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Vehicle Innovative Powertrain Experimental Research (VIPER) Equipment Capabilities

by Mark Riggs and Adrian Hood

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Weapons and Materials Research Directorate,
DEVCOM Army Research Laboratory

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14. ABSTRACT The US Army Combat Capabilities Development Command Army Research Laboratory recently acquired the Vehicle Innovative Powertrain Experimental Research (VIPER) testbed. VIPER enables Army, academic, and industry partners to engage and explore new technologies under replicated flight loads to increase power density, endurance to increase operational reach, and payload for future rotorcraft. The Army will use VIPER to readily accommodate rotorcraft driveline research priorities with highly controlled and repeatable experiments, a modular design for transmission platform reconfiguration, and engineered capability to operate through a variety of failure modes to push the limits of analysis and new technology. VIPER can transmit power through research transmissions with up to two 1,000 hp input motors, a 2,000 hp load absorption motor for the vertical mast, and a 250 hp load absorption motor for the tail rotor shaft. In addition to power transmission, flight maneuver loads can be applied to the transmission with a mast actuation system providing loads along the X-Y-Z coordinates and moments about the roll, pitch, and yaw axes. The purpose of this report is to record VIPER's equipment capabilities to facilitate discussions about reconfiguration for company-specific platforms to research technologies aligned with Army priorities.						
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1. Introduction

The Vehicle Innovative Powertrain Experimental Research (VIPER) testbed is a newly installed research asset that was designed to enable the innovation and characterization of next-generation power transmission systems and disruptive transmission concepts for vertical lift and mobility. The Army is interested in researching drivetrain dynamics analysis, hybrid gears, multiple speed transmissions, survivability studies, tribology, sensors, efficiency, drop-in-place component improvements, novel components, and other advances in technology. These research areas are often studied in company-specific transmission platforms.

VIPER was designed to be reconfigurable to enable collaboration with a wide range of partners using company-specific transmissions. The reconfigurable pieces that enable experimentation with a wide range of transmission test articles include two 1,000 hp (746 kW) input drivelines and a 250 hp (186 kW) load absorption driveline. These drivelines are mounted on skids and may be placed around VIPER's 2,000 hp (1491 kW) mast driveline and load actuator system. The 2,000 hp driveline and load actuator system are fixed to the mainframe due to their size and required reaction loads.

VIPER incorporates data acquisition systems to monitor the facility's operation and health to record experimental sensor signals from instrumentation attached to the test articles. Data is stored for postprocessing, analysis, and documentation with the goal of transitioning technology to the Soldier through the collaborating company, advancing technology readiness levels, and the vertical flight research community through unclassified publications and presentations.

2. Technical Specifications

2.1 1,000 hp Input Drivelines

There are two 1,000 hp input drivelines available to power the transmission test article. Each driveline contains a dual-ended motor, speed-increasing gearbox, torque limiter, shaft support assembly, torque meter, and a driveline skid as shown in Fig. 1. The two 1,000 hp drivelines are mirror images of each other, as shown Fig. 2, to allow for tight side-by-side inputs. Appendix A provides manufacturer and product identification information for major components.

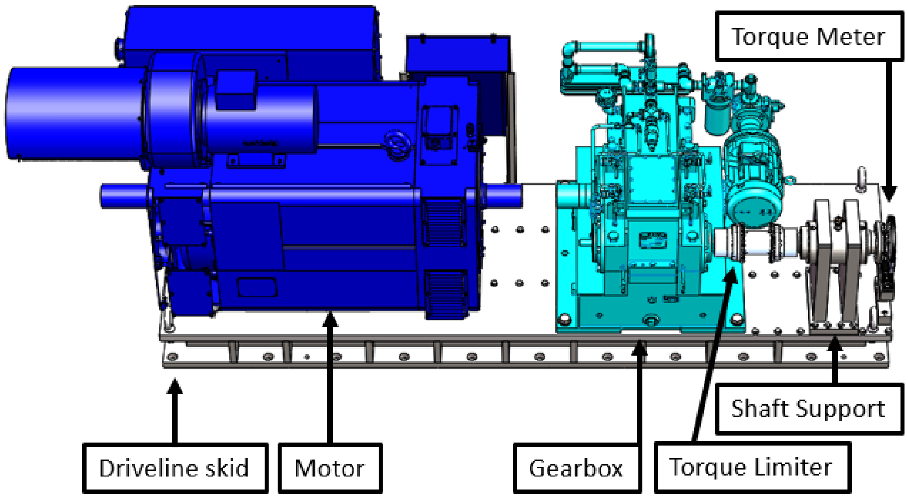


Fig. 1 1,000 hp driveline with annotated components

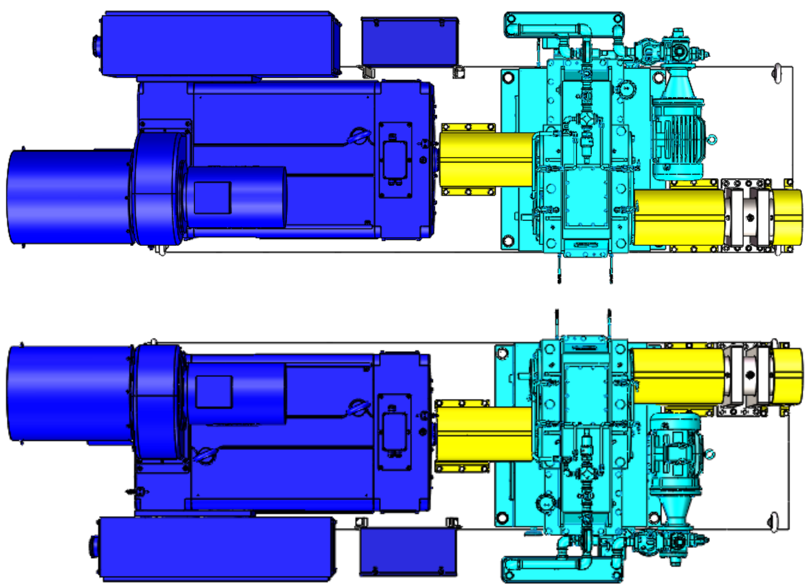


Fig. 2 Top view of both 1,000 hp drivelines, with yellow shaft guards, showing the mirror image configuration. Driveline 1 is in the top image and Driveline 2 is in the bottom image.

Motors 1 and 2 (MT 1 and MT 2) are the primary input motors for each input driveline with a rated power of 1,000 hp. The motor's constant torque region ranges from 0 to 3,000 RPM with a maximum torque of 1,752 ft-lb (2,375 Nm). The motor's constant power region ranges from 3,000 to 6,000 RPM with a maximum torque of 876 ft-lb (1,187 Nm) at top speed. While the motors are primarily used as input motors, they are also capable of absorbing power. The motors are dual ended, and the primary configuration uses an inline speed-increasing gearbox.

Gearboxes 1 and 2 (GB 1 and GB 2) are used in tandem with MT 1 and MT 2 to increase the input driveline maximum speed to 10,000 RPM. The gearboxes have a single reduction parallel shaft using double helical gears providing a 0.6:1 gear ratio. The gearboxes were designed to match MT 1 and MT 2 torque capabilities with a safety factor of 1.5. This allows the input driveline to perform at the maximum capability of the motors without limiting performance due to gearbox specifications. Application of the speed-increasing gearbox creates a driveline constant torque region from 0 to 5,000 RPM with a maximum torque of 1,051 ft-lb (1,425 Nm). The driveline constant power region is from 5,000 to 10,000 RPM with a maximum torque value of 526 ft-lb (712 Nm) at top speed. The input driveline torque and power are plotted against speed in Fig. 3 with and without the speed-increasing gearbox.

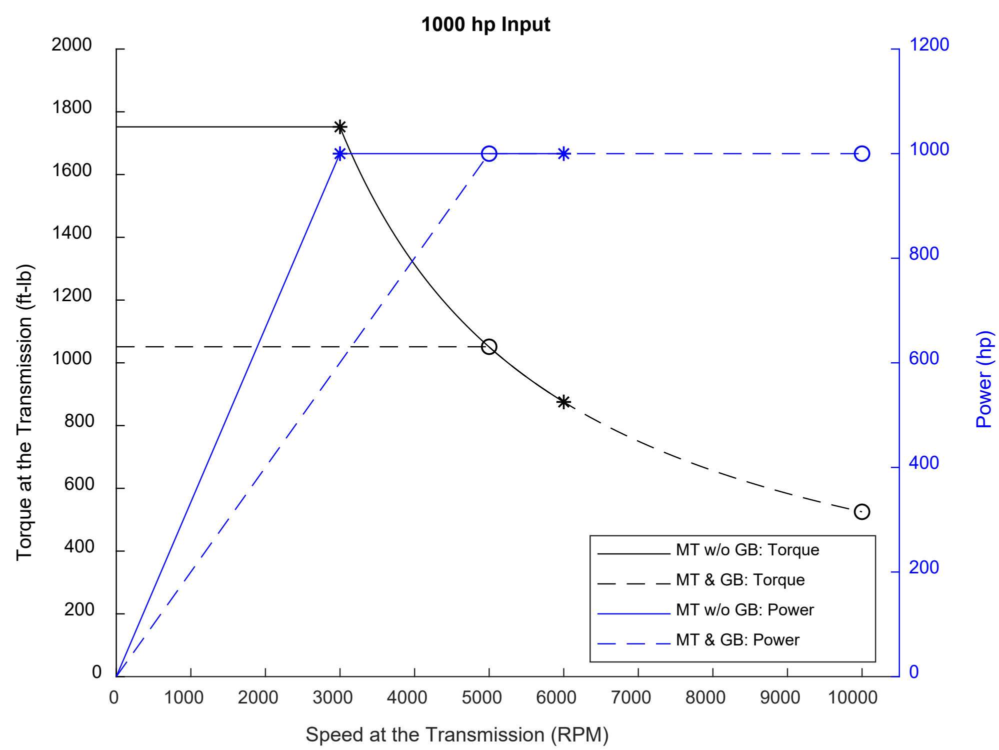


Fig. 3 Motor performance curves for torque and power against speed for MT 1 and MT 2 with and without a gearbox

Each input driveline contains a speed encoder, torque meter, temperature and vibration switches, and torque limiters to monitor operating conditions and protect equipment from damage. Torque limiters 1 and 2 (TL 1 and TL 2) limit the torque between the high speed end of the gearbox and the shaft support assembly. TL 1 and TL 2 are designed with sacrificial pins to act as a mechanical fuse at 1,575 ft-lb (2,136 Nm).

