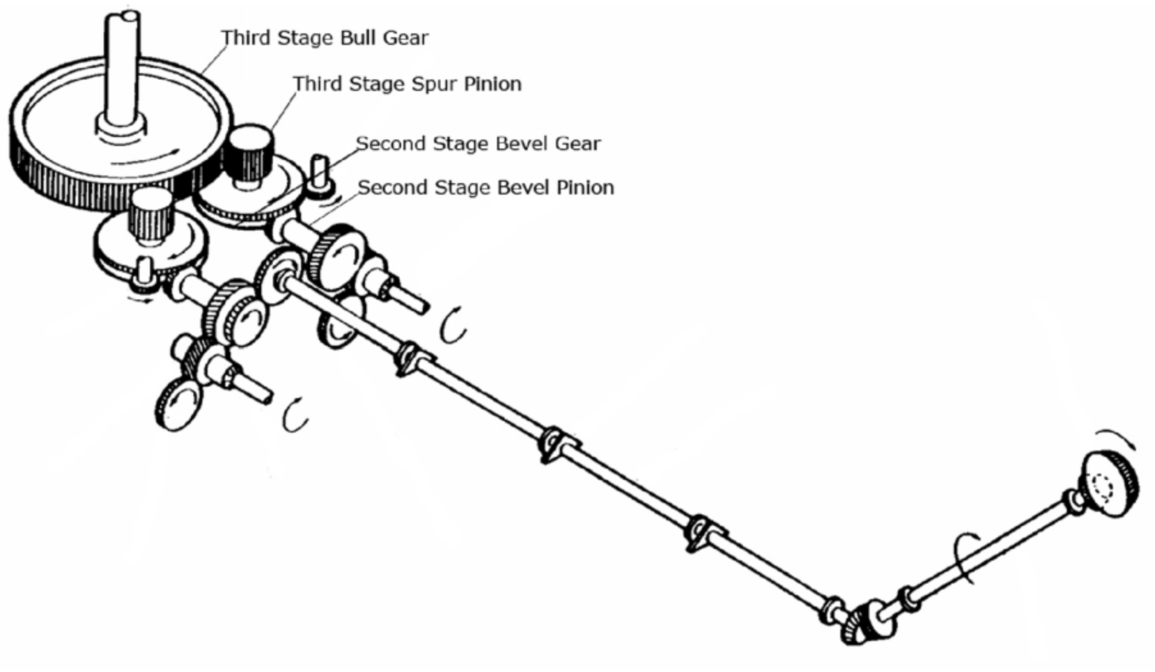

Figure 3: Schematic of an S-76C+ drivetrain which highlights the gears Superfinished during the project.

Table 1: Surface roughness measurements of the S-76C+ main transmission gears as-received prior to Superfinishing.

Measurement parameter	Second stage bevel pinions and gears (µin.)	Third stage spur pinion (µin.)	Third stage bull gear (µin.)
R_a	13 to 18	16 to 17	13 to 17
R_z	80 to 115	97 to 101	83 to 113
R_{max}	109 to 167	119 to 129	133 to 141
* All measurements taken at Lt = 1.5 mm and Lc = 0.25 mm using a 5 micron radius stylus tip.			

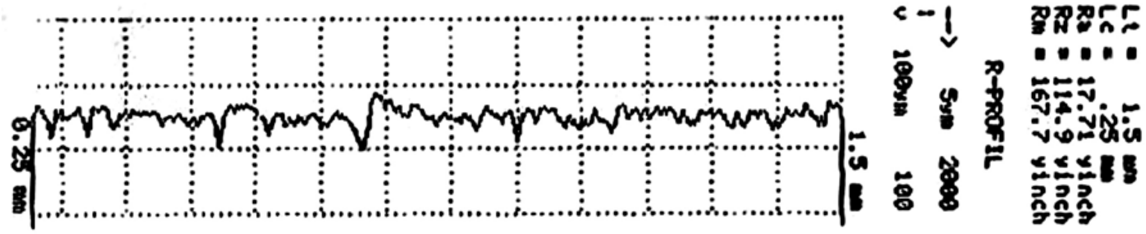

Figure 4: A typical surface roughness measurement for an as-received (un-Superfinished) S-76C+ main transmission gear. The trace was taken along the profile and within the active profile region of the tooth flank on a third stage spur pinion. This measurement is typical of all as-received gears used in the project. The scale to the right of the profile indicates that each vertical segment represents 5 µm and each horizontal segment represents 100 µm.

