RCS Rotator/Pylon Architecture – Pushing Back the Boundaries of Structural and Operational Performance

J. Mark Hudgens, Eric Kim
MI Technologies, 1125 Satellite Boulevard, Suite 100
Suwanee, GA 30024-4629

***Abstract* – Radar Cross Section (RCS) test systems typically employ 2-axis compact positioners mounted atop low-observable support structures. The positioners are most often configured as azimuth over elevation, and are referred to as *rotators*. The support structures, called *pylons*, are built with very specific geometry that exhibits extremely low RCS. The rotator/pylon system mounts a model, often a full size aircraft, and presents it to the RCS measurement system in various spatial orientations.**

The need to maintain very low observability, along with the need to manipulate the model through a large range of motion, result in a challenging set of problems. These have been effectively addressed over decades of RCS equipment design. In recent years however, RCS applications have become much more demanding. Models are ever larger and heavier, with length exceeding 150 feet, and with weight up to 50,000 lbs. Required accuracy with some applications has increased to ±0.01°, an increase of 67% as compared to legacy values.

MI Technologies has developed products that significantly expand the structural and operational envelopes of rotator/pylon systems to meet the demand for higher performance. This paper presents the various challenges encountered in RCS Rotator and Pylon design, and the innovative solutions that have arisen from recent engineering efforts.

Keywords:
RCS, Radar Cross Section, RCS Rotator, Pylon, Tip Yoke, Tang Yoke, Low Observable, Rotator Architecture

I. INTRODUCTION

A large hypothetical RCS positioning system is shown in figure 1. The system depicted is similar to, though larger than most RCS positioner installations. The pylon, about 120 feet tall in this case, is a monocoque steel weldment. It exhibits very low radar cross section from the perspective of the human in the figure. The pylon is securely anchored to the ground. Attached to the top of the pylon is a highly-engineered rotator, the purpose of which is to place the model (full-scale aircraft) in various orientations about azimuth and elevation axes. The rotator resides almost completely within the target so that its RCS may be minimized.

It is suggested that the reader review the material referenced at the end of this paper for a discussion of RCS positioner basics.

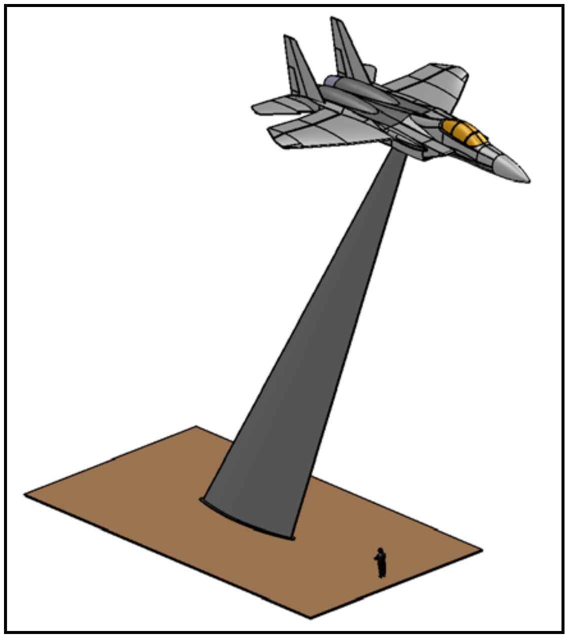

Figure 1 - A Large RCS Positioning System

RCS Rotators have been made for decades. They have always been highly stressed machines, requiring a high degree of engineering to satisfy their structural and powertrain demands. These demands have increased to levels that were unknown just a few years ago.

The engineering challenges relating to this migration into higher performing rotators are weighty. But innovative approaches address these issues. New architecture and materials solve structural problems. New component applications allow higher torque density. New analysis techniques provide rigorous and accurate results. The challenges have, at least for present demands, been met. The following paragraphs present some of those challenges and their solutions.

II. Rotator Operation & Key Attributes

Typical RCS rotator axis configuration is azimuth over elevation. The target is usually stepped to the desired elevation angle and scanned through full azimuth rotations. The results of these machinations are the application of large moments about both axes, and large delivered torques from the drivetrains of both axes to counteract the applied moments. This is the crux of rotator design – to create, in an astonishingly small space, a structure and a machine that is capable of performing these tasks.

The complete list of specifications for an RCS rotator is lengthy. There are a few line items in that list that are of particular interest to this discussion. Chief among them is the rotator's ability to deliver enormous torque about its elevation axis ($\pm M_y$ in Figure 2).

