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Evolved SeaSparrow Missile Jet Vane Control System Prototype Hardware Development

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Rapid response to a high-speed, low-altitude, incoming missile imposes very stringent design requirements on an air-defense missile, the Evolved SeaSparrow Missile. A successful solution was devised using a jet vane control system for missile maneuvering during the boost phase of the shipboard vertical launch. By the location aft of the rocket motor nozzle, the vanes are inserted into the propellant stream for the purpose of generating maneuvering forces. After rocket motor burn out, the jet vane assembly detaches from the missile and falls away to not degrade the rocket motor specific impulse during flight to target. The four vanes are mounted at right angles to each other with each having its own mounting support and geartrain assembly. Each vane is connected through a detachable coupling to the steering control system of the missile, such that actuation of the steering control simultaneously actuates the jet vanes. The Evolved SeaSparrow Missile consortium successfully designed, analyzed, prototype developed, and flight tested a jet vane control prototype and has implemented the design into the program. Empirical test data were found to correlate well with the analytical techniques used to predict vane performance and resulted in a system capable of meeting the missile operational requirements.

Introduction

THE mission of missile defense requires that a defensive missile be launched in the direct line of attack after a very short warning time. The incoming missile may come from any direction and at any altitude, frequently at a very low altitude. A mechanical launcher that directs the defense missile in the correct direction is feasible in principle, but carries response time penalties. A more appropriate system is vertical launch and redirection of the in-flight defensive missile; however, this approach presents difficulties when the incoming missile is at very low altitude. Rapid transition from vertical to sea level flight is the enabling maneuver to achieve the in-flight redirection and is the impetus for the development of the jet vane control (JVC) system for the Evolved SeaSparrow Missile (ESSM).

ESSM is an international cooperative development of a sea-launched antimissile system that successfully addresses this difficult mission. ESSM is an upgrade of the highly successful, widely deployed NATO SeaSparrow Missile. Loaded in a quadpack canister for the Mark 41 vertical launch system (VLS), or in a trainable Mark 29 and vertical Mark 48 single-pack launcher, this tail-controlled missile with JVC and its quick start guidance section offers a significant increase in load out, response time, and fire power for NATO SeaSparrow consortium navies. Compatible with the NATO Mark 91, the Dutch Cluster IV configuration, the Anzac, and the Aegis weapon systems, the versatile ESSM will readily integrate with a broad range of ship platforms and fire control systems. Figure 1 shows an ESSM with a tail-mounted JVC aft of the steering control section (SCS) in a Mark 25 quadpack canister, and top-level technical specifications are listed.

ESSM is primarily designed to protect allied fleets and commerce shipping from airbreathing missile threats. Offensive missiles such as cruise missiles are constructed to fly at low altitudes, just above treetops or water surfaces, to avoid detection by enemy radar. In such situations, a targeted ship may have just a few seconds first to identify the threat and then to take countermeasures, such as firing one of its defensive missiles. In conventional designs, a shipborne defensive missile is launched from a canister or missile launcher in a vertical direction, where it must achieve sufficient velocity before its airfoil surfaces are able to effect any substantial maneuvers. However, this means that the missile has to reach an altitude of thousands of feet before it is able to pitch over and begin seeking the incoming missile threat. The time needed for these maneuvers is now considered to be too long for effective defense against modern cruise missiles.

The major design rationale for incorporating a thrust vector control (TVC) system (of which a JVC is just one concept) onto an ESSM airframe is to allow the missile to maneuver itself immediately after launch to intercept low-flying, enemy cruise missiles. A hard pitchover maneuver (POM) after missile egress is necessary to align properly the flight vehicle for the most direct propelled flight route to the target. Aerodynamic control at launch by fin stabilizers is inadequate due to low vehicle velocities such that rocket plume deflection by the TVC is required. Figure 2 shows a comparison of flight trajectories necessary to intercept low-altitude or ground targets resulting from a standard ballistic launch vs one incorporating a launch POM, as assumed for a TVC-equipped missile. The ballistic launch trajectory is obviously inefficient, time consuming, and limits the missile sensor line-of-sight capabilities for optimum target detection and tracking. Range and time to target will be greatly enhanced with a TVC equipped interceptor missile.

Previous Studies

A number of TVC systems have previously been developed in an attempt to address this problem.[1–6] Some of these concepts may be categorized as jet tabs, jet deflector blade, domed deflector, hot-gas injection, jetavator, gimbal nozzles, liquid injections, and JVC systems. However, devices using these systems are generally inadequate for many current applications. Retractable jet vanes[7] are incompatible with the requirement for any launch-canister-loaded missile with stringent volume constraints as exhibited in Fig. 3. Detachable jet tabs systems, comprising auxiliary propulsion units pivotally attached to the missile fins for coupled bidirectional motion, similarly conflict with folding control surfaces and require increases in launch canister cross section for additional volume external to the missile fuselage structure.[8]

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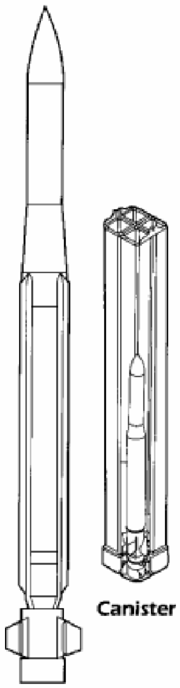

Fig. 1 ESSM Mark 41 VLS configuration and technical data: 145.5 in. long, 8 and 10 in. in diameter, 615-lb weight, supersonic speed, blast fragment warhead, dual propellant motor, proportional navigation, inertial/command midcourse guidance, and home-all-the-way, sample data homing terminal.

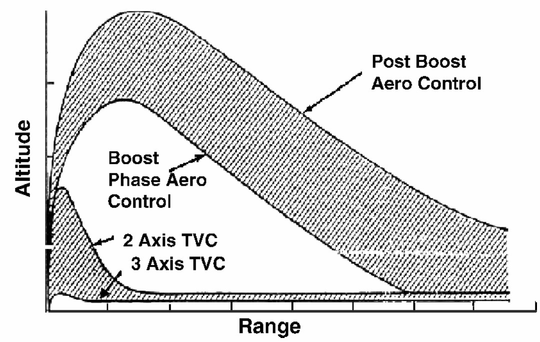

Fig. 2 Vertical launch trajectories against low-altitude targets.