Superfinish process

The Superfinishing process consisted of the following steps:

1. Critical areas of the five gears such as bearing journals, threads and bolt holes were masked in order to prevent stock removal during the Superfinish process.
2. The exposed sections of the gears were cleaned of grease, oil and contaminants in order to ensure a uniform reaction with the active chemistry.
3. Superfinish (stock removal phase) using commercially available active chemistry.
4. Burnish (cleaning) using commercially available burnishing compound.
5. Unmask critical areas.
6. Rust prevent using commercially available rust preventative.

Final condition of the test gears after Superfinishing

After processing, the gears were photographed and final surface roughness measurements were taken of each gear. Visual inspection of the gears showed that the directional asperities had been removed leaving a smooth and flat contact surface in its place. The appearance of the gears was bright and highly reflective, indicative of a highly polished surface. Figure 5 shows a section of teeth from the third stage bull gear after Superfinishing. Note the reflections of the other teeth across each flank.

Figure 5: An image of a section of teeth from the third stage bull gear after Superfinishing. Note the reflections of the other teeth across each flank.

The final surface roughness of the gears were again measured by REM Chemicals, Inc. after Superfinishing using a Hommel T1000 profilometer fitted with a 5 micron radius stylus and following the ISO 4288 specification for the measurement of surface roughness. A Tracing Length (Lt) of 1.5 mm and a Wavelength Cut-off (Lc) of 0.25 mm are specified for a non-periodic surface pattern and R_a between 0.8 µin. (0.02 µm) and 4.0 µin. (0.1 µm). The surface roughness results of the Superfinished gears is listed in Table 2. A typical surface roughness profile and data printout for a Superfinished gear is shown in Figure 6. This printout is from a third stage spur pinion gear.

Table 2: Surface roughness measurements of the S-76C+ main transmission gears after superfinishing.

Measurement parameter	Second stage bevel pinions and gears (µin.)	Third stage spur pinion (µin.)	Third stage bull gear (µin.)
R_a	3.5 to 3.9	2.4 to 3.1	1.6 to 3.5
R_z	21 to 28	21 to 23	10 to 34
R_{max}	30 to 40	29 to 34	15 to 76
* All measurements taken at Lt = 1.5 mm and Lc = 0.25 mm using a 5 micron radius stylus tip.			

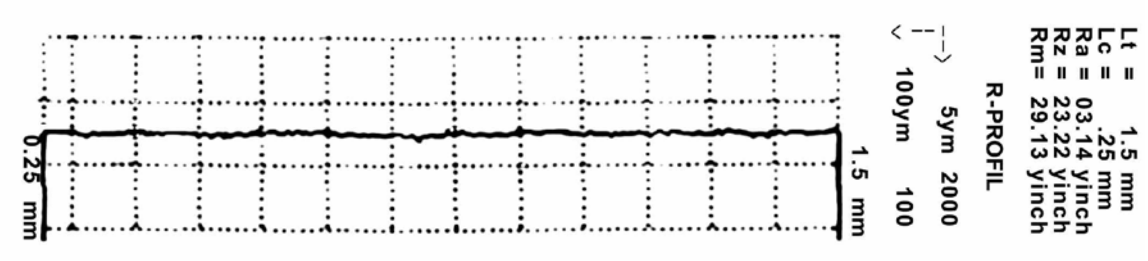

Figure 6: A typical surface roughness measurement for a Superfinished S-76C+ main transmission gear. The trace was taken along the profile and within the active profile region of the tooth flank on a third stage spur pinion. This measurement is typical of all gears Superfinished during the project. The scale to the right of the profile indicates that each vertical segment represents 5 μm and each horizontal segment represents 100 μm

Gear Testing

Test stand

After Superfinishing, the gears were returned to Sikorsky Aircraft for final inspection, assembly and testing. Once assembled, the S-76C+ main transmission was fitted with accelerometers in various locations to best measure amount of vibration generated by the Superfinished gears during the Acceptance Test Procedure (ATP) and ultimately the 200 hour endurance test. Figure 7 shows an image of the assembled S-76C+ main transmission.