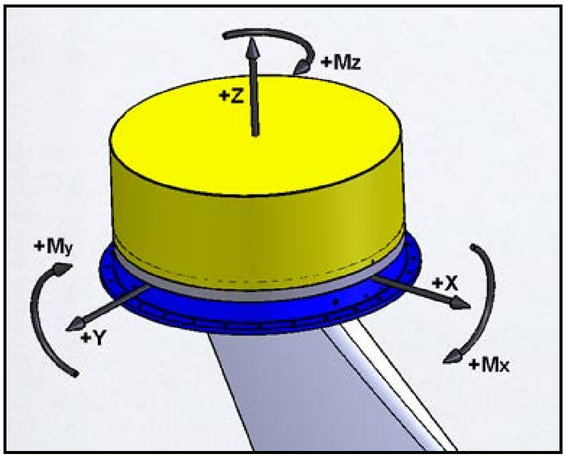

Figure 2 – Rotator Moments and Loads

As a rotator's elevation axis is depressed, a moment load is applied to it. For example, a large rotator may depress its elevation axis 30° as shown in figure 3. As the target pitches forward, the rotator must deliver increasing torque to resist the applied moment. In very large rotators, the *maximum delivered elevation torque* may reach 300,000 ft-lb.

Another critical rotator attribute is its ability to resist gravity loading (-Z in Figure 2). This key rotator specification is referred to as *maximum vertical load*. The range of current design for this specification is from 500 lb to 50,000 lb.

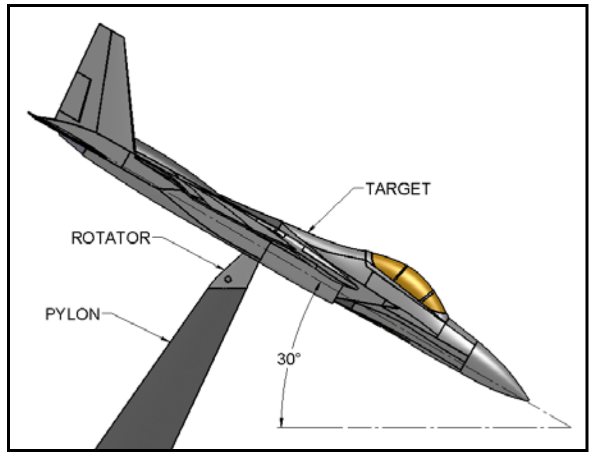

Figure 3 – Elevation Axis Depressed 30°

The two attributes introduced in the preceding paragraphs, along with others, are responsible for high stresses throughout the rotator's mechanical and structural systems. High strength materials and advanced structural architecture accommodate the high stresses. Still, factors of safety (FOS) must be maintained below aceptable levels to meet safety standards. Typical FOS is 5.0 referenced to material UTS.

III. Elevation Torque – Rolling Element Screw

As previously stated, perhaps the biggest design challenge in an RCS rotator is the need to deliver extraordinary elevation torque in very cramped quarters. The traditional solution to this problem – application of an Acme screw, the axis of which lies in a vertical plane corresponding to the X axis – has been effective. However, more recent performance demands have made this approach obsolete. Rolling element screws have been substituted for Acme type. These screws exhibit greatly improved thrust capability and much higher efficiency. For example, the elevation screw thrust for a rotator rated at 300,000 ft-lb elevation torque exceeds 500,000 lb. Figure 4 depicts a rolling element elevation axis screw for a large rotator.

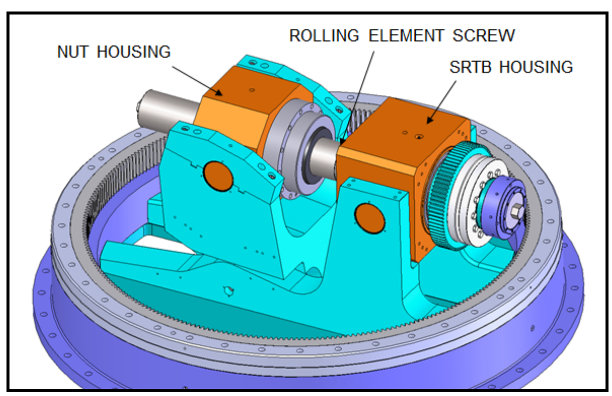

Figure 4 – Rolling element Screw

Greatly increased screw thrust allows for greater delivered elevation torque, but creates an interesting design challenge. That is, what kind of thrust bearing can support such loads, and still occupy a minimum of axial space? The solution arrived at is *the spherical roller thrust bearing*, or SRTB. These remarkable bearings make use of a self-aligning spherical geometry, but with contact angles that are optimized for carrying thrust. Figure 5 shows an SRTB design for an elevation axis rolling element screw.

