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OVERVIEW OF THE SLS CORE STAGE THRUST VECTOR CONTROL SYSTEM DESIGN

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The Space Launch System (SLS) Core Stage (CS) Thrust Vector Control (TVC) consists of four independent hydraulic systems. The SLS CS TVC system is comprised of 8 mechanical feedback Shuttle heritage Type III TVC actuators and four RS-25 engines, each attached to a Shuttle heritage gimbal block/bearing. Each hydraulic system nominally provides hydraulic power to one RS-25 engine and two actuators. Additionally, each system provides redundant control capability to one actuator on each of its neighboring systems. The RS-25 uses hydraulic power to control propellant valves, and the TVC actuators are used to move the engine in the pitch and yaw gimbal planes. The TVC system design leverages hardware from the Space Shuttle program as well as new hardware designed specifically for the Core Stage. The Space Shuttle heritage hardware directly reused on SLS includes the Orbiter TVC hydraulic servo-actuators (with two slight design modifications), the Orbiter hydraulic circulation pumps, the Orbiter gimbal block/bearing, and the Solid Rocket Booster hydraulic pumps. The Solid Rocket Booster APU turbines are powered by hot gas produced by a catalyzed hydrazine decomposition. The SLS Core Auxiliary Power Unit (CAPU) is derived from the Space Shuttle Orbiter Auxiliary Power Unit (APU); on the SLS Core Stage, the CAPU turbine is spun using cold gas tapped-off from the RS-25 to CS liquid hydrogen autogenous pressurization line. The remaining hardware in the TVC system (hydraulic Filter Manifold (FM), hydraulic Supply Accumulator (SA), hydraulic Return Accumulator (RA), Hydraulic Reservoir, Exhaust Gas Heat Exchanger (EGHE)) as well as the avionics providing control and telemetry (TVC Actuator Controller (TAC) and CAPU Controller (CAPUC) are new components developed for SLS. This paper is the first installment in a seven-paper series surveying the design, engineering, test validation, and flight performance of the Core Stage Thrust Vector Control system. In this paper, the overall design architecture of the CS TVC is presented, with a focus on the interfaces between the TVC actuators, the engines, their hydraulic power systems, and the avionics that provide commands from the SLS Vehicle Management (VM) software to effect stable and robust flight control for the integrated SLS launch vehicle.

INTRODUCTION

The Space Launch System (SLS) Core Stage (CS) Thrust Vector Control (TVC)) system provides the capability to position the SLS RS-25 Core Stage Engines (CSE) thrust vector as well as provide hydraulic power to the CSE hydraulic actuation system (HAS) propellant control valves.

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TVC SYSTEM OVERVIEW

The CS TVC system consists of four main assemblies: the TVC Actuators (TVCA) and TVC Actuator Controllers (TAC) which provide thrust vector control, the Core Auxiliary Power Units (CAPU) and CAPU Controller (CAPUC) which provide hydraulic power, the hydraulic system components which support the operation of the TVC system, and the pre-launch thermal conditioning components which maintain acceptable hydraulic fluid temperature prior to launch.

There are two thrust vector control actuators for each of the four RS-25 engines, one located in the pitch axis, and one located in the yaw axis. The actuators provide the force and control capability to position the engine nozzles for vehicle steering. All eight actuators communicate to four actuator controllers. The gas system includes check valves, filters, flex hoses, CAPU, exhaust flex duct, and CAPU controller. The hydraulic system components consist of a main pump, circulation pump. reservoir, filter manifold, supply accumulator, return accumulator, quick disconnects, flex hoses, exhaust gas heat exchanger, and check valves. The system also includes line wrap heaters for thermal conditioning during tanking. The CS TVC system is designed to be single fault tolerant at the system level, although select sub-components require additional redundancy as defined within the component specifications. The TVC subsystem also includes electrical cabling from the TAC and CAPUC to the TVC components, hydrogen, helium, and hydraulic tubing, and secondary structure for mounting components.