2.2 2,000 hp Output Driveline and Swashplate Actuation Assembly

The 2,000 hp output driveline includes a swashplate actuation assembly to apply maneuver loads to the mast as it is transmitting torque. The output driveline and actuator assembly are shown in Fig. 4 with the mainframe structure. This structure was built with a robust platform and load reaction cage to support the equipment weights and actuation forces. The support structure is hidden in Fig. 5 to provide an unobstructed view of the driveline and swashplate actuator assembly. The test article's mast attaches to a rotating shaft within the swashplate assembly. Five actuators apply loads to the mast shaft through the swashplate. The mast continues with a shaft containing constant velocity joints, a torque meter, and a two-stage right angle gearbox before the power is absorbed with a 2,000 hp motor.

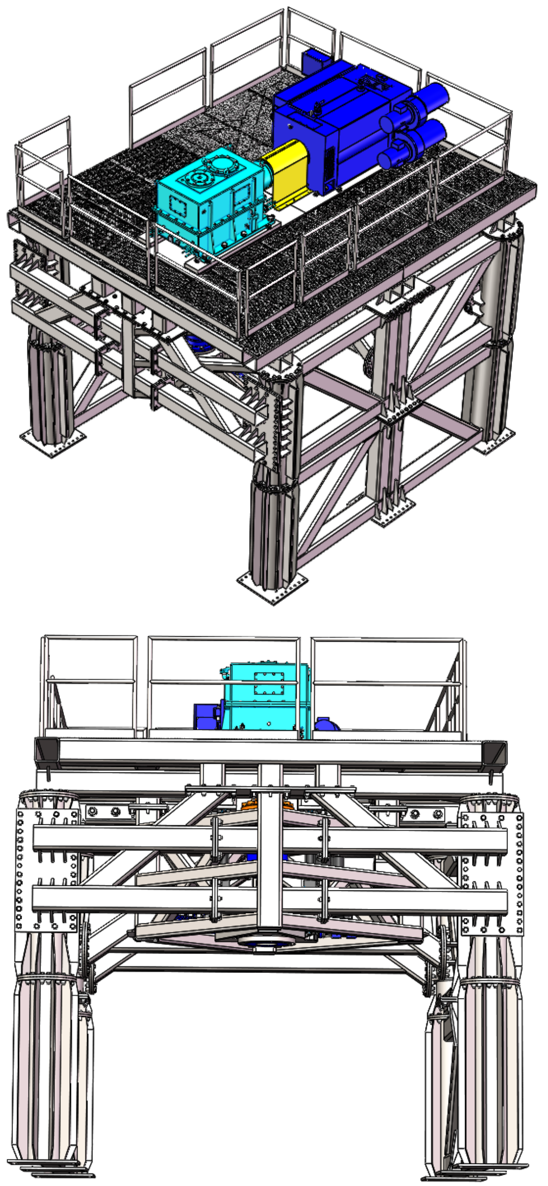


Fig. 4 The 2,000 hp driveline and swashplate assembly are supported by the mainframe with an integrated swashplate load reaction cage, as shown with an isometric view (top) and a front view (bottom)

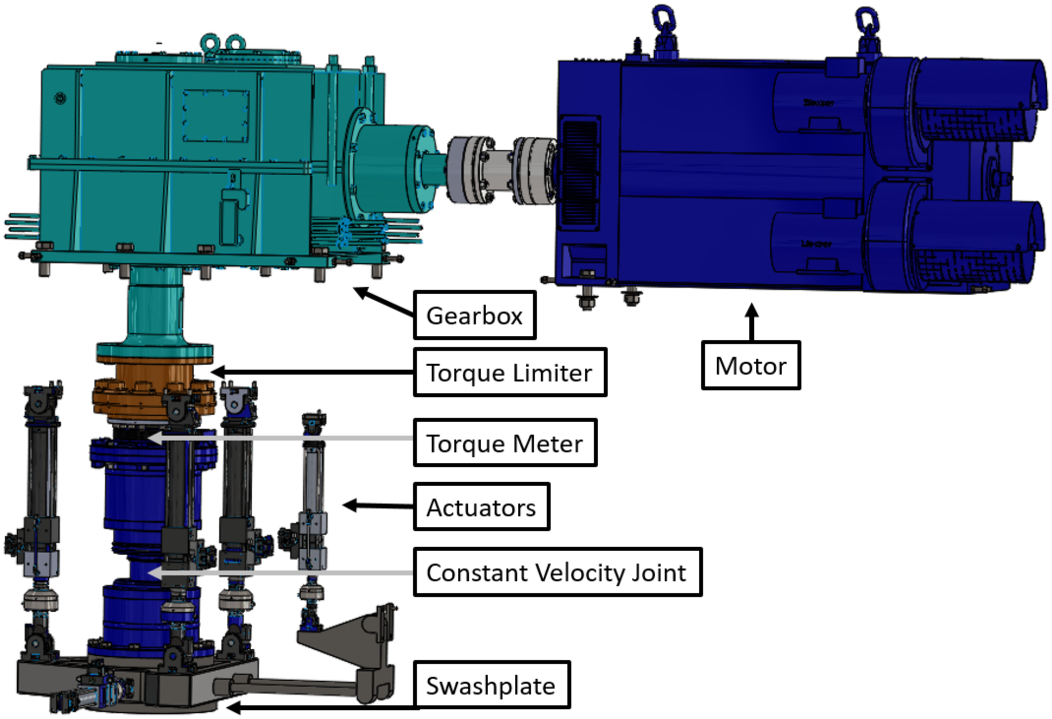


Fig. 5 2,000 hp output driveline and swashplate assembly with annotated major components

Motor 3 (MT 3) is the primary load-absorbing motor for the vertical mast with a rated power of 2,000 hp. The motor's constant torque region ranges from 0 to 940 RPM with a maximum torque of 11,175 ft-lb (15,151 Nm). The motor's constant power region ranges from 940 to 2,386 RPM with a maximum torque of 4,403 ft-lb at (5,969 Nm) at top speed. While the motor is a dual-ended dyno, it is fixed on the test stand and only intended to be used with its corresponding gearbox.

Gearbox 3 (GB 3) is used in tandem with MT 3 to increase the transmission's main mast speed and change its direction to be horizontal with a 4.717:1 gear ratio. The gearbox was designed to match MT 3 torque capabilities with a safety factor of 1.5. This allows the output driveline to perform at the maximum capability of the motors without limiting performance due to gearbox specifications. Application of the gearbox creates an output driveline constant torque region from 0 to 200 RPM with a maximum torque of 52,523 ft-lb (71,210 Nm) at the transmission's main mast. The driveline constant power region is from 200 to 508 RPM with a torque value of 20,694 (28,054 Nm) at top speed. The 2,000 hp output driveline torque and power are plotted against speed in Fig. 6 with and without the mast speed-increasing gearbox.

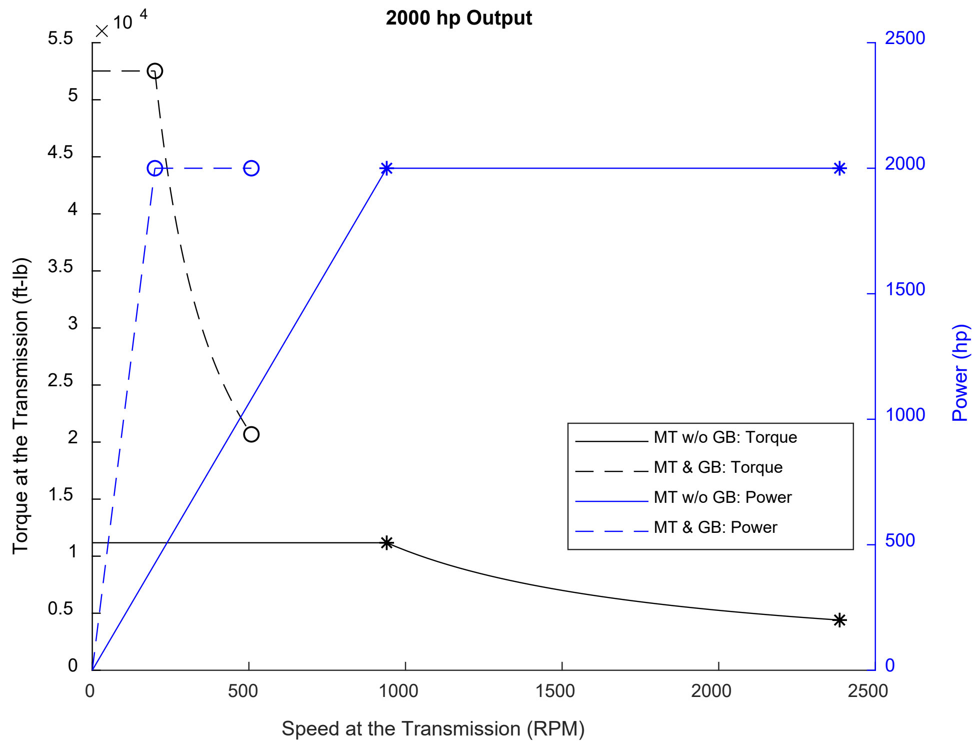


Fig. 6 Motor performance curves for torque and power against speed for MT 3 with and without a gearbox

The mast driveline contains two speed sensors, a torque meter, temperature and vibration switches, and a torque limiter to monitor operating conditions and protect equipment from damage. Torque limiter 3 (TL 3) is directly in line with the vertical output shaft before the right angle gearbox. TL 3 is a ball detent torque limiter with 10 ball elements designed to disengage at 65,650 ft-lb (89,009 Nm).