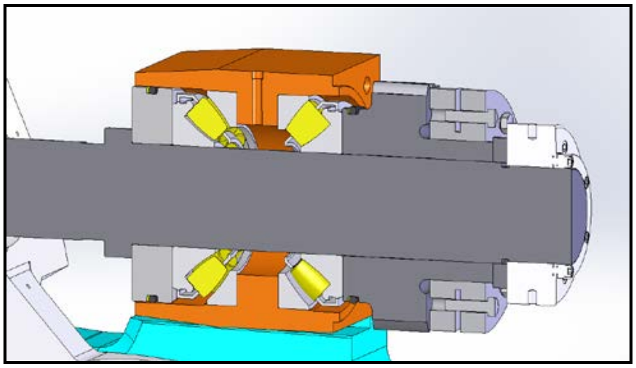

Figure 5 – Spherical Roller Thrust Bearings

Smaller rotators exhibit the same problems as large ones. The thrust bearing solution for a 3,000 lb vertical load rated rotator is shown in figure 6. Here, match-ground angular contact ball bearings with optimized thrust contact angles equally share the thrust load of a small rolling element screw.

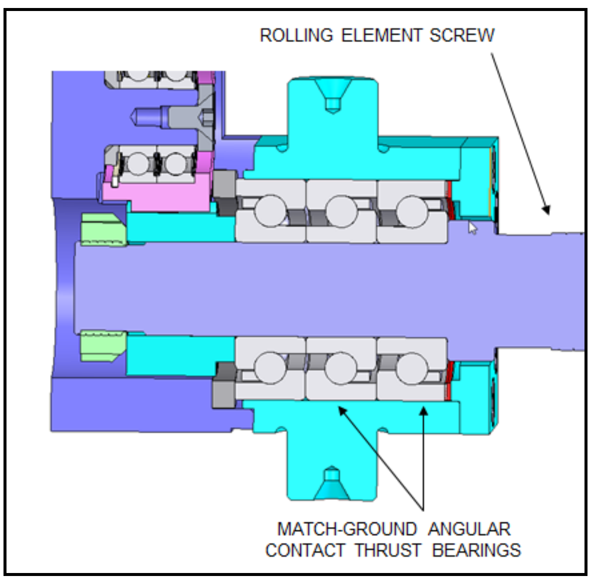

Figure 6 – Small Rotator Thrust Bearings

IV. PRIMARY STRUCTURAL ARCHITECTURE

This is an area that has seen a great deal of development in recent years. Traditional attachments of rotators to pylons have been shown inadequate as stress levels climb. Particularly, for large rotators, a new architecture is called for. Two distinct types of primary rotator structures have been developed; (1) *tang yoke* and (2) *tip yoke*. Both are shown in figure 7. The tang yoke is on the left. Its tang is a carefully machined taper. There is a socket in the pylon with matching tapers. When the tapered parts are engaged, sufficient bearing area and shear area are brought into service so that the rotator connection to the pylon is secure. The taper is self-holding. That is, the two parts must be coaxed apart by integral jackscrews.

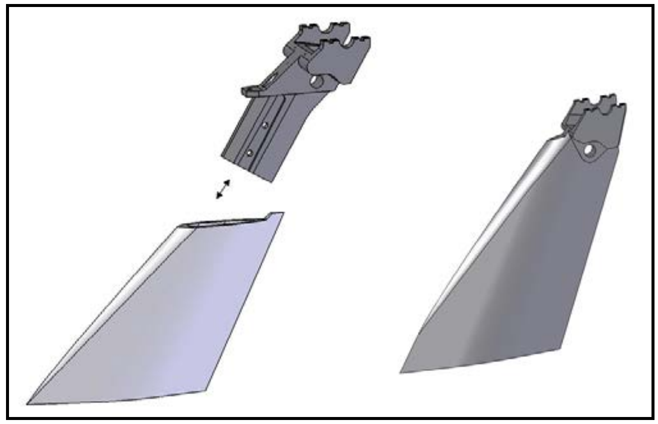

Figure 7 – Tang Yoke & Tip Yoke

The tip yoke is a more elegant and higher strength solution to rotator / pylon attachment than the tang yoke. With a tip yoke, the structural features required to support the rotator are integral to a structural element that has the same cross section as its pylon. Like the tang yoke, the tip yoke is monolithic. It is machined from a large forging of high-strength material. Its primary advantage over the tang yoke is that it offers a much larger cross section at its interface with its pylon, allowing higher loads for a given size.