Figure 7: S-76C+ main transmission after assembly.

The transmission was then mounted on the test stand. Once mounted, several thermocouples were attached. The placement locations of the thermocouples are dictated by the ATP specification. Two thermocouples of great interest are located at the oil-into transmission (out of the oil cooler) and the oil-out of the transmission (into the oil cooler). An image of the mounted transmission and test stand is shown in Figures 8 and 9. The S-76C+ helicopter is a dual engine aircraft, so the main transmission has two power input points. The test stand consists of two electric motors supplying the input power into the transmission and a water brake attached to the rotor shaft to supply the resistance and load.

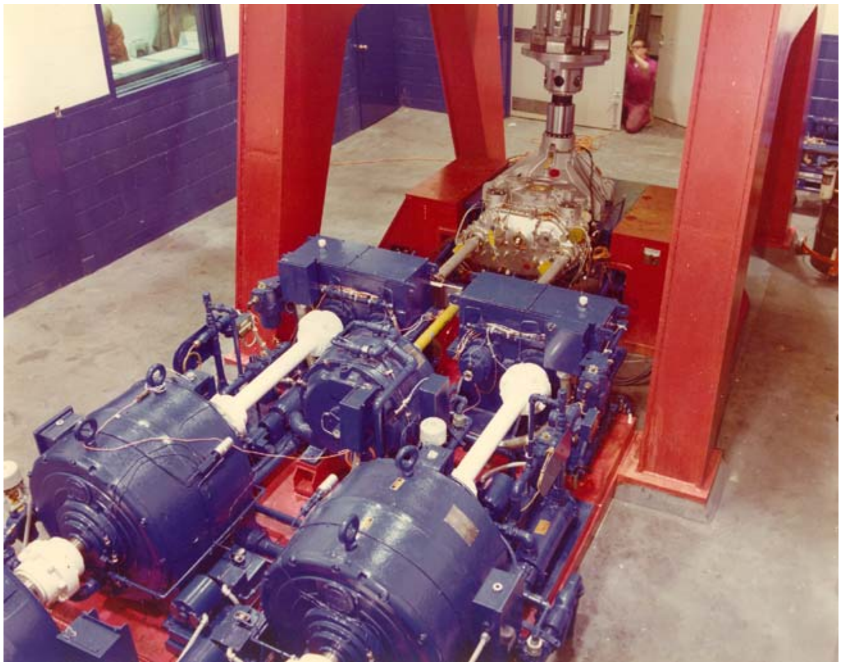

Figure 8: Rear view of the S-76C+ main transmission mounted on the test stand ready to begin the Acceptance Test Procedure (ATP) and 200-hour endurance test.