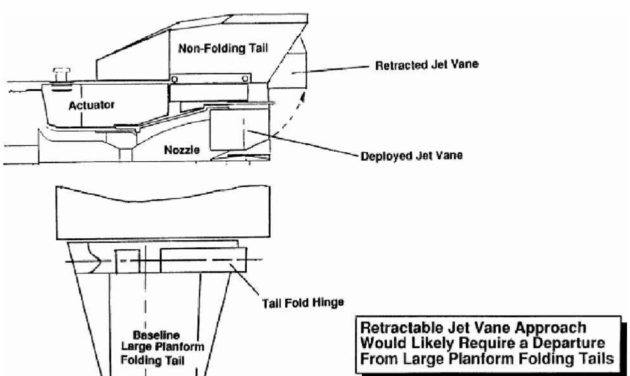

Fig. 3 Retractable jet vane incompatibility to ESSM.

The other alternative designs also have significant drawbacks. Gimbal nozzle systems are heavy, mechanically complicated, and not detachable. Liquid injection systems do not provide sufficient thrust vector angles. Existing jet vane mechanisms are either nondetachable or incorporate actuation systems with feedback control electronics redundant to the missile SCS unit. Nondetachable jet vane mechanisms limit range and performance with rocket thrust degradation throughout the missile's trajectory. Self-actuation jet vane mechanisms are heavy and inherently complicated and, hence, require more rocket propellant for missile launch and lack sufficient reliability. Some designs have attempted to correct some of these problems. For example, a shipboard defense system made by Raytheon and used on the Canadian SeaSparrow System has vanes in the missile plume. However, this system includes actuation elements that are redundant to those found in the missile midbody SCS and adds unnecessary weight, complexity, and cost.

Trade Studies

TVC System Downselection

Conceptual trade studies were performed by Raytheon to derive the most cost effective TVC system for ESSM. Eight TVC candidates, as shown in Figs. 4 and 5, were conceptualized and qualitatively evaluated: 1) moveable nozzle, 2) liquid injection, 3) jetavator, 4) hot-gas injection, 5) jet tab, 6) jet vane, 7) axial jet deflector, and 8) domed deflector. The liquid injection and axial jet deflector were dropped due to insufficient thrust vector angle capability. The jetavator and domed deflector had packaging difficulties, and the hot-gas injection candidate had valve development risks. From the original list of candidates, the moveable nozzle, jet tab and jet vane candidates were selected for a quantitative trade study. Table 1 is a summary of the downselection trade matrix that quantifies characteristics of each candidate. Based on inputs from propulsion, flight dynamics, design, thermodynamics, and program management disciples, the detachable JVC concept scored best on both technical and cost basis and was considered less complex to develop and integrate than the other two candidates. The jettisonable JVC optimizes the original structural and aerodynamic design characteristics of the missile. Actuator power application from the missile SCS to the detachable power takeoff (PTO) coupling mechanism is simple and very reliable. Figure 6 shows the conceptual SCS and JVC coupling scheme, and Table 2 lists the ESSM vehicle benefits resulting from the JVC incorporating a modular design, PTO engagement mechanism, jettisonable feature, and roll control.

PTO Coupling Mechanism Downselection

After this evaluation, the JVC/SCS separation requirements were defined and 16 candidate PTO coupling mechanisms were conceptualized. PTO coupling mechanism requirements at the SCS/JVC interface were defined as follows: 1) maximum torque transmission capacity in clockwise and counterclockwise directions, 2) accommodation of offset between SCS and JVC PTO shafts, 3) decoupling with vehicle bending loads applied across JVC/SCS interface, 4) coupling mechanism outside diameter no greater than 1 in., 5) phasing capability between SCS and JVC PTO shafts for control surface and jet vane alignment, 6) geartrain backlash resulting from the PTO coupling mechanism minimized, 7) mechanism compliance minimized to mitigate geartrain resonance, 8) ease of part fabrication and minimization of manufacturing costs, 9) limitation of manual manipulation of coupling mechanism during JVC/SCS mating, and 10) accommodation of axial assembly tolerance stackup between SCS and JVC at PTO shaft.

The candidate concepts were evaluated and scored as to how well they met the requirements. The Cardan coupling concept, easily integrated into the SCS/JVC geartrain as shown in Fig. 7, proved the most desirable with the maximum total score during the evaluation. The detail design effort incorporated the PTO Cardan coupling mechanism inside the SCS/JVC Marman clamp interface, within the JVC length envelope specified.

Preliminary Design Description

A modular jettisonable JVC system was selected to provide roll control for vertical launch because it maximized missile performance and effectiveness yet allowed discarding the system after it had performed its function. Minimal complexity and low parts count result in low cost and a reliable means of accomplishing pitchover. The JVC is the only TVC candidate capable of providing the roll control necessary for missile orientation during pitchover. Roll control will stabilize missile roll expected at launch resulting from dorsal fin vortex shedding and high pitchover velocities coupling with the vehicle roll–pitch inertial product. Roll control minimizes the time to align the missile seeker antenna against close-in threats. Additional design optimization studies immediately focused on the large volume of existing data and technical literature available to initiate jet vane material evaluations, hardware design, and detailed analysis.[9–20]

Table 1 TVC concept downselection trade study matrix

TVC concept	Roll control	Additional servos required	Exhaust plume survivability risk?	Thrust degradation	Jettisonable	Modular at round level	Restrained fire debris risk	Launch weight, lb	Postpitchover weight, lb	Additional length required to implement TVC, in.	Ease of assembly	TVC blending with tails
Moveable nozzle	No	2	No	Cosine only	No	No	No	62	62	3.5 (electronics)	Poor	Good
Power takeoff jet vane	Yes	0	Yes	11%[a]	Yes	Yes	Yes	54	36	5.5 (vane mechanism)	Good	Good
Jet tab	No	4	Yes	1%/deg	No	No	Yes	72	72	2.2 (tabs) 2.9 (electronics)	Fair	Good
Power takeoff jet tab	No	0	Yes	1%/deg	Yes	Yes	Yes	66	36	2.2 (tabs) 2.5 (tab mechanisms)	Fair	Fair
ServoJet tab	No	4	Yes	1%/deg	Yes	Yes	Yes	72	36	2.2 (tabs) 4.0 (actuators)	Fair	Good

[a] Average during pitchover.