Hydraulic Supply System

The hydraulic supply circuit provides supply pressure (nominally 3,000 psi) to the TVCAs and the RS-25 engine. The RS-25 engine uses hydraulic supply pressure to operate the engine HAS valves which are used to start, throttle, and shutdown the engines. Two hydraulic supply circuits (two independent systems) connect to each actuator to provide redundant hydraulic pressure to the actuators, referred to as cross-strapping. Only a single supply circuit is connected to the engine, therefore, redundant hydraulic pressure is not provided to the engine. Each engine can use pneumatic pressure from the MPS system in the event of a hydraulic pressure loss.

The hydraulic supply circuit begins at the main hydraulic pump where the hydraulic fluid is pressurized to the nominal 3,000 psi required for operation. The hydraulic fluid exits the pump to a hydraulic flex hose, which enables the shock mounted CAPU/main pump assembly to connect with the hard mounted vehicle tubing. Vehicle tubing carries the hydraulic fluid to the filter manifold. The filter manifold includes a high-pressure relief valve (HPRV) that will divert supply circuit flow directly to the reservoir in case of a system overpressure. Upon exiting the filter manifold, the hydraulic fluid is routed to the supply accumulator. From the supply accumulator the vehicle tubing separates the supply flow between the engine and four actuators. Nominally, flow only goes to two actuators. However, if the neighboring CAPUs fail the system in question will pick up control of two additional actuators. Therefore, a single TVC system can power up to four TVCAs and one engine HAS.

When the CAPU/main pump is not operating, the circulation pump is utilized to push flow through the TVC system at a much lower supply pressure. The main pump discharge and case drain are isolated with check valves located in the filter manifold.

Hydraulic Return Circuit

The hydraulic return circuit begins within the actuator and engine where the hydraulic fluid from the supply circuit is returned to the TVC system at a significantly lower pressure. The return flow from the engine is routed to the return accumulator. The flow out of the return accumulators is combined with the return flow from the three actuators and is routed through vehicle tubing to the Exhaust Gas Heat Exchanger (EGHE). After cooling, the flow is routed through vehicle tubing and combined with any flow diverted by the high-pressure relief valve and filtered main pump case drain flow from the filter manifold to the reservoir. Lastly, flow leaves the reservoir and goes to the main pump suction line via a flex hose if the main pump is operating. If the circulation pump is operating, flow goes to the filter manifold then the circulation pump suction.

Hydraulic Case Drain Circuit

The hydraulic case drain circuit begins at the hydraulic main pump. While the main pump is operating, fluid flows through the pump for lubrication and cooling of the rotating machinery components and exits the pump at the case drain port. The hydraulic fluid exits the pump to a hydraulic flex hose and routes through vehicle tubing to the filter manifold. The filter manifold case drain circuit is protected by a check valve which prevents flow back into the main pump case drain. It also includes a filter. Flow exits the manifold and connects with return flow from the EGHE.

Hydraulic Fluid

The SLS TVC Hydraulic fluid is MIL-PRF-83282D "Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base." This is the same fluid that was used on the Space Shuttle Program in both the Orbiter and SRB. The hydraulic fluid used for this application is MIL-PRF-83282 (tested to NASA Micronic 882 requirements). TVC Hydraulic fluid system components are designed with proof and burst factors of safety per AS5440, Class 3000.

Gas System

Each SLS CS has four separate but identical gas systems. Each gas system incorporates a CAPU powered by gaseous hydrogen from the Core Stage Main Propulsion System (MPS) while the RS-25 engines are firing, or gaseous helium supplied from the ground system for pre-launch operations prior to CSE start. Speed control, including over-speed and under-speed protection, of the CAPU is provided by the CAPUC. The cold gases are used to spin a turbine which, in turn, drives the main pump (see Main Pump component section for more details). The EGHE is used to transfer heat from the hydraulic fluid to the CAPU exhaust gas thereby cooling the hydraulic fluid during system operation. A small portion of the GH2 / GHe flow to the CAPU is diverted directly to the EGHE to maintain positive pressure within the exhaust duct to ensure the exhaust flow is not re-ingested into the vehicle during flight.