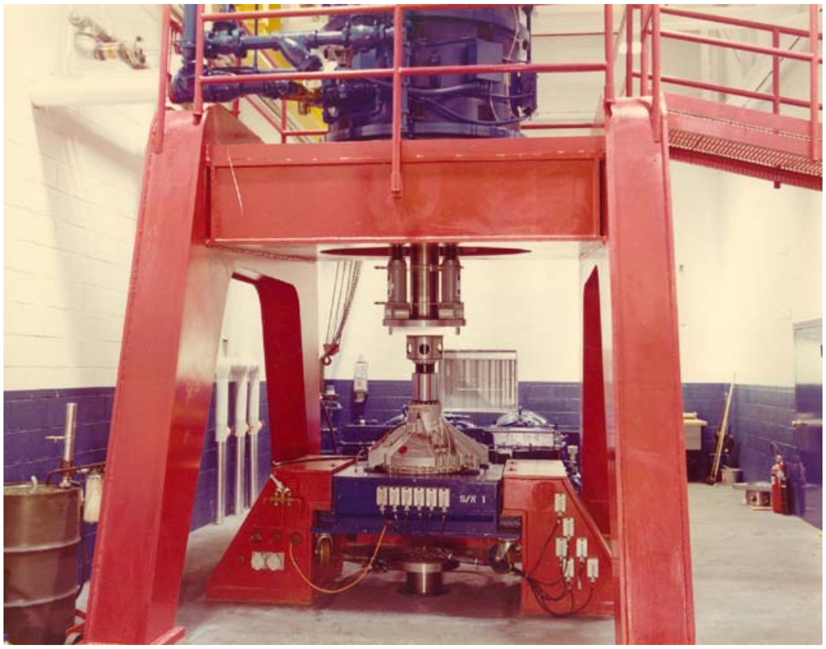

Figure 9: Front view of the S-76C+ main transmission mounted on the test stand ready to begin the ATP and 200-hour endurance test.

Acceptance Test Procedure (ATP)

The ATP is a mandatory test that all production transmissions must satisfactorily complete to be accepted as flight worthy. This test simulates typical torque loadings experienced by the transmission during normal operation. To be accepted, the transmission must meet specifications for several parameters, but the parameters most important during this test were visual inspection for scuffing, vibration levels and oil temperature. The specification states that input temperature of the lubricant must be maintained at 75° +/- 2° C throughout the testing. The minimum main shaft thrust load throughout all testing is to be 11,000 lbs. with the tail take-off load set at 155 ft-lbs. Failure criteria are scuffing on the bevel pinions or gears, a vibration signature of no more than 35 G's acceleration at specified frequencies and a maximum oil-out of transmission (into cooler) temperature of 115° C.

The testing started with the transmission being serviced with DOD-L-85734 lubricating oil to the top of the sight glass. The first stage of the ATP was a 2 hour break-in cycle, after which the bevel pinions and gears are visually inspected for scuffing. None was seen. This was done while the transmission was still mounted on the stand. The second stage was a 6 hour break-in cycle. The bevel pinions and gears were inspected twice during this period for scuffing just as before during the 2 hour break-in cycle. None was seen during either inspection. After the break-in cycle was completed, the 2 hour "bench test" was conducted. This consisted of seven test conditions at varying lengths of time that totaled one hour. The sequence is repeated at the end of the seventh test condition to give two hours of test time. This was the actual ATP test and the period at which all measurements for oil temperature and vibrations were recorded.

200-Hour Endurance Test

Following the initial ATP test, the main transmission was subjected to 200 hours of endurance testing. This testing was conducted on the same test stand with the same data collection system in place. The test was conducted using a load spectrum consisting of 21 steps which total 10 hours of test time. The load spectrum was repeated twenty times to total 200 hours of torque loadings which simulate normal operation. The bevel pinions and gears were visually inspected several times throughout the test. The seals were visually inspected for oil leakage every 5 hours. The testing conditions and durations are listed in Table 3.

Table 3: 200-hour endurance test load conditions and durations.

Step #	Condition	Duration (minutes)
1	Idle Power	5
2	60% Max Continuous Power	60
3	80% Max Continuous Power	60
4	Idle Power	5
5	90% Max Continuous Power	60
6	Idle Power	5
7*	Max Continuous Power	180
8	Idle Power	5
9	Takeoff Power	5
10	OEI-2.5 minute Power (L/H)	2.5
11	Idle Power	5
12	OEI-2.5 minute Power (L/H)	2.5
13	OEI-30 minute Power (R/H)	30
14	Idle Power	5
15	Takeoff Power	5
16	OEI-2.5 minute Power (R/H)	2.5
17	Idle Power	5
18	OEI-2.5 minute Power (R/H)	2.5
19	OEI-30 minute Power (R/H)	30
20	Idle Power	5
21	Max Continuous Power	120

* 658 ft-lbs. Input torque per engine input = 100% transmission torque.