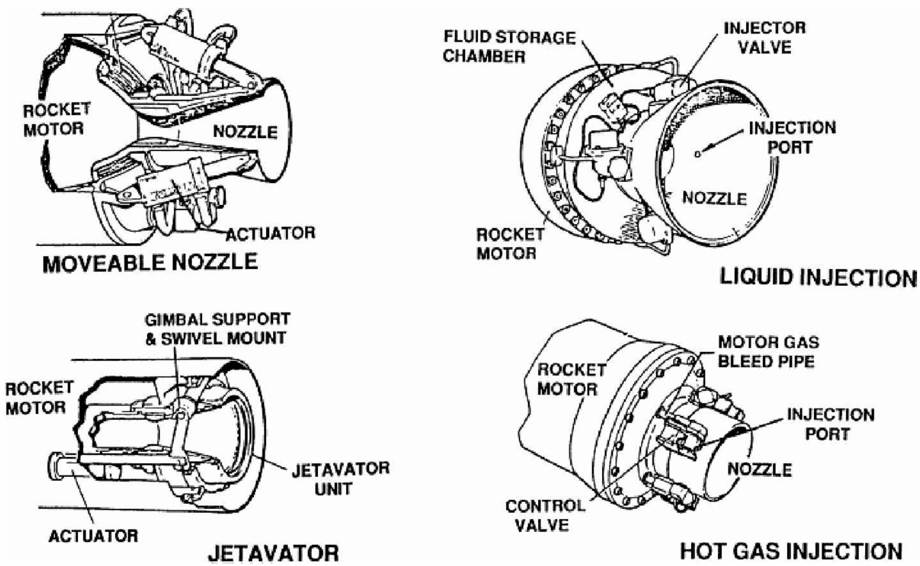

Fig. 4 TVC candidates incorporating direct plume diversion mechanisms.

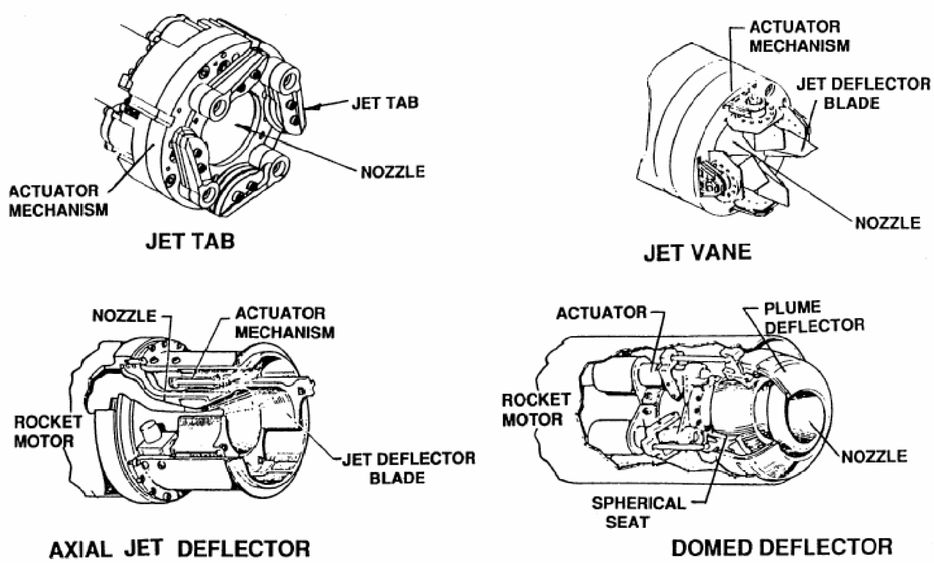

Fig. 5 TVC candidates incorporating mechanical flow interference mechanisms for plume diversion.

The JVC is 10.00 in. in diameter and 6.14 in. long. The JVC is divided into four independent quadrants. Each quadrant houses a jet vane mechanism and a geartrain assembly, which are assembled onto an annulus ring structure and covered by an external skin. The rocket plume exits though a nozzle extension cone created by the annulus ring structure and impinges on the jet vanes located in the propellant stream before exiting the JVC system. Each geartrain assembly receives power directly from the missile SCS by a PTO engagement mechanism. The PTO engagement mechanism couples one of the four SCS control surfaces to the JVC vane aligned within the same quadrant. The SCS power actuation system for each quadrant, therefore, drives the control surface and coupled jet vane simultaneously. A Marman clamp mechanically attaches the JVC to the aft missile structure. After the missile has achieved sufficient velocity, aerodynamic control is feasible, and the JVC is no longer required. The JVC is jettisoned by activating two pyrotechnic clamp bolt cutters, allowing the Marman clamp to expand radially and decouple the JVC from the SCS.

Figure 8 shows the external and internal side views of the JVC. The right-hand sectional view shows the geartrain assembly for a single quadrant and two views of the jet vane mechanism. The jet vanes rotate ±25 deg during deployment, yet are designed to rotate ±30 deg, and experience tip-to-tip interference with the adjacent vane when the two vanes simultaneously rotate ±33.5 deg. Marman clamp interfaces, which are required to mate structurally with the SCS and shipboard Mark 41 VLS, are incorporated with the front and aft flanges, respectively. Two pyrotechnic clamp bolt cutters (not shown) are at each interface. Each set of redundant bolt cutters is activated for the aft and forward Marman clamps to expand radially and to decouple the ESSM from the shipboard VLS before launch, as well as to accomplish JVC separation from the SCS for JVC jettison after missile pitchover.

The JVC skin, with an integrally machined front Marman flange, slides over the inner ring housing assembly and is fastened to the inner ring housing. Fastening the aft mounting ring to the JVC skin to form the aft Marman flange then completes the detachable JVC system assembly. The JVC skin and aft mounting ring are fabricated from 2014 aluminum alloy. The exposed inner surfaces are coated for thermal protection from the rocket plume with an ablative, epoxy filled resin. The JVC skin configuration allows the four vane shaft bolts to protrude beyond the 10 in. outside diameter, yet retain ease of assembly, and provide vehicle weight load transfer from the forward flange to the launcher without straining the geartrain assembly. The geartrain assembly may potentially bind and freeze the jet vane mechanism from properly moving during deployment, if the tightly toleranced geartrain bearing seats creep under the constant strain of carrying the vehicle weight as the ESSM rests in the launch canister. Material creep in the inner ring housing about the geartrain has been eliminated with the JVC skin configuration.

Figure 9 shows the inner ring housing assembly with views looking aft and forward. The left-hand section shows the four quadrants and the geartrains positioned with respect to each jet vane (dashed).