Actuators and Controllers Assembly

The CS TVC system consists of eight hydraulic actuators (two per engine) and four TACs. These actuators are reused from the Space Shuttle Orbiter. The Orbiter used Type I, II, and III actuators, but the SLS CS only uses the Type III actuators. The TACs are new and were developed specifically for the SLS CS TVC system.

Actuator Hydraulic Supply Cross-Strapping

There is one independent hydraulic system for each of the four engines. The four hydraulic systems are cross strapped at the actuators such that a failure in a single hydraulic system or power string allows for the availability of hydraulic power for thrust vector control from the remaining hydraulic systems. Two systems provide hydraulic power, one to each actuator of the failed system. To accommodate the additional loading, the CAPU controllers of the affected systems will be commanded to high-speed mode by the flight computers. This cross-strapping provides the required redundancy for a single fault tolerant TVC system but does not provide redundant hydraulic power to the engine HAS. Should a TVC system failure occur resulting in loss of hydraulic power to the main engine, the engine will continue to operate, but in fixed-throttle mode, and when commanded to shut down, will shut down pneumatically.

TVC System Pre-launch Thermal Management

The circulation pump is used to circulate the hydraulic fluid in each hydraulic circuit to maintain an acceptable pre-launch temperature of the hydraulic fluid while the liquid oxygen and liquid hydrogen are being loaded into the CS MPS tanks (the circulation pumps are not operational during launch or flight). The TVC system uses the heritage Orbiter Circulation Pumps, an electric-motor-driven, two stage positive displacement gear pump. The filter manifold assembly contains a check valve which prevents hydraulic flow back to the circulation pump outlets when the main pump is operating. Within the filter manifold assembly, the circulation pump flow is connected to the hydraulic supply circuit and routed to the four actuators and the engine for that system. Similarly, the hydraulic fluid circulates through both the actuator and engine hydraulic return circuits to the filter manifold, where it is again routed to the circulation pump.

Line wrap heaters are installed to supplement the circulation pumps during propellant tanking. Additionally, the main pump discharge, suction, and case drain lines are isolated from circulation pump flow by check valves in the filter manifold, so heaters are also located on those lines. The line heaters are ground powered, and ground controlled. The ground controllers receive feedback from surface mounted resistance thermal detector (RTD) temperature sensors installed on the lines.

Prior to CAPU start, the EGHE does not remove significant heat from the hydraulic fluid as there is no cold gas exhaust flow to accept the heat. Just prior to CAPU start, the circulation pumps will be shut off and left off for the flight. As the hydraulic fluid would be circulating under the main pump power, the line wrap heaters will also be shut off and left off for the duration of the flight.

Once the CAPUs are started on GHe from the ground, the hydraulic fluid temperature will begin to rise due to the heat energy input by the main pumps. The cold gas flow in the CAPU exhaust duct flows through the EGHE to cool the hydraulic fluid. A more detailed discussion of EGHE design considerations is contained in the component discussion section.

COMPONENT DESCRIPTIONS

The components of the TVC system are assembled into four separate hydraulic systems. The four hydraulic systems are composed of identical primary components, although tubing and cable lengths slightly vary due to the vehicle layout. The functionality of each component adds to an aspect of the overall system performance and response. This section describes the purpose and functionality of each component of the TVC system.

TVC Actuator

Each actuator has a locking valve, a switching valve, four servo valves, and a power valve. Each servo is connected to one TAC which sends current to said servo valve. The servo valves meter flow to the power valve to create a pressure differential across the power valve. The power valve meters flow to the actuator piston. Flow metering by the power valve and the servo valves is dictated by the TAC commands and feedback from the internal workings of the actuator which include the piston position, the power valve position, the servo dynamic pressure feedback assembly and the servo flapper position. This servo-valve combination is called Passive Majority Voting and can overcome faulty contributions from one of the servo-valves, either a null or a full extend/retract input. Feedback from each servo valve is provided back to the TAC showing the secondary pressure delta for that valve. This allows the TAC to determine if a single control string is in a fault condition, and the TAC can activate a bypass valve to remove that string from the force sum.