Results

The Superfinished S-76C+ transmission completed both the 2-hour ATP and the 200-hour endurance test with flying colors. The visual inspections of the bevel pinions and gears throughout both tests indicated that no scuffing occurred during either test. In fact, it was noted that the gears appeared as if they had never been "run-in" at all. After all testing, the gears did not have any wear or contact pattern formation on the contacting areas of the teeth.

During the ATP, both vibration and temperature were measured during the run. Since this is a standard test that all production main transmissions must complete, there was a wealth of baseline data to compare with the Superfinished transmission. The first surprising result was that the vibration levels of the third stage bull gear 1x mesh (776 Hz) and the second stage bevel pinion 1 x mesh were significantly reduced. When compared to the baseline data, this indicates a 7 decibel reduction at the third stage bull gear 1x mesh and a 3.7 decibel reduction at the second stage bevel pinion and gear 1x mesh. As discussed earlier, it is these two frequencies that cause the most aural discomfort in the cabin and/or cockpit of a helicopter. These are also the most difficult to abate due to their vibro-acoustic nature, that is, these frictional excitations are carried through the shafts to the housings where are then transferred to the airframe, thus creating noise inside the cabin and /or cockpit. Figure 10 shows the measured ATP vibration levels of the S-76C+ main transmission, baseline versus Superfinished.

The second surprising result was that the oil-out temperature (oil into the cooler) was approximately 5° C lower than baseline S-76C+ main transmissions. Figure 11 compares the oil-out temperature as measured by the thermocouple with three production S-76C+ main transmissions that had also recently completed the ATP. It should be noted that the temperature reduction was not at only one torque loading, but was consistently lower throughout the entire torque band. Figure 11 shows baseline data being collected at 450, 500, 550, 600 and 650 ft-lbs of torque. The Superfinished trend line shows one point at 329 ft-lbs of torque and then three points at each of the following loads, 526 and 592 ft-lbs. The reason for the multiple points is that the Superfinished main transmission was run through the ATP test several times in order to verify the results and establish a trend line to use as a comparison.

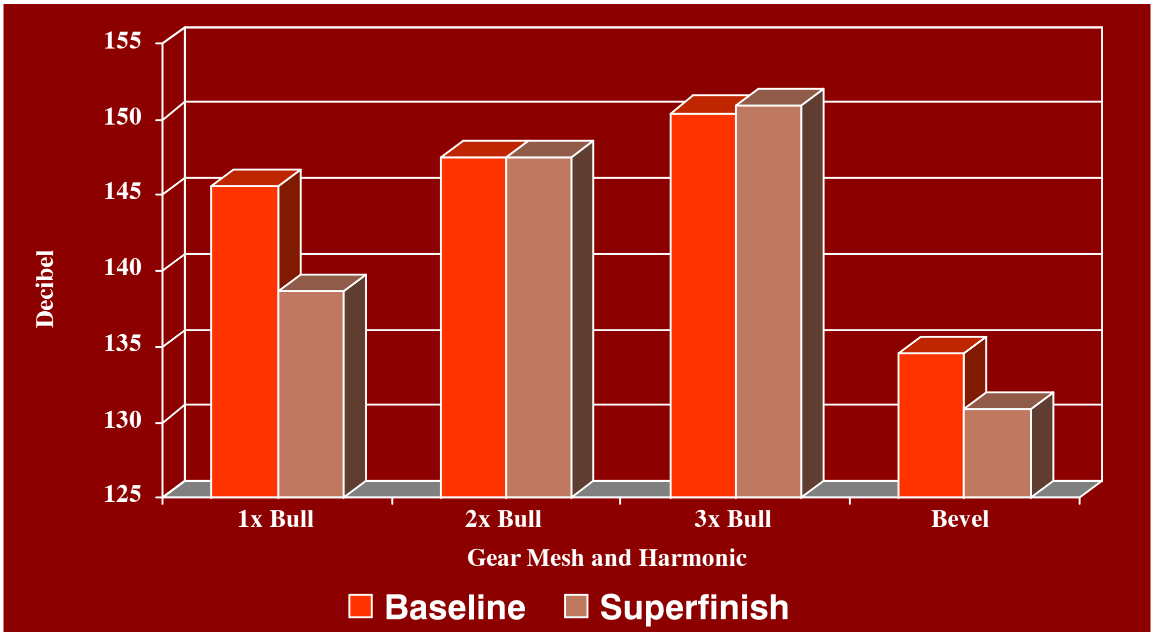

Figure 10: Measured ATP vibration levels for S-76C+ main transmissions, baseline versus Superfinished. Note the 7 decibel reduction at the third stage bull gear 1x mesh and the 3.7 decibel reduction at the second stage bevel pinion and gear 1x mesh.

