SMA TECHNICAL MEMO
TM 146

Title: SMA- Antenna transporter drive system test, evaluation and analysis

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Introduction:

SMA antenna transporter first experienced problems when moving Antenna 5 from Pad 11. It showed sluggish movement. Drive problems became apparent when moving Antenna 8 from Pad 15 to the assembly building. It stalled on the steep grade by pad 15 and the operator was only able to climb the slope after several attempts.

To investigate the possible causes for stalling under these conditions, a test procedure, required equipment and test plan were developed. A full test program was conducted the week of March 4-8, 2002 on the summit of Mauna Kea, Hawaii to evaluate the transporters hydraulic drive (propel) system.

To aid in understanding the report, the reader is reminded that the hydraulic drive system is composed of two identical (synchronous) systems. Each drive is composed of a pump and three wheel drive motors. They are arranged in a cross pattern with one front and two rear motors. The rear motors are the ones either side of the transported antenna.

Propel system evaluation:

The following are the test results and evaluations. These tests were conducted by loading the transporter with the partially assembled Antenna 6. Its estimated weight is 65,000 pounds. The transporters' weight is approximately 46,900 pounds (measured previously). The total vehicle weight for these tests then was 111,900 pounds. The tests were conducted by operating the transporter on level terrain, 9.3% grade and 10.5% grade. All terrain surfaces were lava gravel (unpaved) roadways.

To begin testing, gauges were installed in the test ports of the right propel pump. With the transporter on the grade and propel circuit engaged but not attempting to propel. The pressure gauges were read and recorded as follows:

- Test port “A”: ________________________________ 400 psi
- Test port “B”: ________________________________ 400 psi
- Charge pump output test port: ____________________ 420 psi
- Charge pump inlet test port: ______________________ 10 psi
- Flow meter on first motor case drain: ________________ *
- Flow meter on second motor case drain: ______________ *
- Flow meter on third motor case drain: ________________ *

  * The flow meter was not installed for these tests.

Note: Flow measurements were planned if the pumps needed to be evaluated. This testing determined that the pumps were operating to their specifications and flow measurements were not required.

With the transporter on the grade, the wheel motors in the high-speed range and the propel circuit engaged and attempting to ascend the 9.3% grade. The pressure gauges were read and recorded as follows:

- Test port “A”: ________________________________ 400 psi
- Test port “B”: ________________________________ 4000 psi
- Charge pump output test port: ____________________ 420 psi
- Charge pump inlet test port: ______________________ 10 psi

At this point in the testing, it is concluded that the right pump, the left front motor, and the right rear motors are in good condition. The gauge showing the charge pump output pressure remains at 420 psi when the system is stalled at 4000 psi confirms this. The pressure reading of 4000 psi at the “B” test port indicates that this pumps pressure limiter valve is not set at 6000 psi as the pump model code indicates. Also, 6000 psi was the transporters design pressure.

The gauges were installed in the test ports of the left propel pump to evaluate the other drive circuit. With the transporter on the grade and the propel circuit engaged but not attempting to propel The pressure gauges were read and recorded as follows:

- Test port "A": ________________________________ 400 psi
- Test port "B": ________________________________ 400 psi
- Charge pump output test port: ____________________ 420 psi
- Charge pump inlet test port: ______________________ 10 psi

With the transporter on the grade, the wheel motors in the high-speed range and the propel circuit engaged and attempting to ascend the 9% grade. The pressure gauges were read and recorded as follows:

- Test port "A": ________________________________ 400 psi
- Test port "B": ________________________________ 4000 psi
- Charge pump output test port: ____________________ 420 psi
- Charge pump inlet test port: ______________________ 10 psi

At this point in the testing, it is concluded that the left pump, the right front motor, and the left rear motors are in good condition. The gauge showing the charge pump output pressure remains at 420 psi when the system is stalled at 4000 psi confirms this. The pressure reading of 4000 psi at the "B" test port indicates that this pumps pressure limiter valve is not set at 6000 psi as the pump model code indicates.

Other indications propel circuit pumps and motors are in good condition is: hydraulic oil, pump and wheel motor external temperatures remained low (less than 100^0 F) after a period of extended operation. Also when the Hydraulic reservoir was changed the fluid was clear, without smell and appeared "like new".

At the conclusion of these tests, the pressure limiter valves in both the right and left pumps were re-adjusted to 5500 psi.

Propel system testing:

Knowledge that the pumps and motors where operating as specified, additional tests were devised to determine the transporters' grade capability while carrying a full weight antenna. An area around the inner circle of pads was selected to provide an unpaved level terrain for testing. Also portion of unpaved roadway, which contained two slopes, was selected for grade capability testing. The first section contained a slope of 9.3%, and the second section contained a slope of 10.5%. The transporter with antenna 6 was first operated on the level terrain area, then in reverse ascending the two grades. The wheel motors were placed in the low speed (maximum displacement) mode for these tests. Pressures were recorded as in the previous testing. The use of forward and reverse directions is only to document the test configuration. Forward direction has the antenna ahead of the driver. Transporter power is equal in both directions.