The swashplate has five total actuators exerting force in the three Cartesian coordinate directions as defined in Fig. 7. The longitude actuator is mounted vertically with a bell crank mechanical arrangement to transfer the force in the horizontal plane along the X-direction with a maximum force of 5,500 lb. The latitude actuator is mounted horizontally along the Y-direction with 5,500 lb of force. Three actuators are mounted vertically on the swashplate along the Z-direction to replicate lift and apply moment loads. A maximum Z-direction force of 40,500 lb can be exerted on the swashplate if the horizontal forces are not applied, and a 20,000 lb Z-direction force may be applied with all actuators acting simultaneously. A summary of the actuator forces are provided in Table 1. The simultaneous ratings are capable of being applied in combination with one another and the nonsimultaneous ratings are the maximum capability if all other loads or moments are zero. For example, if all other loads and moments are zero, a maximum lift force of 40,500 lb may be applied to the transmission. If maximum loading is desired in all axes and moments, the maximum lift force is 20,000 lb. If the platform-specific loading requirements request loading capability between the simultaneous and nonsimultaneous values, an analysis will need to be done to determine the feasibly of accomplishing the specified loading requirements. The constant velocity (CV) shaft prevents lateral and moment loads at the swashplate from being transmitted to the right angle gearbox.

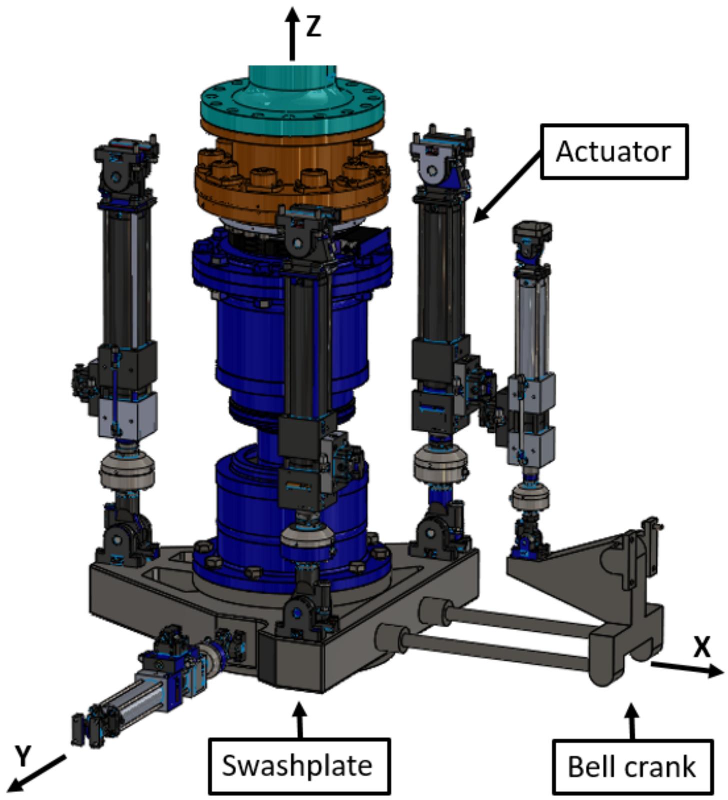


Fig. 7 Swashplate system

Table 1 Actuator forces and moments

System status	Fx (lb)	Fy (lb)	Fz (lb)	Mx (ft-lb)	My (ft-lb)
Simultaneous	5,500	5,500	20,000	3,333	12,500
Nonsimultaneous	5,500	5,500	40,500	40,900	47,250

2.3 250 hp Output Driveline

The 250 hp output driveline absorbs power through motor 4 (MT 4) to apply tail rotor loads on a transmission shown in Fig. 8. It has a constant torque region from 0 to 3,000 RPM with a maximum torque of 437 ft-lb (593 Nm). The motor's constant power region ranges from 3,000 to 6,000 RPM with a maximum torque of 219 ft-lb (297 Nm) at top speed. While the motor is primarily used as a load absorption motor, it is also capable of delivering power. The input driveline torque and power are plotted against speed in Fig. 9. Torque limiter 4 (TL 4) is between MT 4 and the corresponding torque meter. TL 4 is a ball detent torque limiter with four ball elements designed to disengage at a torque of 657 ft-lb (891 Nm). The 250 hp output driveline has a similar set of instrumentation compared to the 1,000 hp input drivelines with switches for temperature and vibration and analog output signals for torque and speed.

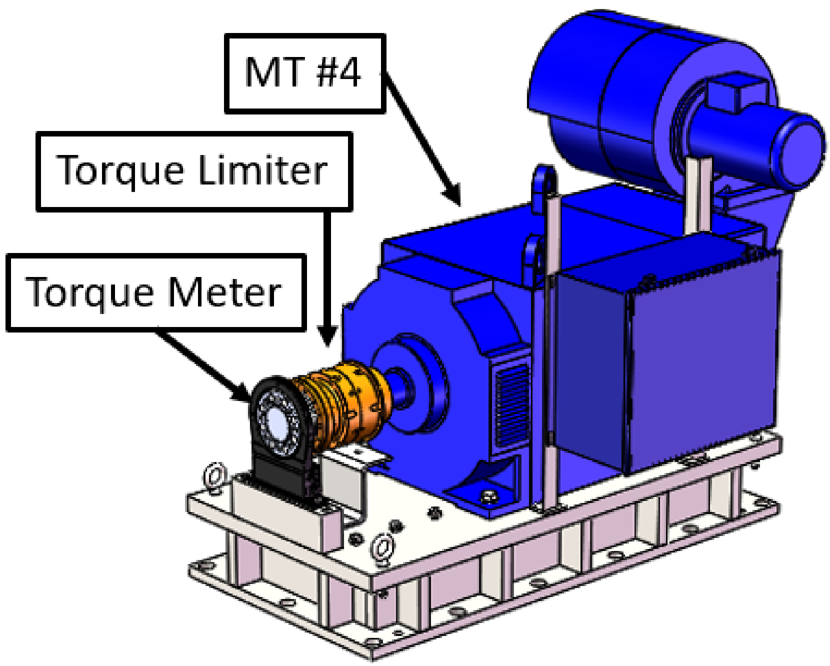


Fig. 8 250 hp driveline with annotations

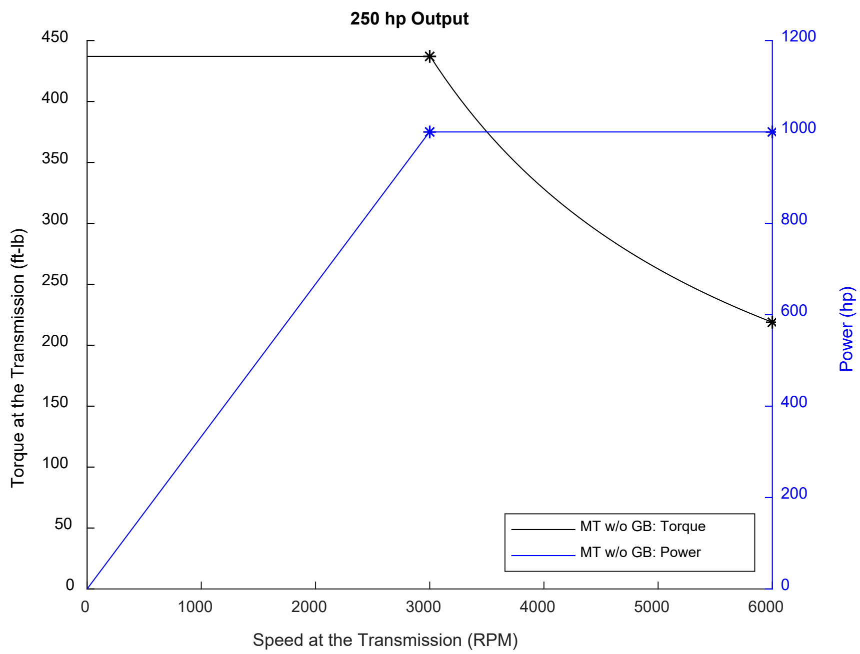


Fig. 9 Motor performance curves for torque and power against speed for MT 4

2.4 Driveline Summary

VIPER's key pieces of equipment center around the driveline skids and the main mast load absorption system. The two 1,000 hp input drivelines (1 and 2) provide power to the transmission. The 2,000 hp load absorption driveline (3) replicates flight loads on the main mast through a motor torque and actuation forces. The 250 hp load absorption driveline (4) replicates tail rotor loads through a motor torque. These primary pieces of equipment have been presented individually and their compiled ratings are listed in Tables 2 and 3. The motor and gearbox configuration is the nominal end use configuration with the exception of Driveline 4, which does not need a gearbox to reach the relevant speed and torque characteristics desired for the VIPER test stand.

Table 2 Motor ratings used for each driveline

Driveline	Primary purpose	Power (hp [kW])	Nominal speed (RPM)	Nominal torque (ft-lb [Nm])	Max speed (RPM)	Torque at max speed (ft-lb [Nm])
1 2	Input power to the transmission	1,000 [746]	3,000	1,752 [2,375]	6,000	876 [1,187]
3	Absorb main mast load	2,000 [1,491]	940	11,175 [15,151]	2,386	4,403 [5,969]
4	Absorb tail rotor load	250 [186]	3,000	437 [593]	6,000	219 [297]

Table 3 Driveline ratings including the motor and gearbox

Driveline	Gear ratio	Power (hp [kW])	Nominal speed (RPM)	Nominal torque (ft-lb [Nm])	Max speed (RPM)	Torque at max speed (ft-lb [Nm])
1 2	0.6:1	1,000 [746]	5,000	1,051 [1,425]	10,000	526 [712]
3	4.717:1	2,000 [1,491]	200	52,523 [71,210]	508	20,694 [28,054]

3. Modular Design

3.1 Configuration Parameters

The configuration envelope is flexible to accommodate many company-specific transmissions used for vertical flight through reconfigurable driveline skids and cable lengths allowing utilization of any location on the bedplate. Figure 10 shows the footprint of the bedplate, mainframe side walls, and height of the swashplate. These dimensions establish the available space for reconfigurable driveline skids. The approximate driveline skid dimensions are shown in Fig. 11. The skids may be placed anywhere on the bedplate, and the associated cabling is rerouted accordingly. The cable support system needs to be taken into account after the configuration is established. The primary driveline reconfiguration characteristics are summarized in Table 4.