Table 2 TVC optimization characteristics

Design feature	Performance enhancement
Modular TVC	Need only install TVC on missiles flying from nontrainable launchers
	SCU common to boosted and unboosted missiles
Tail actuator PTO	No additional servos required for TVC
Jettisonable	Lowest flight weight
	Thrust losses eliminated after POM
Roll control	Optimum for pitchover flight control
ELX packageable within allocated volume	Maximizes propulsion

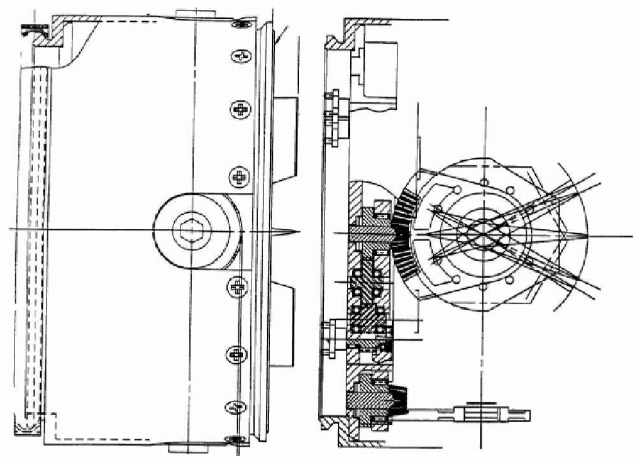

Fig. 8 Detachable JVC system, side views.

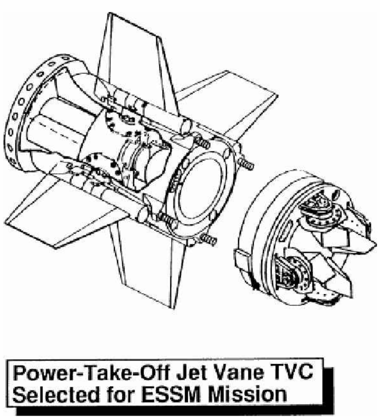

Fig. 6 ESSM jet vane TVC conceptualization.

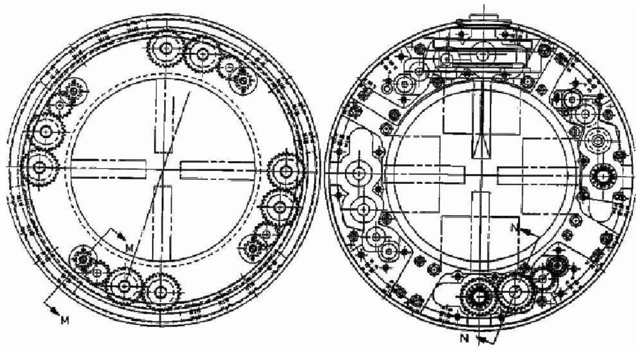

Fig. 9 Detachable JVC system, aft and forward looking views.

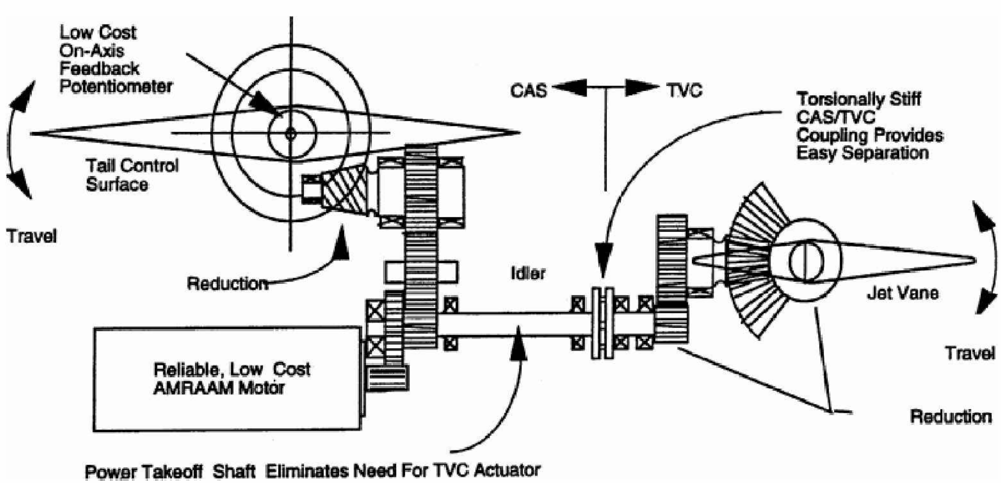

Fig. 7 Cardan PTO coupling mechanism and Control Activation System (CAS) to JVC geartrain.

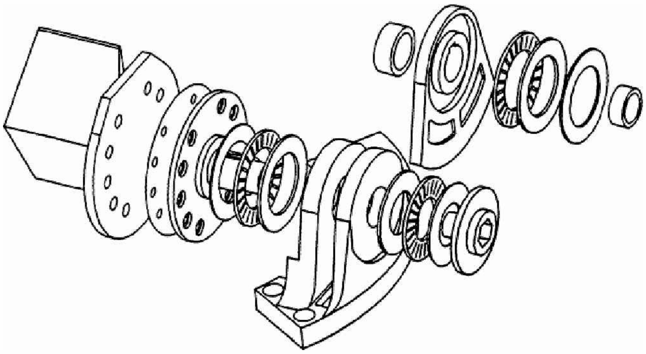

Fig. 10 JVC vane mechanism, exploded view.

A conical glass/phenolic nozzle insert is bonded inside the inner ring housing for thermal insulation from the rocket plume. The right-hand section provides four views, one at each quadrant, illustrating the inner ring housing assembly at different stages of construction. The port side view (9 o'clock) shows the machined inner ring housing and geartrain bearing seats. The bottom view has the four gears with the bottom bearings assembled into the housing. The starboard view (3 o'clock) shows the completed geartrain assembly with the gear mounting plate housing the top bearings, fastened to the inner ring housing, and covering the geartrain. All geartrain bearings are standard, off-the-shelf purchase items. The top view shows the jet vane mechanism fastened to the inner ring housing, completely encapsulating the geartrain assembly below, and the vane bevel gear meshing with the geartrain torque transfer gear. The Cardan PTO engagement mechanism contains two shafts that couple for torque transfer. A circular adapter plate with four elliptical slots allows for shaft offset on JVC vehicle integration, decoupling ease as the JVC is jettisoned, and minimum mechanism compliance under torsional load. The inner ring housing and gear mounting plates are machined from 6061 aluminum alloy. The geartrain PTO pinion, two idler, and torque transfer gears are fabricated from case-hardened, high strength American Iron and Steel Institute (AISI) 9310 steel.