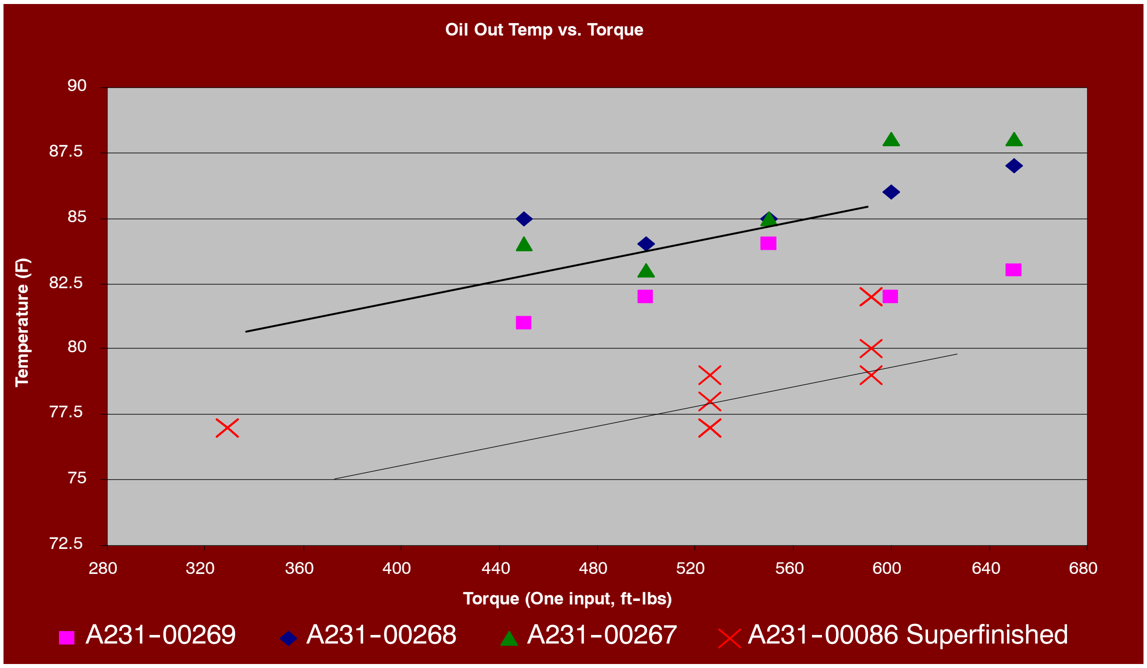

Figure 11: Oil-out temperature of S-76C+ main transmission. Plotted are three production transmissions as the baseline (top trend line) and one Superfinished transmission run through the ATP test three times to verify the results and establish a trend line (bottom line).

Conclusions

The Superfinish Process is a viable method to significantly reduce the in cabin and/or cockpit noise and vibrations which occur at the lower and most noticeable frequencies. It does this by reducing the friction between the meshing gears by lowering the surface roughness through a controlled process that removes the surface irregularities (asperities) caused by machining, grinding and/or shot peening. This produces a very unique surface texture that is described as isotropic (non-directional) and is characterized by an $R_a < 4$ µin. (0.1 µm) The data presented in this paper indicates that Superfinished S-76C+ main transmission gears have the following qualities:

1. Lower friction.
2. Lower vibro-acoustic noise.
   - Third stage bull gear 1x mesh reduced by 7 decibels.
   - Second stage bevel pinion and gear 1x mesh reduced by 3.7 decibels.
3. Lower operating temperatures.
   - 5° C temperature reduction when compared to baseline main transmissions during the ATP.

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