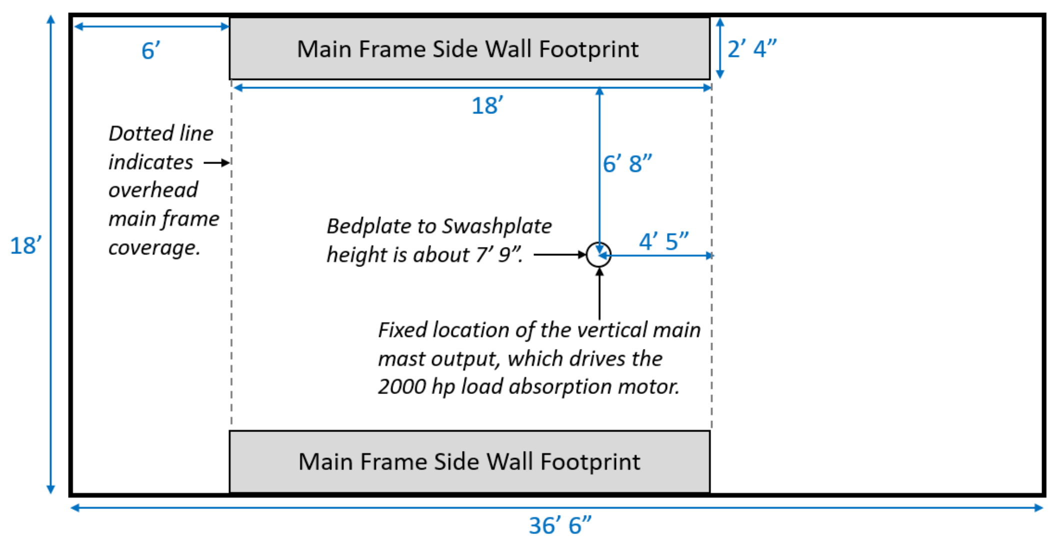
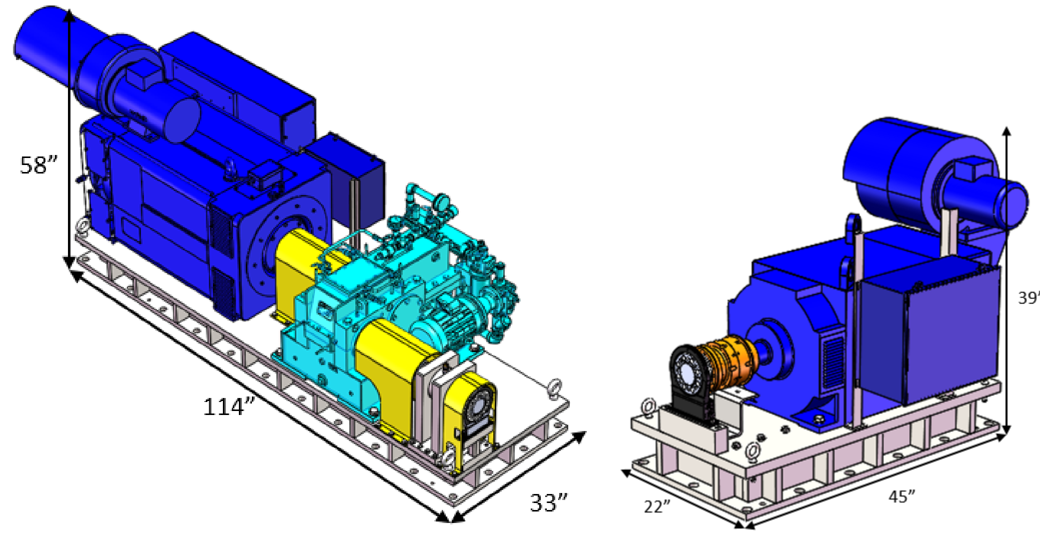


Fig. 10 Bedplate dimensions with the mainframe walls and the location of the main mast output



(a) (b)

Fig. 11 Skid dimensions for a) 1,000 hp and b) 250 hp drivelines

Table 4 Summary of reconfiguration parameters

Driveline	Overall dimensions L×W×H (inches [cm])	Shaft location		Cable specifications			Maximum skid angle above or below horizontal
		Height (inches [cm])	Along the width (inches [cm])	Qty	Weight (lb/ft [kg/m])	Bend radius (inches [cm])	
1 2	114 × 33 × 58 [290 × 84 × 147]	21 [53]	10 [25.4] Off-center	3	6.8 [10]	19 [48]	15°[a]
4	45 × 22 × 39 [114 × 56 × 99]	16 [41]	Centered	2	3.8 [5.7]	15 [38]	20°[b]

[a] Angle is gearbox limited.
[b] Angle is motor limited.

3.2 Envelope of Potential Configurations

The bounds of potential configurations are explored with first-order estimates using CAD to better understand the design envelope. The maximum and minimum spaces between 1,000 hp inputs were found to be 14 and 137 inches, respectively, as shown in Fig. 12. The largest angle between inputs to maintain a traditional helicopter configuration is 109° as shown in Fig. 13. Tilt-rotor applications may be evaluated in the vertical flight mode with Fig. 14 using two motor inputs to represent an engine input and a cross-shafting input for the tilt-rotor helicopter. The 1,000 hp motors also have enough space to be driven in a back-to-back configuration as shown in Fig. 15, although this would require a higher horsepower driveline gearbox for speeds above the motor's top speed of 6,000 RPM.

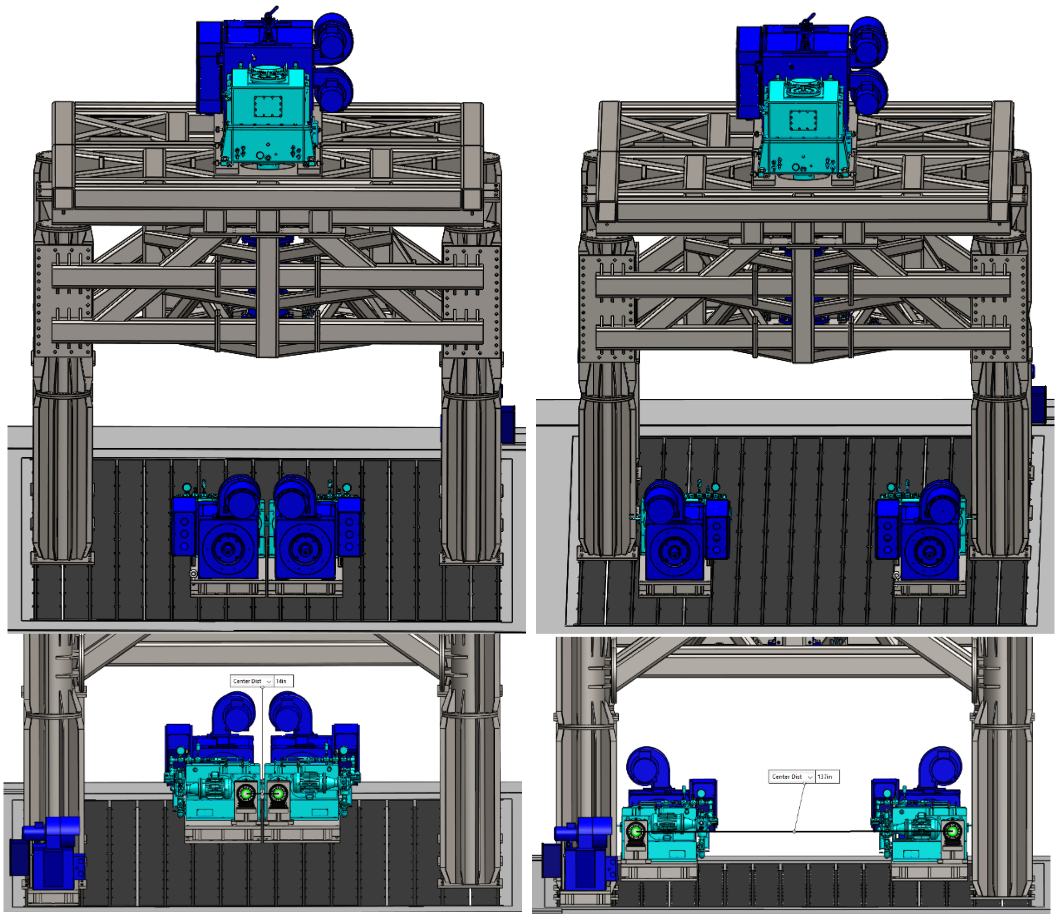


Fig. 12 Minimum (14 inches) and maximum (137 inches) spacing between 1,000 hp inputs

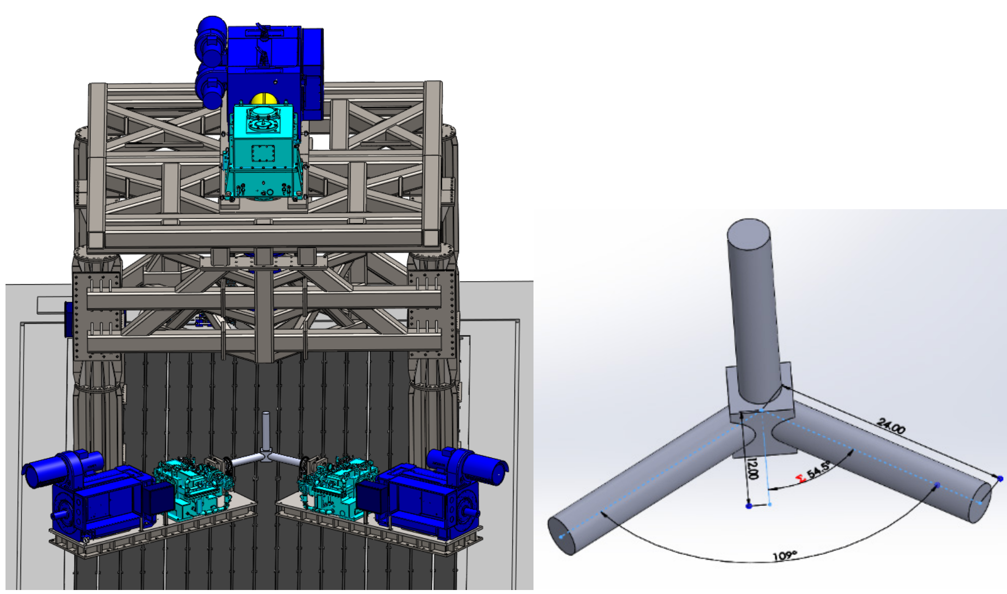


Fig. 13 The maximum angle between two 1,000 hp inputs for traditional helicopter configuration is 109°