Level terrain operation, in the forward direction:

- Test port "A": ________________________________ 1200 psi
- Test port "B": _________________________________ 400 psi
- Charge pump output test port: _____________________ 420 psi
- Charge pump inlet test port: _______________________ 10 psi

9.3% grade operation, in the reverse direction:

- Test port "A": _________________________________ 400 psi
- Test port "B": _________________________________2600 psi
- Charge pump output test port: _____________________ 420 psi
- Charge pump inlet test port: _______________________ 10 psi

10.5% operation, in the reverse direction:

- Test port "A": _________________________________ 400 psi
- Test port "B": _________________________________3000 psi
- Charge pump output test port: _____________________ 420 psi
- Charge pump inlet test port: _______________________ 10 psi

Previous attempts to ascend these grades with the wheel motors in the high-speed mode resulted in propel system stall. At the 5500-psi setting, the transporter was able to ascend the 9.3% grade. However, it would require 5500 psi at the "B" port to ascend the 10.5% grade, which is the pressure limiter setting. Therefore its speed would reduce as it approaches the steeper grade and would eventually stall.

Drive system analysis:

The indicated pressure while operating on level terrain can be used to determine the rolling resistance of the transporter with the 65,000-pound load. The actual torque output of the wheel motor is a function of the differential pressure across the motor that is 1200 psi minus 400 psi, or 800 psi. The propel systems output torque can be determined from the following formula:

Note: Formulas are from Womacks' data handbook for fluid power calculations

Torque = (Pressure x displacement x efficiency) / 2 x π
Torque = (800 x 183 x 0.90) / (2 x 3.1416)
Torque = 20970 in-lbs.

Tractive effort = Torque / Wheel radius
Tractive effort = 20970 / 27
Tractive effort = 777 lb. per wheel

Total tractive effort = 777 x 6 = 4662 lb. = Rolling resistance on level terrain.

Theoretical tractive effort required ascending 9.3% grade with 111,900-lb Gross Vehicle Weight (GVW):

Tractive effort = Total rolling resistance + (0.093 x 111,900)
Tractive effort = 15,069 lb.

Motor torque = Tractive effort x wheel radius / number of wheels
Motor torque = 15,069 x 27 / 6
Motor torque = 67,809 in-lb.

Differential pressure required developing 15,069-lb tractive effort:

Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
Pressure = 67,809 x 2 x 3.1416 / (183 x 0.9)
Pressure = 2587 psi (Compared to 2600 psi gauge pressure or pump differential pressure of 2600 - 400 = 2200 psi)

Theoretical tractive effort required ascending 10.5% grade with 111,900 lb. GVW:

Tractive effort = Total rolling resistance + (0.105 x 111,900)
Tractive effort = 16,412 lb.

Motor torque = Tractive effort x wheel radius / number of wheels
Motor torque = 16,412 x 27 / 6
Motor torque = 73,854 in-lbs.

Differential pressure required developing 16,412-lb tractive effort:

Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
Pressure = 73,854 x 2 x 3.1416 / (183 x 0.9)
Pressure = 2817 psi (Compared to 3000 psi gauge pressure or pump differential pressure of 3000 - 400 = 2600 psi)

Projected differential pressure required ascending 15.6% grade with 111,900 lb. GVW:

Tractive effort = Total rolling resistance + (0.156 x 111,900)
Tractive effort = 22,118 lb.

Motor torque = Tractive effort x wheel radius / number of wheels
Motor torque = 22,118 x 27 / 6
Motor torque = 99,531 in-lbs.

Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
Pressure = 99,531 x 2 x 3.1416 / (183 x 0.9)
Pressure = 3797 psi (Gauge pressure = 3797 + 400 = 4197 psi)

Note: This indicates the transporter would stall on 15.6% grade at 111,900 lb. GVW prior to adjusting the pressure limiters to 5500 psi.

Projected differential pressure required to ascend 9.3% grade with 133,900-lb. GVW: Note: 133,900 pounds is the maximum weight projected for the antenna-transporter combination where the Antenna weight is 87,000 lbs.

Rolling resistance = 4662 x 133,900/111,900
Rolling resistance = 5579 lb.

Tractive effort = Total rolling resistance + (0.093 x 133,900)
Tractive effort = 18,032 lb.

Motor torque = Tractive effort x wheel radius / number of wheels
Motor torque = 18,032 x 27 / 6
Motor torque = 81,144 in-lbs.

Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
Pressure = 81,140 x 2 x 3.1416 / (183 x 0.9)
Pressure = 3095 psi (Gauge pressure of 3095 + 400 = 3495 psi)

Projected differential pressure required ascending 10.5% grade with 133,900 lb. GVW:

Tractive effort = Total rolling resistance + (0.105 x 133,900)
Tractive effort = 19,639 lb.