Both the tang yoke and the tip yoke have integral yoke features for mounting a rotator. A large pin passing through a precision machined hole defines the elevation axis. This hole is present with both approaches, as can be seen in figure 7.

V. POWERTRAIN ENHANCEMENT

The elevation axis powertrain may be thought of as a structural system as well as a power transmission system. Failure of most any of its critical components might have catastrophic results. Design for safety has become even more important as payloads become larger and heavier. The following design principles have been adopted to maximize drivetrain integrity:

Number of connections – Each connection, say between a shaft and gear, is a potential point of failure. In evaluating design options for a new generation of rotators, it became a first principle to minimize the number of potential failure points, sometimes requiring higher cost to achieve higher levels of reliability and safety. Primarily, this is achieved by machining components monolithically with the shaft on which they are attached. When a pinion gear is machined monolithically to a shaft, the result is called a *pinion shaft*. An example of this is shown in figure 9.

Types of connections – The traditional gear mounting method involves a key and a set screw, or perhaps a key with two set screws. This connection is prone to failure by at least two modes: (1) Loss of the key due to any of a variety of reasons too numerous to count, and (2) failure of the shaft or gear due to geometric stress concentration.

Key loss or failure usually occurs when the connection is subjected to reversing loads, as in an RCS positioning system. The set screws can loosen, allowing the key to remove itself by creeping axially. When the key has crept a sufficient distance, the gear is no longer securely attached to the shaft, resulting in possible catastrophic failure.

Failure due to geometric stress concentration is more insidious than failure due to key loss. The presence of the key and the security of its set screws may be inspected. However, inspection is more difficult for the type of failure caused by geometric stress concentration. It usually takes the form of a classic fatigue, requiring specific tests be performed if there is any hope of identifying the condition before failure. Figure 8 shows a fatigue crack gear failure *in an antenna measurement positioner* that is due to geometric stress concentration. Note the crack emanating from the sharp corner of the keyway, which has propagated along the entire length of the tooth.

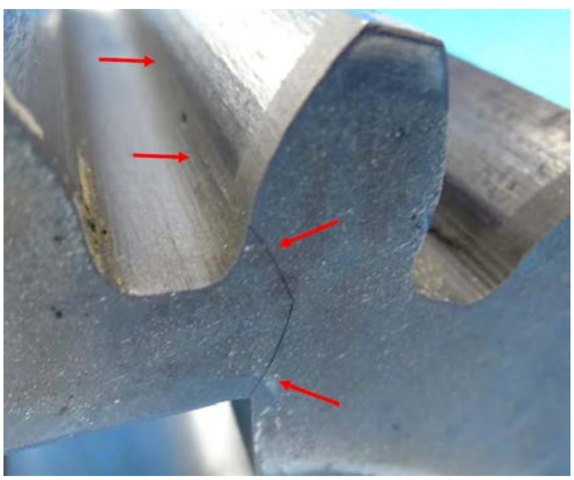

Figure 8

Far better connections than keys are available in the form of keyless bushings and shrink disks. Keyless bushings are hollow cylinders placed between the shaft and gear that may be made to expand and securely grip the shaft and the bore of the gear. Torque is transmitted between the shaft and gear by mere friction. There are no sharp machined keyways to act as stress risers. Drive torque is easily predictable. Installation and removal are simple.

Shrink disks are related to keyless bushings. They work by applying pressure to the outside of a gear hub, and causing it to bear against its shaft. Again, there are no keyways. Friction is the driving principle. Drive torque is easily predictable. Installation and removal are simple. A shrink disk is shown in figure 9. The use of keyless bushings and shrink disks represent an enormous advancement in drivetrain safety and longevity.

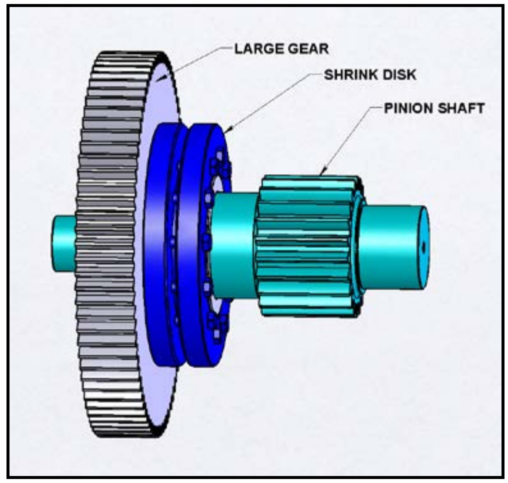

Figure 9 – Monolithic Pinion and Use of Shrink Disk with Large Gear

Design life for gears and bearings – The calculated service life of bearings, gears, and other components is often expressed as "L10 life." This is the number of cycles (rotations) that 90% of the components can be expected to survive. "L5 life is the number of cycles that 95% of the components can be expected to survive.