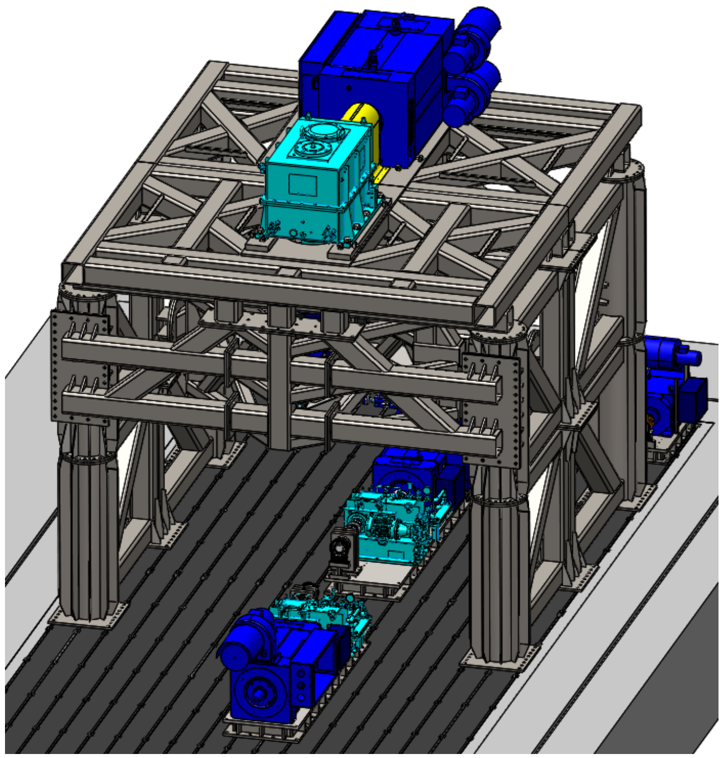


Fig. 14 1,000 hp inputs coming in from both sides representing an engine input and cross-shafting for a tilt-rotor gearbox

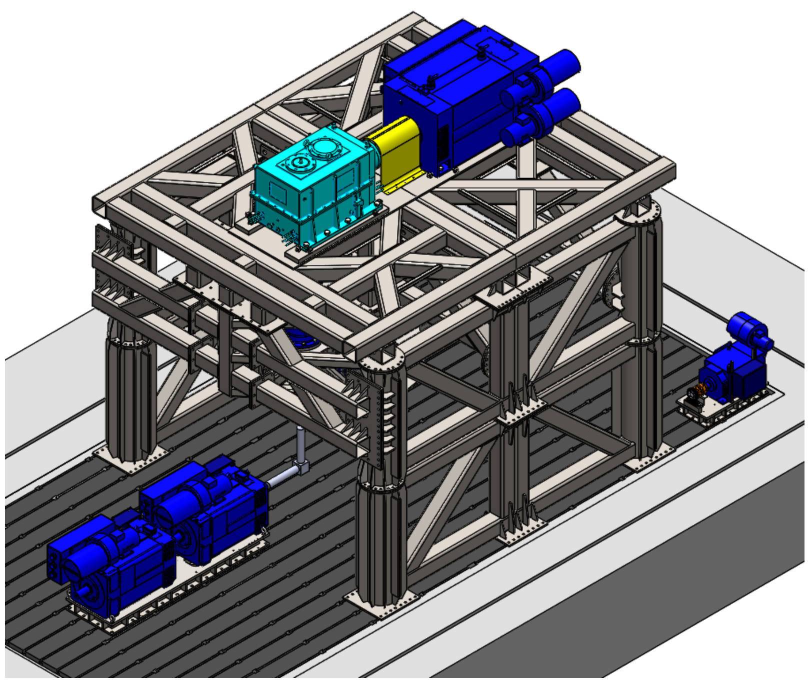
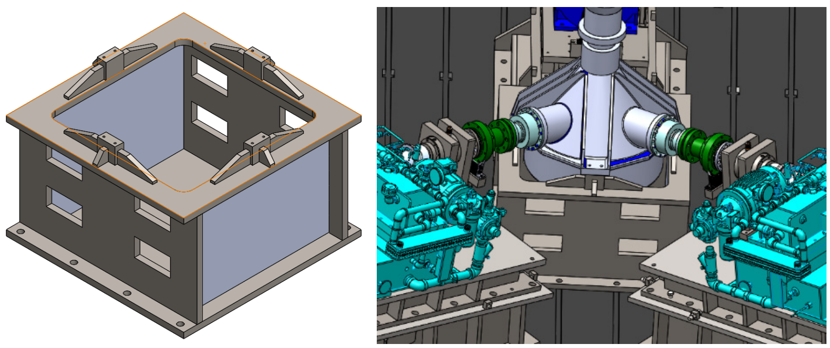


Fig. 15 Back-to-back motor inputs providing one 2,000 hp input to a transmission test article

3.3 Integration Components

The UH-60L main module was chosen to be the first commissioning test article for the VIPER facility and it is useful to show the types of components required for integration. The primary components are as follows:

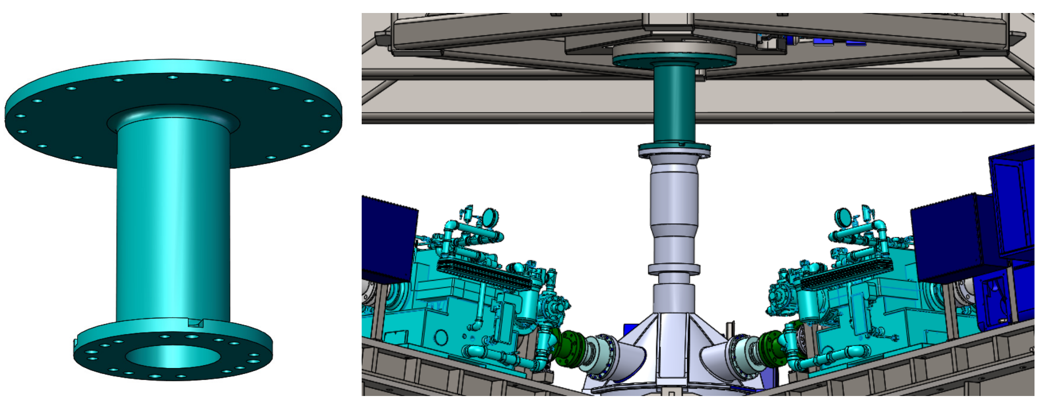
- Transmission Mount. A mount for the transmission, shown in Fig. 16, secures it to the bedplate and ensures the mast is vertical to align with VIPER's mast driveline. The UH-60L is tilted forward a few degrees and the transmission mount accounts for this transmission-specific characteristic.



(a) (b)

Fig. 16 UH-60L transmission mount: a) isolated and b) incorporated into VIPER

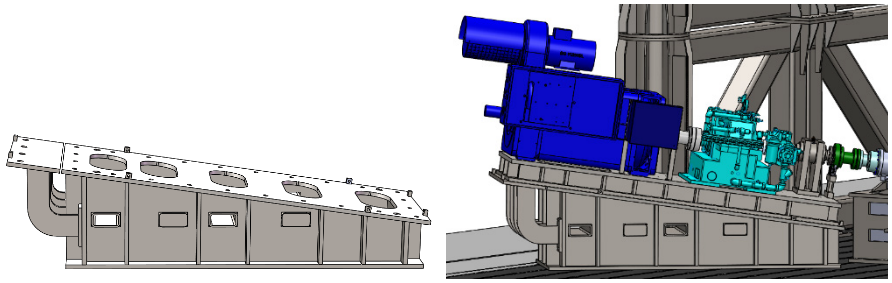
- Shaft Adapters. Shaft adapters, shown in Fig. 17, are required to interface with the test article and the driveline interfaces. The vertical shaft adapter covers the distance between the transmission's output shaft and the shaft interface at the VIPER swashplate. These adapters will interface with the torque meter's bolt pattern for Drivelines 1, 2, and 4 or the swashplate bolt pattern for Driveline 3.



(a) (b)

Fig. 17 Vertical shaft adapter: a) isolated and b) incorporated into VIPER

- Driveline Mounts. Driveline mounts, shown in Fig. 18, support the driveline skids. They account for the shaft heights and angles of the company-specific transmission to align the driveline input.



(a) (b)

Fig. 18 1,000 hp driveline mount: a) isolated and b) incorporated into VIPER

The result of designing and fabricating configuration-specific components for the UH-60L is shown in Figs. 19 and 20. Figure 20 gives a good perspective of the size of the VIPER equipment with a technician viewing the connection between Driveline 1 and the UH-60L transmission. Additional pictures of the installed VIPER test stand at Aberdeen Proving Ground (APG), Maryland, are shown in the Appendix B.