Figure 10 show an exploded view of the jet vane mechanism assembly. Four jet vane mechanisms are mounted to an inner ring housing located behind the ESSM rocket nozzle. The jet vanes are externally bolted to the vane shaft with 10, A286 corrosion resistant steel (CRES) inserts and screws. The vane and shaft are then assembled to the journal block housing with a Belleville spring washer, bevel gear, and standard industry thrust and radial needle bearings. The vane shafts and bevel gears are fabricated from case-hardened, high-strength AISI 9310 steel. The journal housings are machined from 2219 aluminum alloy, and the external surfaces are coated with an ablative, epoxy filled resin for high-temperature applications.

The jet vanes were originally envisioned to be fabricated from three-dimensional carbon fiber-reinforced, carbon matrix composites (C/C) derived from chemical vapor infiltration/chemical vapor deposition (CVI/CVD) processes. CVI/CVD fabricated C/C brake pads are being produced for many airliner landing gears today, hence commercial synergy is possible to minimize cost. A rhenium metal surface was to be plated onto the C/C jet vanes for oxidation protection as is currently applied to C/C rocket motor throat inserts, but more work was required to develop this concept. Copper infiltrated tungsten (CIT) was later incorporated in a multipiece jet vane design to ease developmental risk, though much heavier and costly than the C/C variants, to assure program schedule compliance.

The off-the-shelf thrust and radial needle bearings are utilized to transmit large vane shear and bending loads to the journal block housing while simultaneously allowing the vane shaft to rotate freely, mitigating the possibility of jet vane sticking or binding. The journal block housing has inherent structural strength and rigidity with the dual pillow block configuration to distribute evenly vane loads for robust JVC operation. Placement of the bevel gear at the inertial neutral axis of the journal block housing limits radial and translational strain movement, enabling consistent jet vane torque transfer and bevel tooth engagement with the geartrain assembly.

Detailed Design Development

A formal design process was followed from requirement definition through detailed design presentation. On successful completion of this formal design and review process, the TVC entered into engineering and manufacturing production where 30 units were produced for various flight tests.

The requirements development and flowdown process included development of both the critical mechanical and electrical interfaces. The primary electrical interface to the TVC was the explosive bolt squib line and its return path. The majority of the interface development effort was mechanical in nature. Several mechanical interfaces required definition such as the TVC to SCS, TVC to rocket motor, TVC to Mark 41 launcher, and TVC to Mark 48 launcher. The interface details were controlled using interface control drawings that were continually updated and formally controlled throughout the design process. The critical TVC to SCS interface details included the Marman clamp groove, alignment key, explosive bolt electrical connector, PTO shafts, and rear reference antenna waveguide. The TVC to rocket motor critical interface included the extension of the rocket motor nozzle and hot-gas exhaust seal. The TVC to Mark 41 launcher critical interface included the holdback Marman clamp groove, sealing to the exhaust gas obturator, and antirotation features. The TVC to Mark 48 critical interface details primarily consisted of exhaust gas obturation and ensuring sufficient volume existed for the TVC system.

A six-degree-of-freedom (6DOF) TVC simulation was developed for further TVC performance requirements definition. The simulation could be implemented in three modes, TVC standalone, SCS and TVC, or fully integrated with the ESSM vehicle 6DOF. The model was also used for design and development of the POM control algorithms and included equations of motion, geartrain stiffness, backlash, damping, stiction, coulomb friction, viscous friction, and jet vane forces and moments. The initial analysis included data from previous documented studies and used theoretical methods for estimating jet vane loads. The data were empirically adjusted based on ESSM exhaust flow characteristics. Isentropic supersonic flow theory (linear mach theory) was used to compute the two-dimensional pressure distribution and integrated to obtain the vane forces and moments. The simulation was later verified and validated against test data gathered during TVC development tests such as cold flow, ballistic evaluation motor (BEM) firings, propulsion section development (PSDEV) firings, and control test vehicle (CTV) test firings.

Cold-flow testing was conducted at the U.S. Naval Weapons Center, China Lake, California, where supersonic airflow was used in lieu of actual rocket motor exhaust to obtain preliminary TVC performance characteristics. Supersonic airflow testing enabled data to be obtained from nearly an unlimited number of firings using the same hardware. The jet vane cold-flow testing eliminated the vane erosion, nozzle erosion, and detrimental effects of heat on the test hardware. A 75% scale TVC was used in the tests. The scale of the TVC was limited by the volumetric capability of the cold-flow apparatus. The cold-flow nozzle exit conditions, pressure, and Mach number were matched to the rocket motor nozzle to achieve dynamic similarity. In this case, the exit conditions were Mach 3.8 and fully expanded flow at 1.0 atm. The vanes could be positioned at 0, ±12.5, and ±25 deg. A five-component strain gauge balance was used to measure the vane lift and drag forces as well as the vane hinge moments. The results indicated that the lift was highly linear with vane deflection; however, lift was increased when an adjacent vane's trailing edge is deflected toward the vane of interest. The results of the cold-flow testing were analytically adjusted to predict loads during an actual rocket motor firing and used in the 6-DOF simulation to establish performance requirements early in the design phase.

As the TVC development continued toward the first rocket motor static firings, attention was focused on jet vane and vane shaft survivability. A lumped mass thermal model was used to predict the vane and shaft temperatures. The thermal model indicated that the stagnation temperature of the vane leading edge would reach approximately 4000°F after 2 s and that the shaft temperature would reach approximately 1550°F. During BEM firings, shaft temperatures were measured at 1200°F. After review of published TVC test data, CIT (90%W, 10%Cu) was selected as the jet vane material, and a titanium–zirconium–molybdenum alloy was chosen as the vane shaft material. The vane shaft design employed a large diameter flange to act as a hot-gas shield and labyrinth seal for the bearings and housing. The vane shaft protrudes well up into the jet vane to react against the vane loads. BEM testing proved that this combination would survive for the duration of the POM; however, survivability during a restrained firing (full duration motor burn) remained to be demonstrated.

TVC Hardware Development Tests

Two developmental live static rocket motor firings, with active TVC systems, were conducted early in the ESSM development phase to characterize TVC performance, validate the 6DOF simulations, determine jet vane and nozzle insert erosion, evaluate the vane shaft hot-gas dynamic seals, and evaluate the Marman clamp release mechanism (with explosive bolts). These development tests were complete end-to-end ground based tests conducted at Nammo Raufoss, Norway.