The actuator position control loop is closed by mechanical feedback from the piston to each servo-valve torque motor. In addition, a double nozzle dynamic pressure feedback (DPF) device provides load feedback to each servo-valve.

A switching valve automatically switches external hydraulic power sources from primary to secondary when the primary pressure drops below a certain value. This enables the redundant hydraulic power supply of the cross-strapped hydraulic system. A Linear Variable Differential Transformer (LVDT) type transducer is utilized to provide an indication of switching valve position. Also contained in the switching valve flow circuit is a flow cut-off which allows low press fluid circulation for thermal conditioning but does not flow when the system is at operating pressure.

Each actuator has an internal lock valve that actuates to the unlocked position when system pressure is greater than a threshold and actuates to the locked position to isolate the main power spool from the piston if hydraulic pressure drops below a low threshold value. This will prevent engine gimbal movement when hydraulic pressure is too low to control the engine position.

TVC Actuator Controller

The heritage orbiter actuator controllers were not compatible with the 1553 SLS avionics architecture. As such, new actuator controllers, known as TACs adapted from the Constellation Program Ares I Upper Stage TVC actuator controllers, were designed to interface with the heritage orbiter actuators required for SLS. Four TACs receive digital position commands from the SLS Core Stage Flight Computers over a 1553 bus, process those commands, convert them into appropriate positioning servo drive current signals, and then output the drive current signals to the servo-valves in the TVCAs. Sensor data from the TVC hydraulic system is also collected by the TACs and passed through to the Flight Computers.

Each of the four TACs provides one drive channel to each of the eight Orbiter actuators. Each TAC monitors the feedback from its respective servo-valve (secondary delta pressure) and can bypass that servo based on the data received. The TACs have redundant connectivity with one of the three flight computers through the 1553 bus for actuator position commands and health and status data. The health and status data includes actuator position, servo-valve current, and servo-valve delta pressure telemetry.

TVC Core Auxiliary Power Unit and Controller

The CAPU and CAPUC are part of the Core Stage TVC subsystem on the SLS Core Stage. Each CAPU contains a supply valve, a speed control valve, a gearbox, a gearbox heat exchanger, and a turbine wheel. The turbine is driven by GH2 from the CSE as well GHe from the ground prior to CSE start. The CAPUC is a separate component that interfaces with the CS avionics.

The turbine rotational shaft speed is reduced through a gearbox which in turn provides mechanical shaft power to drive the attached hydraulic pump. The hydraulic pump is referred to as the Hydraulic Main Pump and is not part of the CAPU assembly. The CAPU provides power during prelaunch and ascent phases for the SLS Core Stage. The CAPUC performs CAPU speed control, sends instrumentation data and health and status data to the flight computers, and controls the electro-depressurization valve (EDV) on the main pump. A single coil solenoid Propellant Supply Valve (PSV) integrated into the CAPU assembly provides GHe and GH2 on/off functionality. The SLS CAPU-CAPUC design utilizes a single solenoid actuated 2-stage Speed Control Valve (SCV) and a Magnetic Pickup Unit (MPU) (speed measurement). The primary function of the CAPUC is to maintain the CAPU turbine speed by cycling the speed control valve open/closed thus controlling the flow of propellant to the CAPU turbine (GHe prelaunch and GH2 after CSE start). The CAPUC commands the PSV open when the start command is received from the flight computer and thereafter commands the SCV open/closed to maintain turbine speed based on the MPU sensor inputs to the controller. The Flight Computer has the capability to command the CAPUC to operate in high-speed mode and command the CAPUC to shut down the CAPU. The CAPUC provides turbine over-speed protection by shutting down the CAPU if the over-speed threshold limit is reached. An MPU reading below the low turbine speed is considered an MPU failure. If both MPU are considered failed (i.e., both reading below the low-speed limit), the CAPUC will shut down the CAPU.

During pre-launch, GHe is supplied from the ground system to the CAPU to power the turbine until the CSEs are started. The pressure of the GHe is lower than the GH2 from the CS engines so when the engines start, the pressure of the GH2 rises above the GHe pressure from the ground system and closes a check valve that isolates the GHe feed from the GH2 feed.