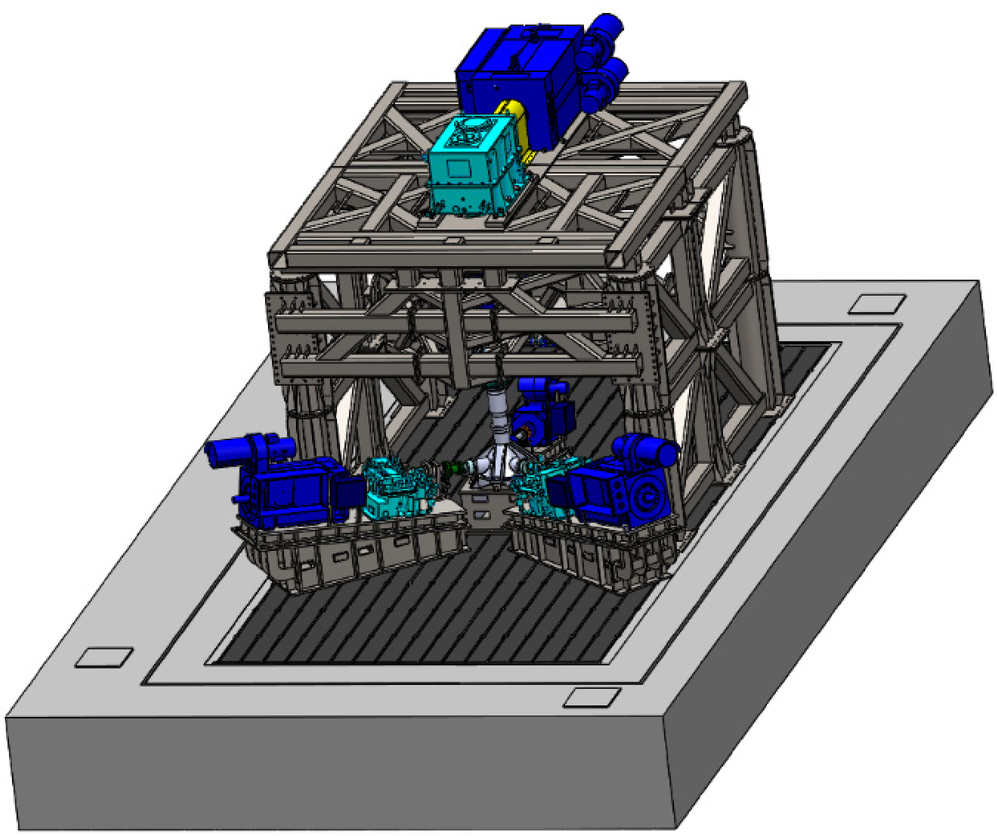


Fig. 19 VIPER configured for the UH-60L

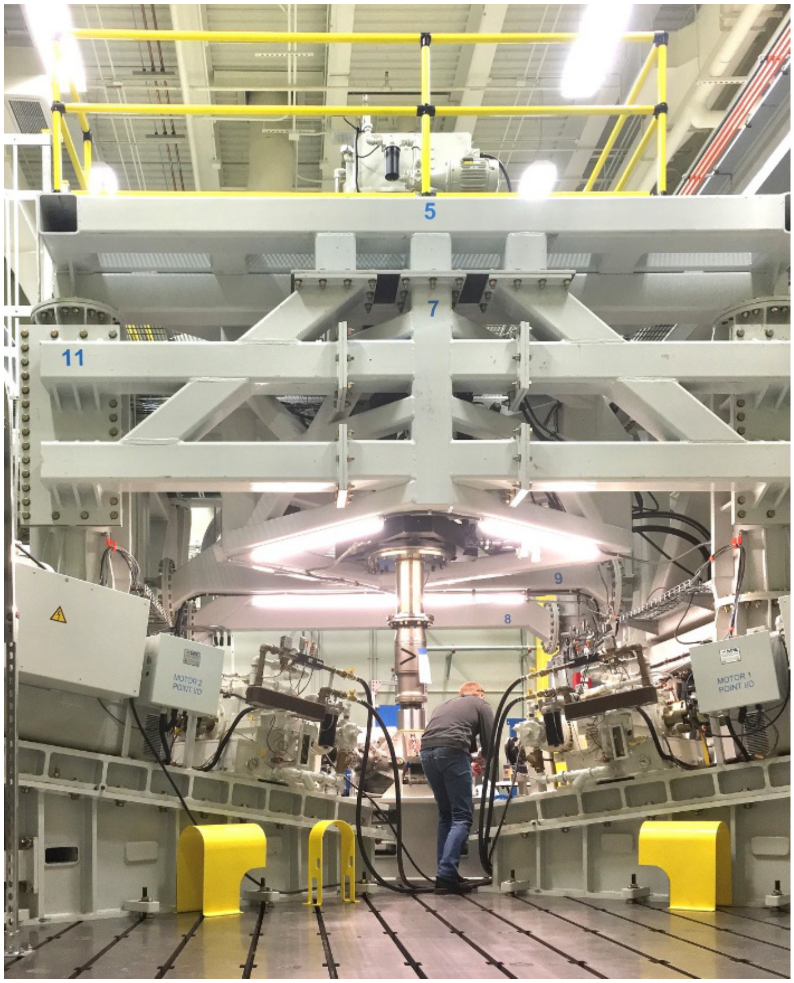


Fig. 20 VIPER installed at APG

4. Conclusion

VIPER is an Army-unique research facility that delivers transformational knowledge to advance next-generation rotorcraft drivetrain technology. The VIPER testbed enables Army, academic, and industry partners to engage and explore new technologies under replicated flight loads to increase power density, endurance to increase operational reach, and payload for future rotorcraft. VIPER is available to accommodate rotorcraft driveline research priorities through highly controlled and repeatable experiments with a modular design. The modular design allows for a wide variety of company-specific transmission platform reconfigurations. VIPER is engineered to operate through a variety of failure modes to push the limits of analysis and new technologies. This report documents the VIPER equipment capabilities to help facilitate the development of experimental studies as we accomplish research objectives aligned with Army modernization priorities.

Appendix A. Equipment Specifications

Equipment	Manufacturer	Product ID	Specification
Motor 1	ATS Ebtalwerk	ARFA 355.6-04-3-153	1,000 hp; max continuous speed of 6,000 RPM
Motor 2			1,000 hp; max continuous speed of 6,000 RPM
Motor 3		ARFA 500.7-04-3-152	2,000 hp; max continuous speed of 2,386 RPM
Motor 4		ACFA 225.2-04-3-153	250 hp; max continuous speed of 6,000 RPM
Gearbox 1	Brad Foote	ZS250-HS / 26803-1	1.667:1 GR; 6,000 RPM in / 10,000 RPM out
Gearbox 2		ZS250-HS / 26803-2	1.667:1 GR; 6,000 RPM in / 10,000 RPM out
Gearbox 3		ZDB445-V / 26803	4.717:1 GR; 940 RPM in / 2,350 RPM out
Torque Limiter 1 Torque Limiter 2	FLEXXOR Coupling	162C Anderson clamp hubs and shear section	Set to 1,575 ft-lb (2,136 N-m)
Torque Limiter 3	Mayr	1S/10-element 60–120k Nm	Set to 65,650 (89,009 Nm)
Torque Limiter 4		01/4030.70406S, 4-element, 600–1200 Nm	Set to 657 ft-lb (891 Nm)
Torque Meter 1 Torque Meter 2	HBM	T40B/2,000 Nm	Rated torque of 1,475 ft-lb (2,000 Nm)
Torque Meter 3 Torque Meter 4		T40FM	
Speed Encoder 1 Speed Encoder 2	Heidenhain	ERM 220	TTL with max speed of 10,500 RPM
Speed Encoder 3 Speed Encoder 4		ROD 426	TTL with max speed of 16,000 RPM
Temperature Switches	IFM Efector	Various models	DI with varying set-points
Thermocouples	Omega	Type-K	AI characterizes performance
Vibration Switches	IFM Efector	VKV021	DI with varying set-points
Accelerometers	Dytran	3224A6	AI characterizes performance
Vertical Actuators	MTS	244.21S	13.5 kip with a 1-inch stroke length
Horizontal Actuators	MTS	244.21S	5.5 kip with a 2-inch stroke length
Force Transducer–Vert.	MTS	661.20F-03	22,000 lb (100 kN) capacity
Force Transducer–Hor.	MTS	661.19F-04	5,600 lb (25 kN) capacity
CV Joint	NTN	DOJ625F612	52,514 ft-lb (71,200 Nm) peak, 500 RPM max

Appendix B. Pictures of the Vehicle Innovative Powertrain Experimental Research (VIPER) Testbed Installed at Aberdeen Proving Ground

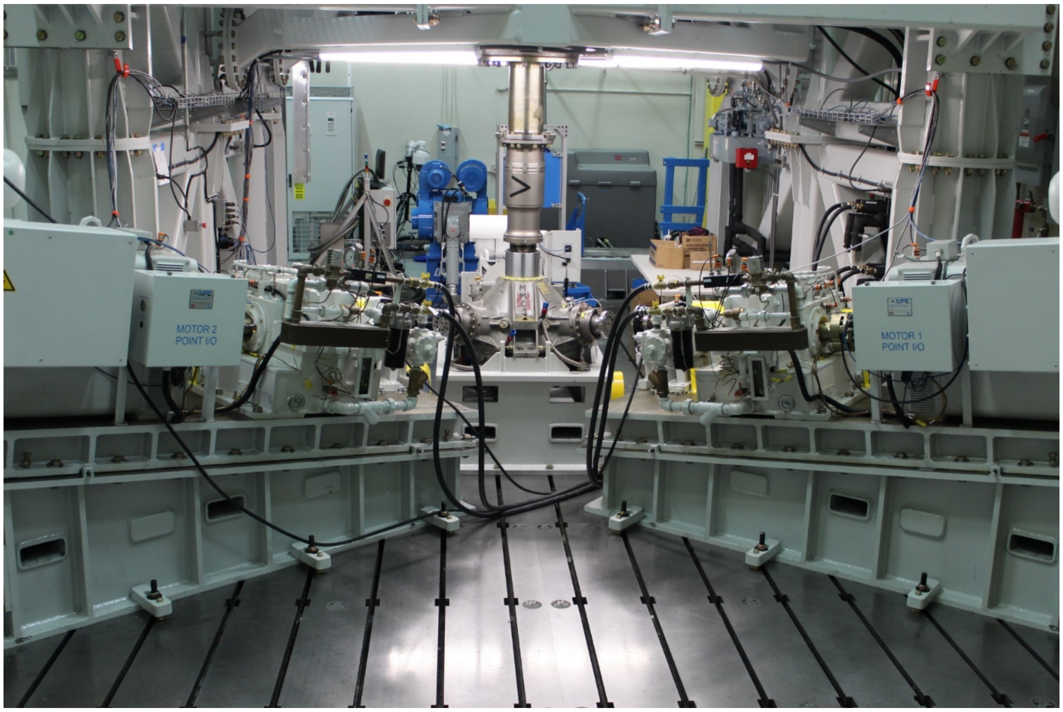


Fig. B-1 The Vehicle Innovative Powertrain Experimental Research (VIPER) testbed configured for the UH-60L main module configuration