The rocket motors were flight-ready, dual solid propellant rocket motors. A fully operational, form factored SCS was provided and was driven by an external test bay to provide the jet vane position commands as well as the TVC jettison command. The external test bay also recorded telemetry such as jet vane position, SCS drive motor current, SCS battery voltage, and thermocouple data. The prototype TVC and live Marman clamp release mechanism were provided. Significant system integration and test activities were conducted including numerous dry runs and prelive runs to ensure proper system operation and to minimize risk during the actual firing.

First Static Firing

The first static firing was conducted at low temperature. The entire rocket motor, SCS, and TVC assembly or kinetic upgrade package was soaked at −25°C for 24 h. The kinetic upgrade package was then transferred into the rocket motor test bay and integrated onto the rocket motor test stand with multicomponent force measuring instruments. The loads from the test stand were resolved into thrust, side loads, and TVC turning moments or equivalent thrust vector angle. The side force data as a percentage of thrust are shown in Fig. 11. During the first static firing, the TVC was successfully jettisoned after 4.0 s. The TVC was recovered and fully analyzed against the test objectives. The jet vane side loads and drag were well within the expected values, as were the jet vane and nozzle insert erosion characteristics. The vane shaft hot-gas seals performed flawlessly by preventing the hot gas and exhaust particulates from contaminating the shaft bearings. The explosive bolt and Marman clamp release mechanism successfully jettisoned the TVC, and the Cardan PTO couplings disengaged properly without binding or causing TVC tipoff. The test was a complete success meeting all primary, secondary, and tertiary objectives.

Second Static Firing

A second developmental live static firing was conducted at high temperature. This time the entire kinetic upgrade package was soaked at +65°C. The TVC was successfully jettisoned after 7.0 s. Although holding onto the TVC for 7 s before jettisoning is twice as long as the maximum expected POM duration, valuable data were gained on jet vane and nozzle insert erosion for the upcoming full burn, restrained firing tests. Again, the TVC was recovered and analyzed against the test objectives. The test was considered a complete success.

Preliminary Flight Rating Test

Before conducting a developmental missile flight test on a missile test range, certain critical parameters must be demonstrated to minimize risk from a safety standpoint. Missile control during the initial stages of the flight is one such parameter. Therefore, a preliminary flight rating test (PFRT) was required of the ESSM TVC system before conducting the first vertically launched CTV flight, designated CTV-3. The PFRT test is a ground-based static test firing with active TVC similar to the two previous developmental static firings. The PFRT test was conducted at Nammo Raufoss. The PFRT test was conducted at high temperature (+65°C). The test was a complete success and allowed the ESSM program to embark on the missile flight-test program.

Qualification Test

Because the ESSM TVC was being developed under a development program and was destined for production, the TVC system required qualification. The qualification plan required subjecting the TVC to environments, including nonoperating environments, such as transportation vibration; handling shock; high-impact shipboard shock; shipboard vibration; high-temperature storage; low-temperature storage; temperature shock; altitude; rain, sand, and dust; washdown; fluid contamination; and humidity. The TVC was also subjected to operating environments such as low temperature, high temperature, free-flight vibration, and launch shock. Two rocket motor static test firings with active TVC systems were also conducted in a similar manner to the previous static firings. The first qualification test was conducted at low temperature (−25°C), whereas the second test was conducted at high temperature (+65°C).

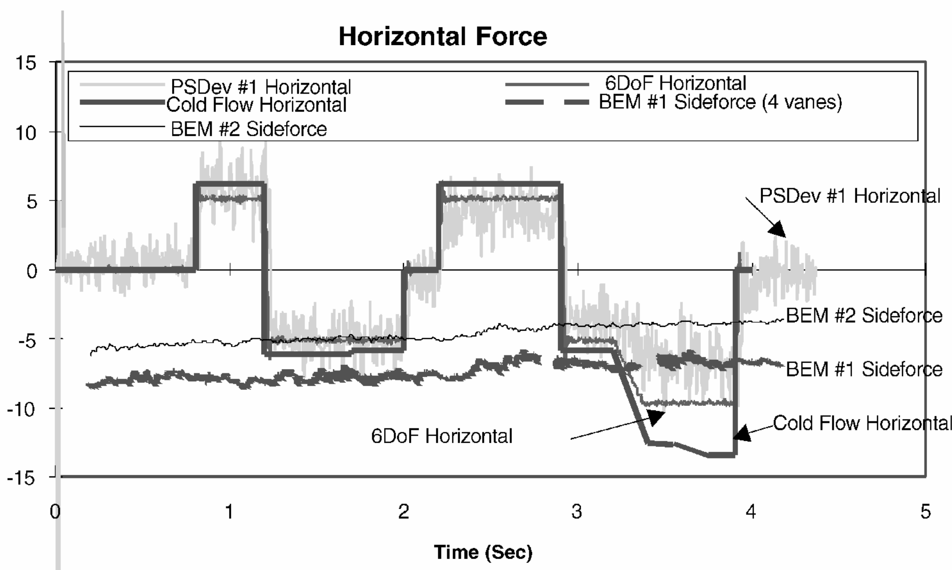

Fig. 11 TVC horizontal force as a percentage of thrust.

The TVC successfully passed all environmental tests as well as the two static firings.

TVC Hardware Flight Tests

Restrained Firing Vehicles

The ESSM Engineering Manufacturing Development (EMD) contract required testing restrained firing vehicles (RFVs) to verify the restrained firing capabilities of the Mark 29, Mark 41, and Mark 48 launchers. Three RFVs were required, one for each type of launcher. The TVC system is not used on a Mark 29 configured missile because the legacy launcher is trainable onto incoming targets. The objectives of the restrained firings were to 1) verify that an ESSM can safely survive a restrained firing, 2) verify the Mark 41 VLS and Mark 25 quadpack canister can safely restrain the vehicle, 3) verify the Mark 48 guided missile vertical launching system with the modified Mark 20 canister can safely restrain the missile, 4) verify safe venting of rocket motor exhaust gases, 5) verify that missile pyrotechnic explosives do not ignite, and 6) verify that the exhaust control system (ECS) can withstand the environment of a restrained firing.