Hydraulic Main Pump

The SLS CS TVC hydraulic main pump is a direct reuse of the Shuttle SRB hydraulic pump manufactured by Parker Abex. The main pump is an AP27V series hydraulic pump that was originally developed by Abex for the F-14 and then developed, fully qualified, and utilized on the Shuttle SRB and Orbiter hydraulic systems. The pump is a variable flow, pressure compensated, axial piston hydraulic pump that is shaft driven by the CAPU. The EDV, when energized, causes the pumps variable displacement mechanism to reduce the pump displacement, thereby reducing CAPU torque at startup. After the CAPU reaches operating speed, the EDV is de-energized for the remainder of the mission. During flight operations, the main pump provides hydraulic fluid flow at a nominal operational pressure of 3000 psig for engine throttling and thrust vector control from engine start to engine shutdown. The main pump does not include any instrumentation.

Filter Manifold

The filter manifold assembly acts as a collector and distributor of hydraulic fluid. The TVC hydraulic system contains four hydraulic circuits, with each circuit containing an identical filter manifold assembly. The filter manifold is a new build component; leveraging design work performed during the Constellation Program Ares I Upper Stage TVC hydraulic system design.

The filter manifold assembly performs the following functions and incorporates the following interfaces and instrumentation for the TVC hydraulic system: pressure relief, filtration, flow/pressure isolation, instrumentation including two pressure transducers for the hydraulic fluid supply pressure (one transducer upstream of the filter and the other downstream) and a pressure transducer for main pump and circulation pump suction pressure, fluid interfaces for the main pump case drain line, HPRV outlet flow, circulation pump suction port, main pump and circulation pump high pressure supply ports, high pressure supply and low pressure return hydraulic fluid flow to the hydraulic service panel, (ground support equipment or (GSE)) and standard test equipment (STE), and electrical interfaces for instrumentation and grounding.

Reservoir

The SLS CS TVC reservoir is a maintenance free bellows style reservoir. The reservoir is new build hardware for SLS. It provides capacity for volumetric changes in the system fluid resulting from temperature changes and variations in system operating conditions, and from system bleeding of entrained air. It also stores the hydraulic fluid from the supply accumulator while the main pump is not operating. The reservoir gas volume is charged with gaseous nitrogen (GN2) pre-charge pressure selected to provide sufficient inlet fluid pressure to the main pump and circulation pump. Finally, the reservoir fluid acts as a heat sink for the hydraulic system during TVC operation.

A GN2 service valve located on the gas side of the reservoir is provides the ability to charge, drain and re-charge using GSE, if needed. Pre-charge levels of the reservoir and return accumulator are chosen to optimize system pressure balance both during CAPU/main pump operations and during non-operating conditions. Unlike the Shuttle hydraulic system which used a boot-strap reservoir, SLS TVC employs a bellows reservoir as discussed above. As such, the supply system and return system pressures are closely coupled. The return and supply pressures will balance by fluid flow between the systems (from supply to return) when the main pumps are off. When the main pump (or GSE pump) is not operating, the fluid volume of the supply accumulator is emptied into the return system. This raises the return system pressure to balance with the supply system, resulting in higher pressures in the return system. A pressure balance is required to meet the two extreme system conditions: maintaining main pump minimum inlet pressures (with the pump running) while the system hydraulic fluid is cold and avoiding excessively high return system pressures at elevated fluid temperatures (which can occur after MECO) when the main pump is off.

The reservoir includes a bleed valve at the high point of the system to facilitate hydraulic fill operations. This bleed valve is opened during initial fill to allow free air to be removed from the TVC system. The valve has provisions to capture any expelled hydraulic fluid during fill & bleed operations. In addition, this valve can be opened during contingency drain operations (if required for a system break-in/component change-out) to ensure that fluid is expelled from the reservoir.

The reservoir incorporates two identical RTD sensors used for measuring the fluid temperature inside the reservoir (two sensors provide redundancy). The reservoir also incorporates an LVDT to measure the fluid volume inside the reservoir by correlation of the position of the bellows to the amount of fluid inside the reservoir fluid volume.