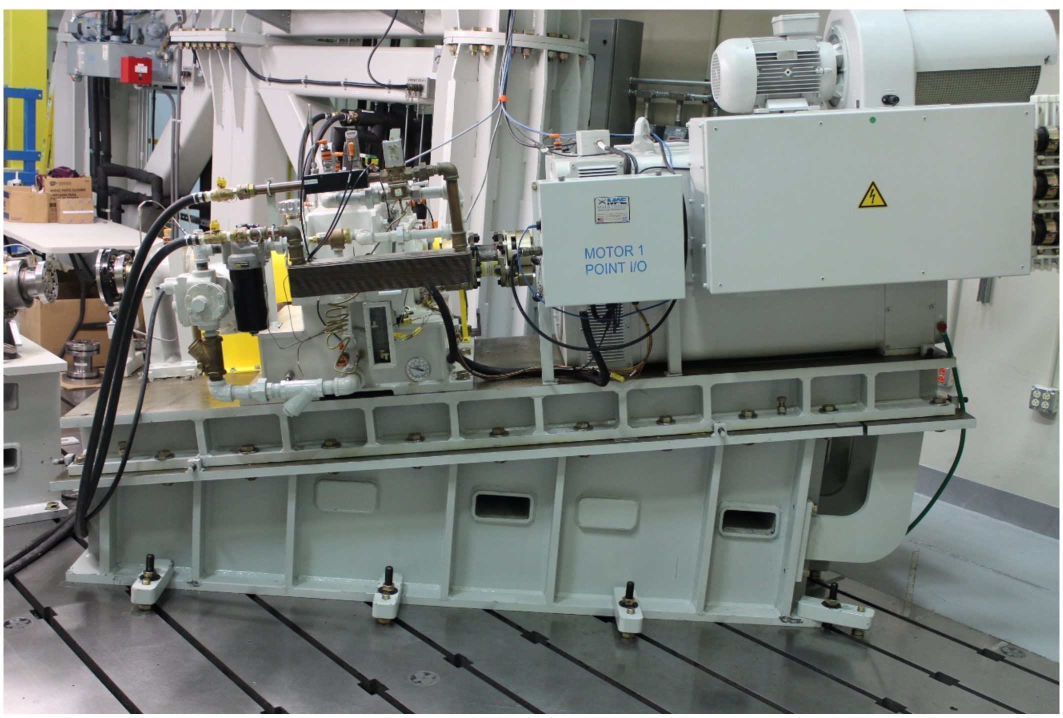


Fig. B-2 Driveline 1 providing an input to the transmission

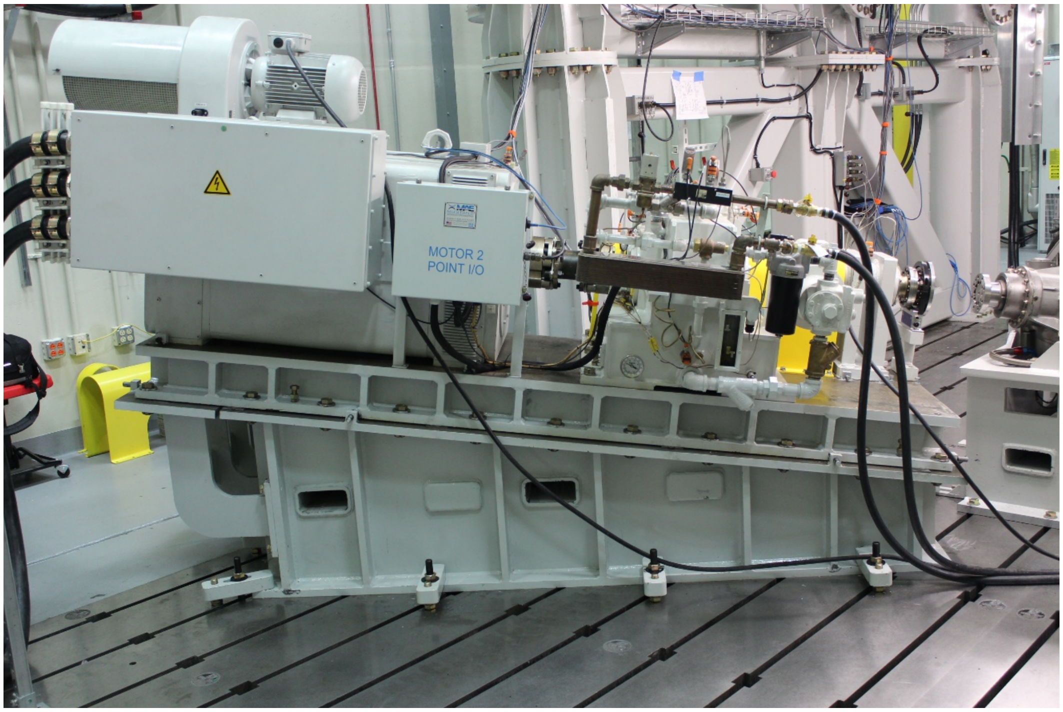


Fig. B-3 Driveline 2 providing an input to the transmission

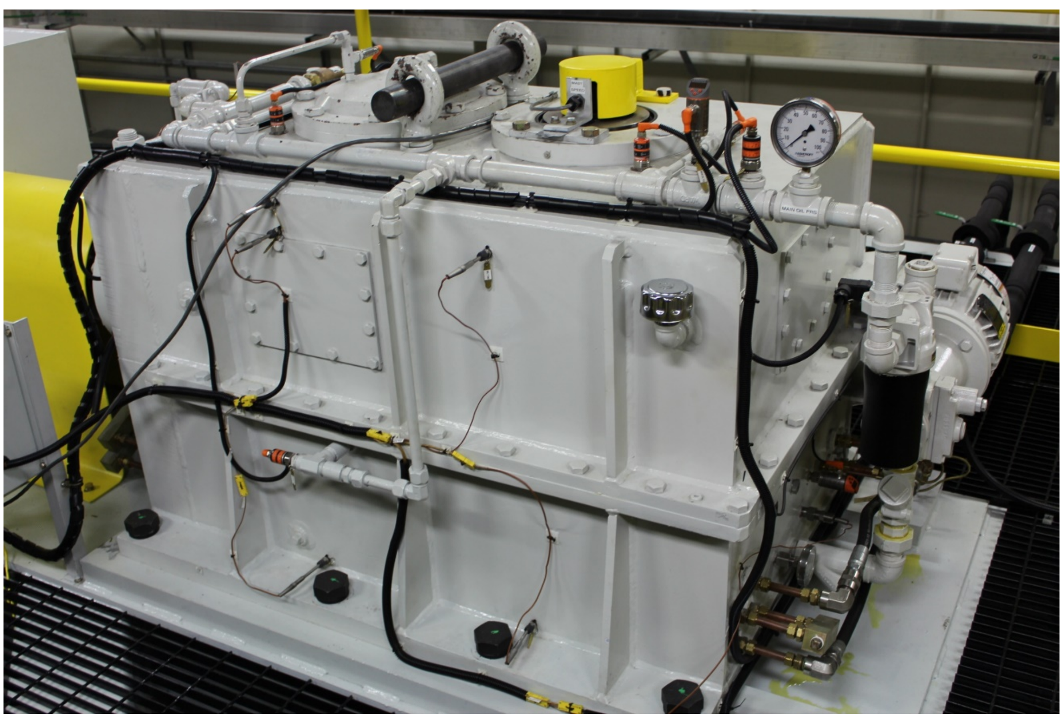


Fig. B-4 Gearbox 3 increases the main mast speed and changes the shaft orientation to horizontal