The TVC requirements document stated that that the explosive bolts used on the TVC Marman clamp withstand a temperature of 205°C (400°F) without detonation. The Mark 41 launcher mechanical interface control document specified that the missile shall remain intact during and after a restrained firing condition. Although not a requirement, a goal of the TVC design was to ensure that the jet vanes degrade gracefully to not damage the launcher by allowing large pieces to be propelled down through the plenum. Also, in the case of a Mark 41 configured missile, the TVC airframe structure provides the direct load path for restraining the entire round. Failure of the TVC airframe structure during a restrained firing could allow the missile to egress the launcher and create a significant safety hazard. In the case of a Mark 48 restrained firing, it is considered acceptable for the TVC to separate from the missile after rocket motor burnout. The Mark 48 configured ESSM is a rail-launched missile restrained within the launcher with hooks and lugs fastened to the top of the rocket motor.

The ESSM round that was designated as RFV-2 was a Mark 48 configured missile complete with a flight-configured rocket motor and TVC system. The SCS was a nonfunctioning unit; therefore, the jet vanes remained fixed at 0 deg during the firing. The rocket motor was instrumented with a pressure transducer to verify a nominal rocket motor burn. The respective international team members provided the missile components. Raytheon conducted the missile final assembly and acceptance tests. The round was fired at the U.S. Naval Air Warfare Center, Weapons Division, White Sands Missile Range (WSMR) in New Mexico. On completion of the test, the missile was decanned from the launcher and fully analyzed against the test objectives. The test was considered a complete success. The jet vane mechanisms remained intact and secure in the TVC housing assembly. The glass/phenolic nozzle insert did not erode through and protected the TVC airframe structure. However, several seconds after the end of the rocket motor burn, an explosive bolt that secures the TVC to the SCS cooked off as a result of the extreme temperatures generated in the launcher exhaust gas management system. The deterioration of the explosive bolt allowed for the TVC to drop from the missile and down into the launcher exhaust plenum. This was considered to be acceptable because it did not occur during the motor burn and the launcher was not damaged.

The ESSM round designated as RFV-3 was a Mark 41 configured missile complete with a full burn, flight rocket motor, and TVC System similar to RFV-2. Again, the rocket motor was instrumented with a pressure transducer and was fired at WSMR. This test was crucial because the TVC airframe structure provided the load path for restraining the entire missile. On completion of the test, the missile was removed from the launcher and fully analyzed against the test objectives. One jet vane and partial vane shaft assembly eroded away and was propelled into the launcher exhaust gas plenum during the test. The launcher was not damaged, and the missile was successfully restrained. The jet vane mechanism erosion was attributed to the unique geometry of the Mark 25 quadpack canister and resultant exhaust gas flowfield. On review of the test hardware the test was considered a success.

Blast Test Vehicles

The ESSM EMD contract required the firing of blast test vehicles (BTVs) to verify launcher separation, canister mechanical performance, and gas management. The BTVs flew ballistic trajectories and did not have an active SCS, autopilot, or guidance section. Two BTVs were required, one for a Mark 48 launcher and one for a ship defense launching system (SDLS), which comprised a Mark 25 quadback canister and Mark 41 VLS. Because these were both vertical launchers, both missiles had TVC systems. The objectives of the BTV firings were to 1) demonstrate proper missile egress from the Mark 25 quadpack canister/SDLS; 2) evaluate SDLS-to-missile communications and launcher control system functions; 3) demonstrate proper Mark 25 quadpack canister explosive bolt, Marman clamp release mechanism, and launch rail and fly-through cover performance; 4) evaluate the Mark 25 quadpack canister and interface seals; 5) quantify ablative erosion and quadpack canister environmental effects; 6) verify the launcher cells can withstand the

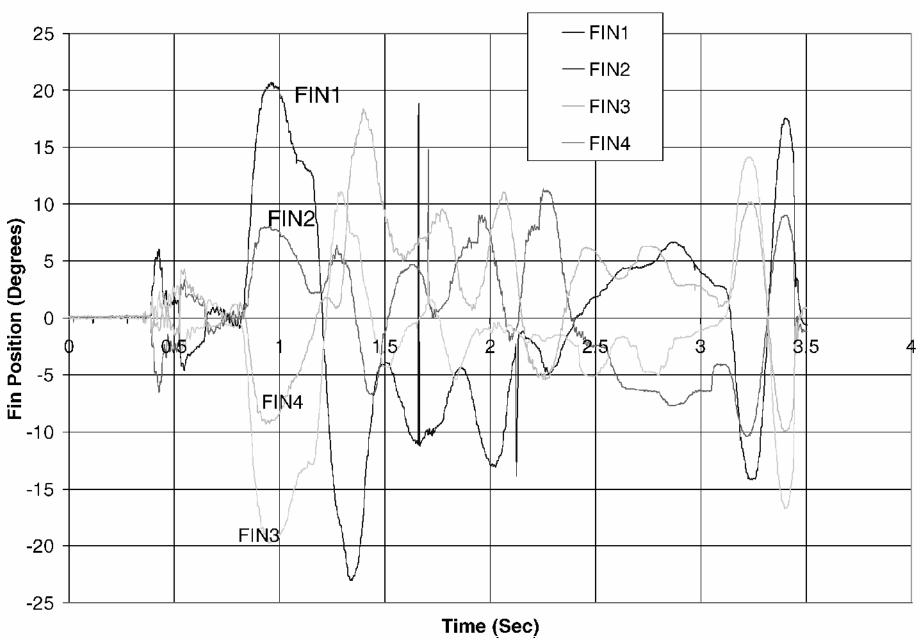

Fig. 12 CTV-3 jet vane duty cycle.

effects of an ESSM launch with only minor restoration required; and 7) verify the launch rail, holdback latch, and other launcher mechanical interfaces to the ESSM function as designed. The TVC requirements also stated that the TVC provide a missile antirotation feature for the Mark 41 configured round during launcher egress.

The ESSM rounds were designated as BTV-2 and BTV-3. The BTV-2 round was a Mark 48 configured missile, and the BTV-3 round was configured as a Mark 41. Each was complete with a flight-configured short burn rocket motor and TVC system. The short burn rocket motor had the exact thrust and thermal characteristics as the flight motor, but with a reduced burn time. The SCS was a nonfunctioning unit; therefore, the jet vanes remained fixed at 0 deg during the flight. Again, the rocket motor was instrumented with a pressure transducer. The missile final assembly and acceptance tests were performed. The Mark 48 configured round was fired at WSMR and the Mark 41 configured round was fired at the U.S. Naval Sea Warfare Center, Dahlgren, Virginia. The TVC systems performed perfectly throughout the tests, achieving all objectives, and the testing was considered a complete success.