Supply Accumulator

The supply accumulator is a maintenance free bellows design consisting of a container that houses a chamber of compressed GN2 and GHe, a chamber for hydraulic fluid, a metal bellows separator between the gas and fluid chambers, and a mounting provision to attach the unit to SLS structure. The supply accumulator is a COPV design for to reduce weight. The supply accumulator is a new design component for SLS. The supply accumulator leverages the accumulator design developed for the Constellation Program Ares I Upper Stage TVC hydraulic system. Each hydraulic system has a single supply accumulator. The accumulator is charged by the supplier and the valve is sealed post charging. The primary purpose of the accumulator is to damp out pressure transients in the supply side of the TVC hydraulic system and supply hydraulic power to the CSE HAS actuators during MECO. The supply accumulator does not include any instrumentation.

Return Accumulator

The primary purpose of the return accumulator is to dampen-out return pressure transients created by the TVC actuators and prevent them from reaching the return side of the CSE HAS. It also provides some limited hydraulic fluid storage capacity. There is one return accumulator in each of the four hydraulic systems. The return accumulator is new build hardware for SLS.

The return accumulator assembly is a maintenance free bellows design, consisting of a container and mounting that houses a chamber of compressed GN2 and GHe, a chamber for hydraulic fluid, and a metal bellows separator between the gas and fluid chambers. The accumulator is charged by the supplier then sealed.

Circulation Pump

The SLS program Core Stage TVC system hydraulic circulation pumps are direct reuse hardware from the Space Shuttle Program. The circulation pumps provide the necessary means to circulate fluid through each TVC system, including the engine HAS and the TVC actuators. The circulation pump is a dual-element gear pump driven by an electric motor. The motor, inverter, and supporting electronic components are immersed in hydraulic fluid to simultaneously dissipate waste heat and warm the circulating hydraulic fluid. The circulation pump is operated during cryogenic propellant loading and is shut down prior to CAPU start. During propellant loading, the pump operates continuously to maintain hydraulic fluid temperatures within the acceptable limits prior to launch. The circulation pump is powered through the ground umbilical, so it has no way to inadvertently power on during flight.

TVC Exhaust Gas Heat Exchanger (EGHE)

The EGHE is new hardware for SLS. There is one EGHE per TVC system. The EGHE is designed to remove heat from the hydraulic system fluid. The CAPU exhaust gas is quite cold as it exits the turbine exhaust housing. The EGHE design utilizes this cold exhaust to cool the hydraulic fluid in each TVC system. The EGHE is designed to remove sufficient heat energy from the hydraulic fluid to maintain the bulk fluid temperature below 220°F to protect the MIL-PRF-83282 fluid from thermal breakdown and hydraulic seals from leaking. The heat exchanger is located on the return leg of the hydraulic system on the upstream side of the reservoir.

To avoid increasing back pressure at the CAPU turbine exhaust gas exit and introducing additional potential GH2 leak paths, the heat exchanger design does not penetrate the CAPU exhaust flow. The ID of the EGHE exhaust flow path is identical to the CAPU exhaust, and the fluid heat exchange is accomplished by flowing through a finned external jacket. An increase in back pressure at the CAPU exhaust could lead to reduced turbine performance or an inability to generate required horsepower to spin the main pump. No isolation capability is included (or necessary) to prevent flow (hydraulic fluid or CAPU exhaust) through the EGHE. As such, there is no active control mechanism for the EGHE. Since the EGHE is not an effective heat exchanger until the CAPU is running, the heat added to the system by the main pump exceeds the total heat removed by the EGHE. This design approach prevents the heat exchanger from over-cooling the hydraulic system fluid.

The CAPU cold gas exhaust flow, which serves as the coolant medium for the EGHE, consists of GHe and GH2, depending on mission phase. The flow is not steady; it is a pulsed flow due to SCV cycling in controlling the CAPU turbine speed. The frequency and pulse width depend on hydraulic load, source pressure, and exhaust exit conditions.

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