Fig. B-5 Motor 3 absorbs the load from Gearbox 3

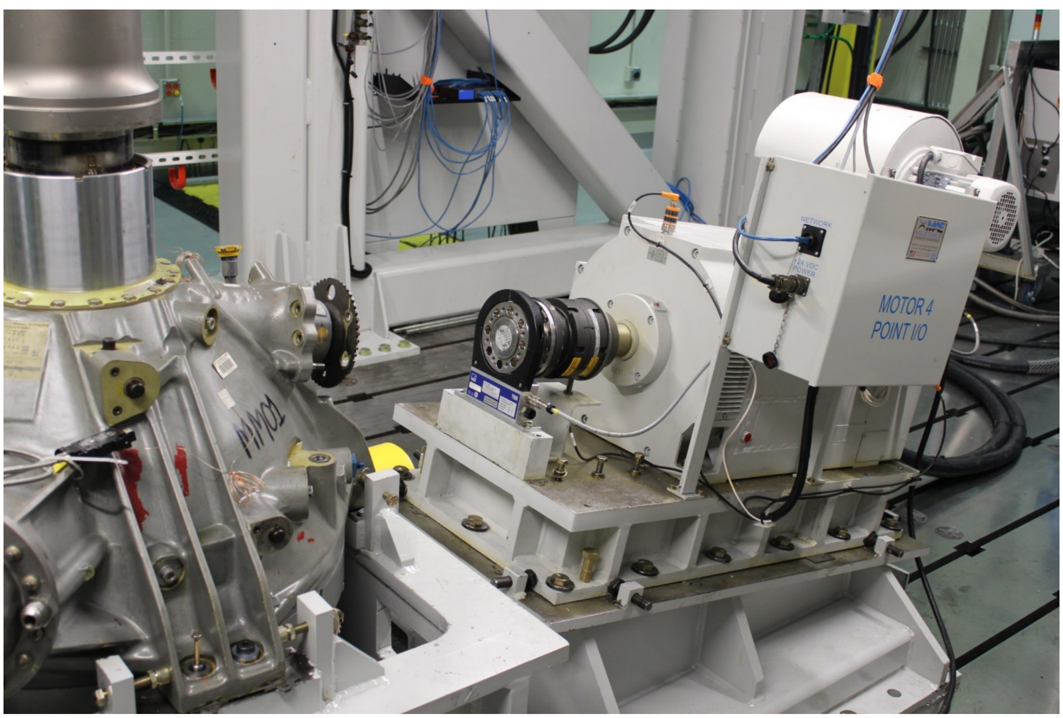


Fig. B-6 Driveline 4 is used to absorb the tail rotor load

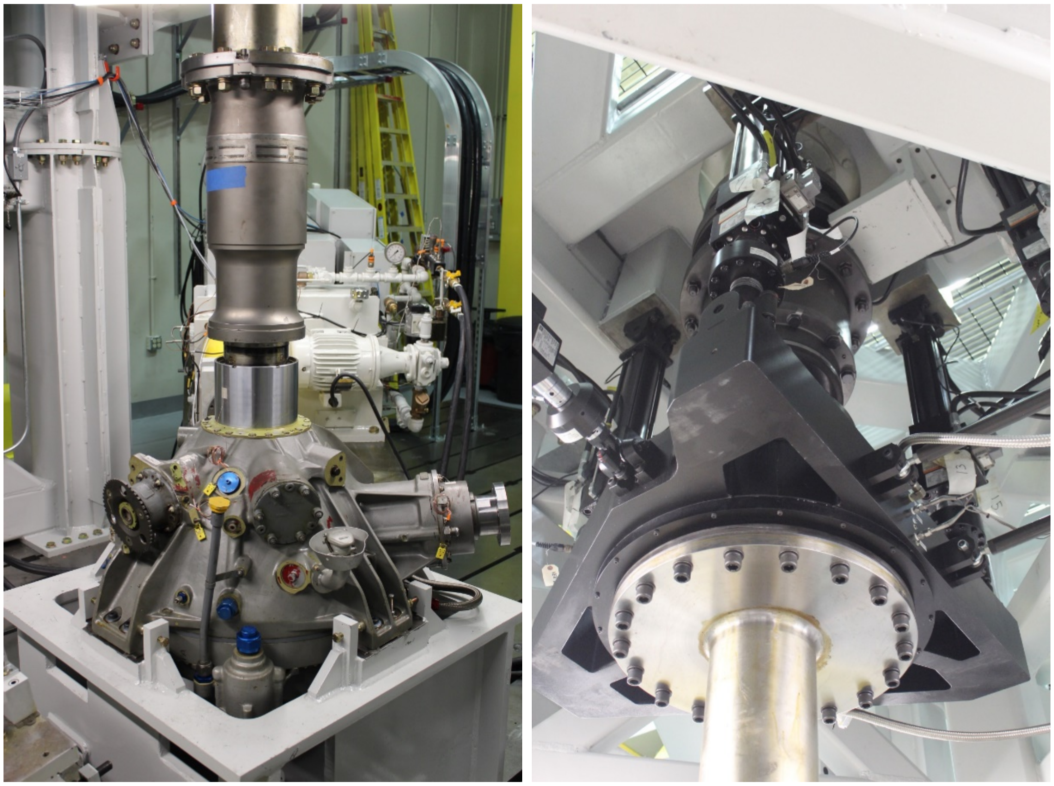


Fig. B-7 The transmission main mast is connected to the swashplate with a custom adapter

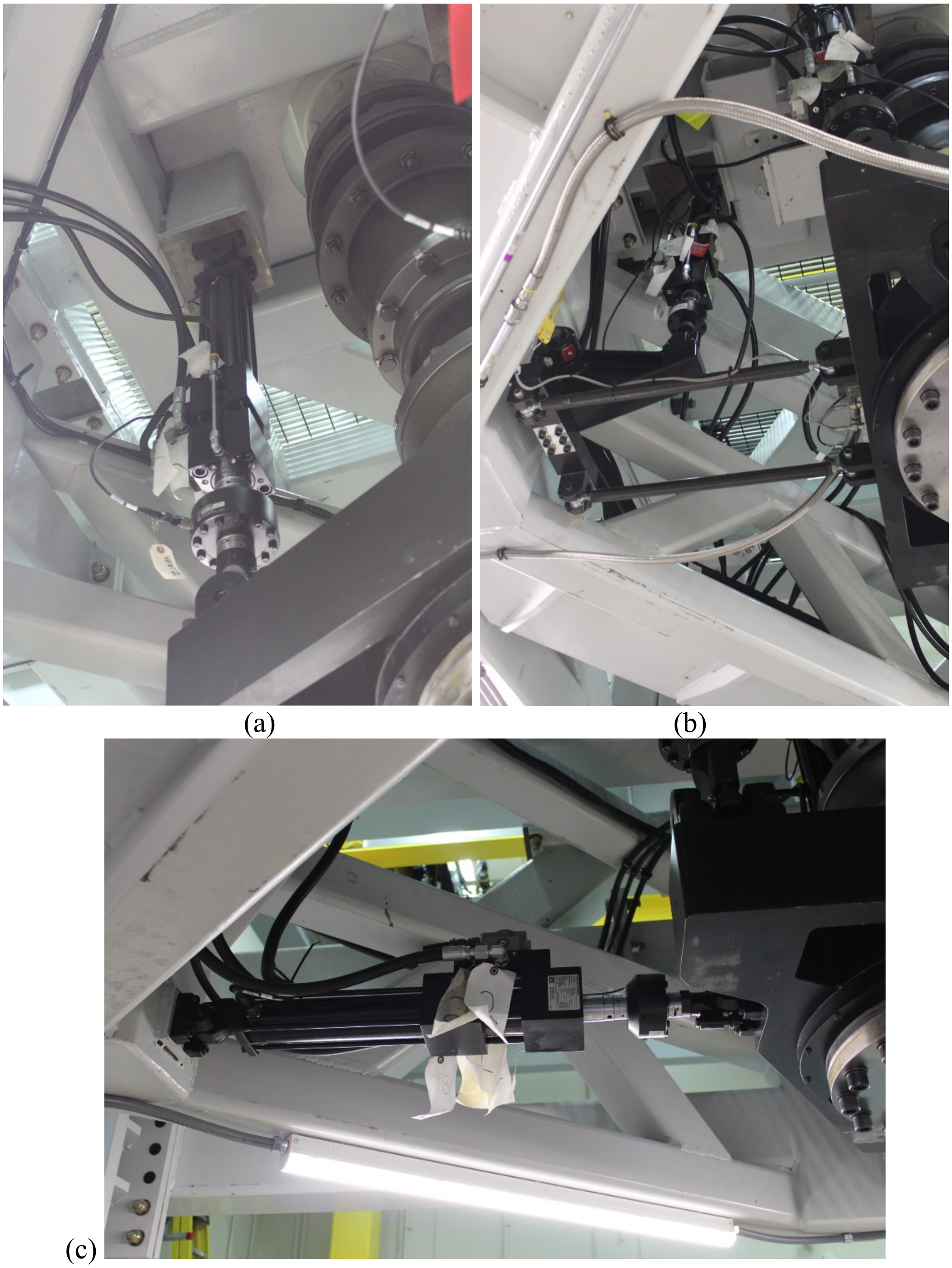


Fig. B-8 Load actuators: a) one of the three Z-axis actuators, b) the X-axis actuator, and c) the Y-axis actuator

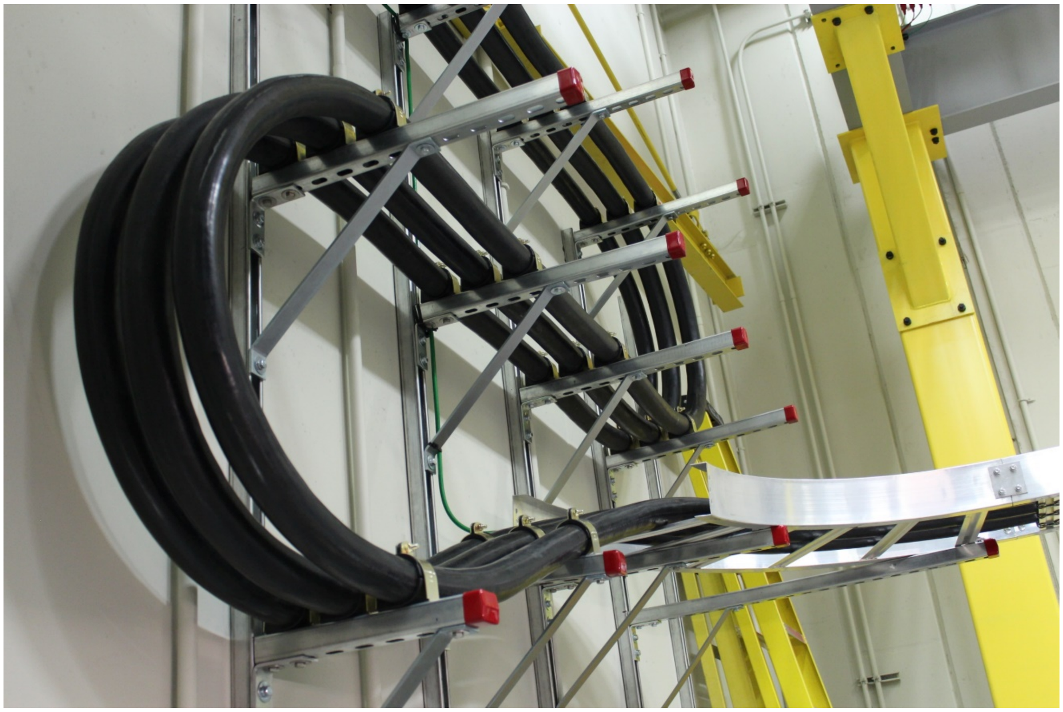


Fig. B-9 Excess variable frequency drive cable lengths were used for Drivelines 1, 2, and 4 to enable reconfiguration

List of Symbols, Abbreviations, and Acronyms

APG	Aberdeen Proving Ground
ARL	Army Research Laboratory
CAD	computer-aided design
CV	constant velocity
DEVCOM	US Army Combat Capabilities Development Command
GB	gearbox
ID	identification
MT	motor
TL	torque limiter
VIPER	Vehicle Innovative Powertrain Experimental Research

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