Bearing L10 life calculations are based on bearing load, speed, material, lubrication, and other factors. Bearing life is calculated using their manufacturer's empirical formulas.

Gear L10 (or L5) life calculations are based on gear loading, geometry, lubrication, material, accuracy, and other factors. The American Gear Manufacturers Association (AGMA) published widely accepted life calculation methods.

A number of custom gears exist in the elevation drivetrain. Their shafts must be supported by rolling element bearings. Given the consequences of a gear or bearing failure (especially a gear failure), it was decided that nothing lower than L10 $\approx \infty$ is acceptable. Using the methods referenced above, all gears and bearings are designed for virtually infinite L10 life. This of course, doesn't mean that all the components will last forever, but it does mean that for use as intended, gears and bearings in a new-generation rotator will statistically survive for 10^{10} cycles (which at rotator speeds, would be centuries for some components).

Designing a powertrain for such life is a significant challenge. Like all other components in a rotator, these devices must be kept as small as possible. However, the stress in a gear for a given torque increases as the diametral pitch and face width of the gear decreases. Thus, large torques imply large gears.

Artful use of high-strength materials helps keep component size to a minimum. Successful high-strength gears are readily made from precipitation hardening stainless steel 17-4 PH. With a simple one-step heat treatment, this material can obtain UTS approaching 200,000 PSI, and has the added advantage of not requiring subsequent grinding after heat treatment for most gears. For especially demanding gear applications, AISI 8620 steel, carburized and hardened, serves well. Post heat-treatment grinding is usually required for this material.

Shafting Details – Gear shafting transmits torque between gears or between a gear and another drivetrain component. A shaft failure could be just as serious as a gear failure. In many ways, strength and life considerations discussed previously also apply to shafting. Figure 9 is an example of a gear shaft that transmits torque between two gears – the pinion on the right and the large gear on the left.

With integral pinions, the shaft material is generally determined, of course, by the pinion material requirements. 17-4 PH is an excellent high-strength shaft material, exhibiting up to 183,000 PSI UTS, depending on heat treatment. For more modest stress levels, 4140 prehardened steel is commonly used in rotator power transmission shafting. This material exhibits UTS of about 124,000 Psi, and is highly resistant to fatigue.

Shaft design is as important as shaft material selection. Small design details can mean the difference in success and failure. Consider the shaft in figure 10. The right hand end is anchored. A torque is applied to the left hand end. The diameters of the two ends are identical. Note that the stress of the transition fillet on the left-hand side of the shaft is much greater than the stress on the right-hand side transition fillet. This is simply (and obviously) due to geometric stress concentration in the smaller fillet. Finite Element Analysis (FEA) allows the stress due to geometric stress concentration to be quantified.

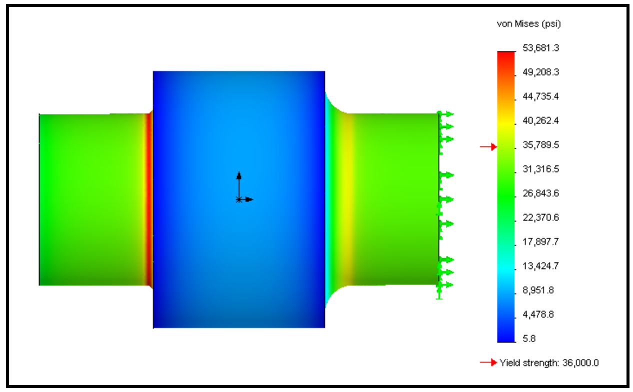

Figure 10 – Effect of Geometric Stress Concentration on a Gearshaft

SUMMARY

RCS rotators and pylons have evolved significantly in recent years. Larger, heavier models are the norm, and in cases where the targets are small, ever smaller rotator envelopes are demanded. Innovative pylon and rotator architecture, and advances in materials and analysis have enabled a new generation of rotators to perform at levels previously umimagined.

REFERENCES

[1] Mark Hudgens, Tim Schwartz, and John Ward, "Achieving the Desired Performance From a Radar Cross Section Pylon Rotator" AMTA 2011.