Motor torque = Tractive effort x wheel radius / number of wheels
Motor torque = 19,639 x 27 / 6
Motor torque = 88,376 in-lbs.

Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
Pressure = 88,376 x 2 x 3.1416 / (183 x 0.9)
Pressure = 3371 psi (Gauge pressure of 3371 + 400 = 3771 psi)

Projected differential pressure required ascending 15.6% grade with 133,900 lb. GVW:

> Tractive effort = Total rolling resistance + (0.156 x 133,900)
> Tractive effort = 26,467 lb.
>
> Motor torque = Tractive effort x wheel radius / number of wheels
> Motor torque = 26,467 x 27 / 6
> Motor torque = 119,102 in-lbs.
>
> Pressure = Torque x 2 x 3.1416 / (Displacement x Efficiency)
> Pressure = 119,102 x 2 x 3.1416 / (183 x 0.9)
> Pressure = 4544 psi (Gauge pressure = 4544 + 400 = 4944 psi)

From these calculations one would feel confidant that the transporter has adequate propel system power to handle Antenna movements. However, other concerns need to be considered, these are:

- Drive pressure required negotiating turns.

Measurements confirmed that propel system required an additional 400 to 500 psi to negotiate a turn due to skidding of the rear wheels.

- Roadbed conditions.

We have no data to confirm the needed drive pressure reserve for handling changes in roadbed surface. However, if "potholes" or other defects cause the tires to lift the load, then a resultant pressure rise will occur. Inspecting the roadbed should the transporter become stalled and correcting the defect is a viable solution. Roadbed conditions can vary the drive power required by a factor of 3-4. Therefore roadbed conditions are a significant concern.

- Anti-spin system

The transporter is equipped with an anti-spin system which prevents total loss of tractive effort should one wheel loose traction. The anti-spin system stops the non-tractive wheel from spinning and transfers power to the remaining wheels. When the system is activated, the transporter has only 5 of its 6 wheels propelling which results in a 20% increase in pressure to produce the same tractive effort (ie.20% power loss).

- Starting from a stopped position (Zero Speed)

The efficiency of the Poclain wheel motors at zero speed is between 70 to 75 % of theoretical, therefore would require up to an additional 1000 psi to begin moving from a stopped condition depending on load and grade conditions. To aid in this discussion, we can determine the maximum grade that the transporter can start from with a full weight antenna by using the previous equations. The result is a maximum grade of 6% or slope of 3.7 degrees. This slope is for a full system pressure of 5500 psi. Therefore, a safe slope would be 2.5 to 3 degrees.

- Pressure fluctuations during transport:

The transporter will experience pressure fluctuations from causes stated above. Also from speed changes due to operator control. The transporters low speed is estimated to be 2 miles/hour with an expected maximum speed change to be 10% happening in 1 second. This results in:

$$F = (W/g * (V_1 – V_2))/ t$$

$$F = ((133900/32.17)* (2.93 - 2.64))/ t$$

$$F = 1207 \text{ pounds}$$

We can estimate the pressure by interpolation using the rolling resistance.

$$P = (1200*1207)/4662 = 310 \text{ psi}$$

Conclusions:

These tests and evaluations indicate that the present transporters propel system is marginally adequate. It should be able to transport Antennas over the steep 15.6% grade if recommendation 2 listed below is strictly adhered to.

Based on these tests, what tractive effort should the drive (propel) system have to handle the increased Antenna weight. One way to look at this is to use the measured pressures.

Pressure required to climb maximum grade (15.6%):	4453
Pressure allowance for turning:	500
Pressure allowance for roadbed conditions:	500
Pressure allowance for speed fluctuations:	310
Pressure required for anti-spin capability:	890
Pressure design contingency (15 %)	1000
Desired pressure level:	7653 psi

The current transporter is set at 5500-psi maximum operating pressure. This is approximately 28 % below the desired level. If the pressure is set to its maximum operating pressure of 6000 psi, then it is approximately 22% below the desire level. Pressure and drive power (Tractive effort) is directly related. Therefore the transporter is under-powered by roughly 25% to cover all antenna-handling situations with an adequate drive power contingency.

Recommendations:

The following recommendations are offered.

1. A design study should be funded to look into how the present transporter could be updated to provide the desired propel power. This would investigate motors, which have the same interface as the present motors to minimize costs and upgrade complexity. The study should also provide cost and schedule estimates.

2. A set of driver instructions must be prepared so that the present transporter can be operated with the greatest efficiency.

3. A planetary gear set should be included in the new proposed motors to improve the power available for maneuvering around pads (starting with load).

4. Also, we should investigate a stronger tire for this increased antenna weight. The present tire has a small safety margin as described previously in the transporters' design review. Also, wear and UV degradation are unknown effects, which required a larger safety margin be considered.