CTV Flight Tests

The ESSM EMD contract required CTV flight tests to verify the kinematic capability and aerodynamic control of the ESSM missile with preprogrammed control maneuvers. The objectives of the CTV firings were to 1) collect structural and thermodynamic environmental data of flight vibration, flight stress loads, body modes, and aerodynamic heating; 2) characterize airframe and autopilot performance by validating digital autopilot time constant and stability, determining induced roll–yaw moments, determining aerodynamic drag affect, and validating roll control; 3) verify missile software by validating inertial reference unit (IRU) software and digital autopilot software, launch modes, and aerodynamic control; 4) characterize propulsion performance and velocity time history; and 5) verify POM algorithm and software.

Two vertically launched CTV missiles were flown from the Mark 41 VLS at WSMR and were designated as CTV-3 and CTV-4. Both the CTV-3 and CTV-4 vehicles were required to perform a POM using the TVC, then jettison the TVC on completion of the POM.

Because CTV-3 was the first missile to perform a POM using the TVC, a relatively mild POM was executed. The vehicle was required to fly vertically for 25 yd to clear the ship, then pitched over from vertical to a 40-deg flight-path angle (40 deg above the horizon). During the POM, the vehicle remained roll stabilized and achieved a maximum angle of attack. The actual jet vane deflection as a function of time is shown in Fig. 12. At 2.9 s the POM was complete, that is, the missile body rates were stabilized within the predetermined values, the TVC was successfully jettisoned, and control was transferred from the transition autopilot to the midcourse/terminal autopilot. Postflight analysis of telemetry and radar data as well as high-speed film indicated that the TVC performed perfectly.

CTV-4 executed a near maximum POM achieving a 0-deg (horizontal) flight-path angle. The launcher, instead of being vertically oriented, was angled 20 deg up range, that is, away from the direction of flight, and simultaneously angled cross range. This represented a launch scenario where the ship has rolled 20 deg away from the target and is pitching. Once again the missile flew straight out of the launcher for 25 yd to clear the ship, then executed a roll

Fig. 14 CTV-4 flight, canister egress.

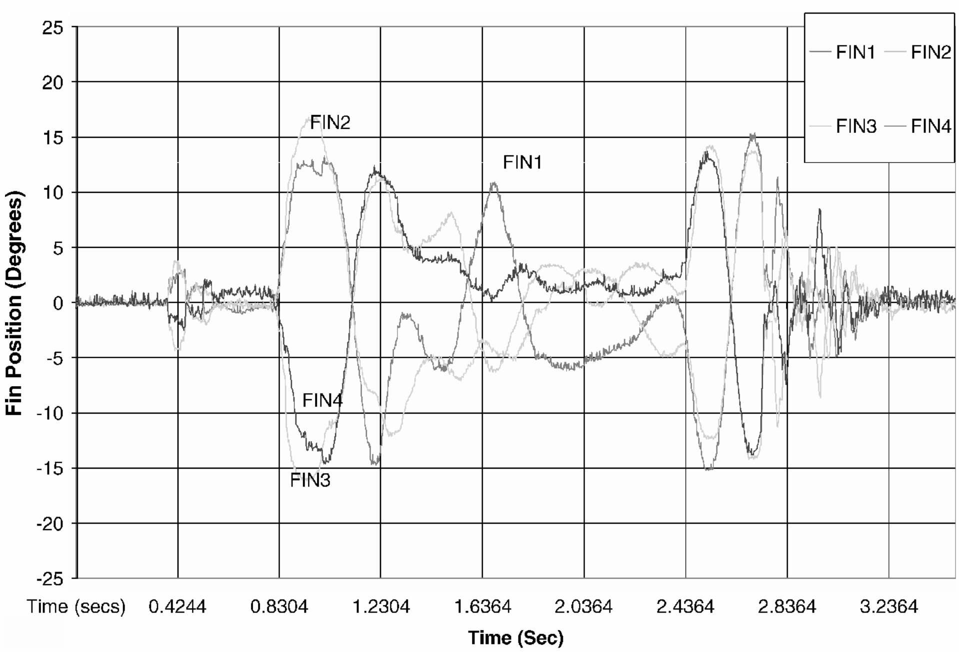

Fig. 13 CTV-4 jet vane duty cycle.

Fig. 15 CTV-4 flight, initial POM.

Fig. 16 CTV-4 flight, POM completion, and horizontal missile fly out.

maneuver to orient itself with the flight path, and then pitched over to the zero flight-path angle. During the POM, the vehicle remained roll stabilized and achieved a maximum angle of attack of 90 deg. The actual jet vane deflection as a function of time is shown in Fig. 13. At 2.9 s, the POM was complete; however, the TVC was not jettisoned due to a failure in the SCS explosive bolt firing circuitry. Figures 14–16 show the CTV-4 flight from canister egress, through pitchover, to horizontal missile fly out, respectively.

Summary

The detachable JVC system has been successfully developed to satisfy the very stringent ESSM TVC requirements. The primary value of the TVC to ESSM is to enable an effective POM immediately after vertical shipboard launch by generating steering forces normal to vehicle flight and eliminating roll instability. The minimization of parasitic weight, limited thrust degradation, and aerodynamic optimization of the missile design, furthermore, enhance the interception of fast, low-flying targets at extended ranges by jettisoning the TVC after pitchover.

The novelty of the JVC concept is in developing a TVC system by coupling the jet vanes to the SCS power actuation system and only jettisoning the passive, mechanical components. The principal advantages of the JVC concept are optimum weight and design simplicity producing a relatively inexpensive and robust TVC system. Significant parasitic weight and TVC cost to the missile system are minimized by coupling the vane mechanism to the SCS power actuation system via the geartrain assembly and PTO engagement mechanism and deleting the requirement for active TVC power actuator and control electronic systems. The remaining passive, mechanical TVC components can then be decoupled from the SCS and jettisoned after significant vehicle velocity is achieved for aerodynamic control to reduce missile weight, eliminate vane plume drag, and enable greater mission range and terminal velocities. Design simplicity gained by eliminating redundant TVC power actuation systems and relying on direct drive mechanical linkages offers greater reliability and ease of vehicle system operation over previously designed pneumatic or autonomously powered JVC systems.

Future Raytheon applications are expected in existing missile programs for product evolutions into areas such as multiple mission capabilities. The JVC concept provides an inexpensive, disposable mechanism for retrofitting high-speed, air-to-air missiles for low-speed surface launches with TVC. A U.S. Patent was published in 1998 for the ESSM JVC, and a number of foreign filings were issued in NATO and other allied countries worldwide.

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