Considerations for Thrust Vector Control (TVC) In-Flight Load Predictions

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NASA TVC Actuator Load Analysis Methodology

- **Methodology developed by NASA MSFC ER63 and based on NASA heritage TVC design methods**

- **Examines summation of static & quasi-static loads over 3D (2-DOF) gimbal range of motion for maximum reaction load in any single actuator**
  - Conducts 3D vectorized gimbal torque summation of load contributors and translates to actuator reaction forces
  - "Scalar" load contributors (e.g. radial thrust offset) assumed to act entirely in actuator line-of-action due to lack of knowledge in full load state (e.g. load direction)
  - Loads described for pitch and yaw actuator at any location in the gimbal range of motion are independent and describe highest load for that actuator
  - Required gimbal range of motion and gimbal-rate determined by GN&C dispersions
  - Inherently conservative methodology due to lack of knowledge of full load state
    - Time-variant loads (e.g. loads to vehicle dynamic state) are not phased with respect to gimbal angular state

- **Potential exists to time-phase load environments for more accurate in-flight load predictions, _**potentially**_ lowering peak predicted load / power requirements in actuator design space (e.g. apply vehicle dynamic states acting on engine system via GN&C time-histories rather than applying constant maximums)**

- **Typical actuator reaction load considerations include:**
  - Translational vehicle accelerations acting on engine CM (typically *relatively* **LARGE** contribution**)
  - Angular vehicle accelerations about the vehicle CM action on engine CM (typically *relatively* **SMALL** contribution**)
  - Angular vehicle velocities about the vehicle CM action on the engine CM (typically *relatively* **SMALL** contribution**)
  - Radial thrust vector offset (typically *relatively* **LARGE** contribution**)
  - Propellant feedline duct displacement (typically *relatively* **MEDIUM** contribution**)
  - Gimbal bearing coulomb friction (typically *relatively* **SMALL** contribution**)
  - Momentum change in propellant feedline flow at engine turbopump interface (typically *relatively* **SMALL** contribution**)
  - Engine turbopump gyroscopic forces (typically *relatively* **SMALL** contribution**)

- **Other actuator reaction loads that may need to be considered given the specific hardware design and mission ConOps:**
  - Translational and angular vehicle dynamics acting on the propellant feedline CMs
  - Propellant feedline installation pre-load
  - Vehicle engine / thrust structure shock / random vibration environments
  - Gravitational / stage-boost (launch) accelerations acting on engine CM during earth-to-orbit ascent environment

- **Includes considerations for NASA-STD-5017 recommended mechanism margins**

/**/ *Assumes example of medium-class liquid rocket engine (i.e., ~25k lb_f thrust capability; e.g., Aerojet Rocketdyne RL10 Liquid Rocket Engine). Actual significance of the magnitude of individual reaction loads need to be considered on a comparison or engine/motor system-to-system basis.*

Engine Gimbal Torque / Actuator Force Transformation

- The following rotation matrix is utilized in several of the subsequent slides as a means to transform variables defined in the gimbaled engine coordinate system frame about the gimbal center-of-rotation into the fixed vehicle coordinate system frame, also about the gimbal center-of-rotation:

$$\boldsymbol{R} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix}$$

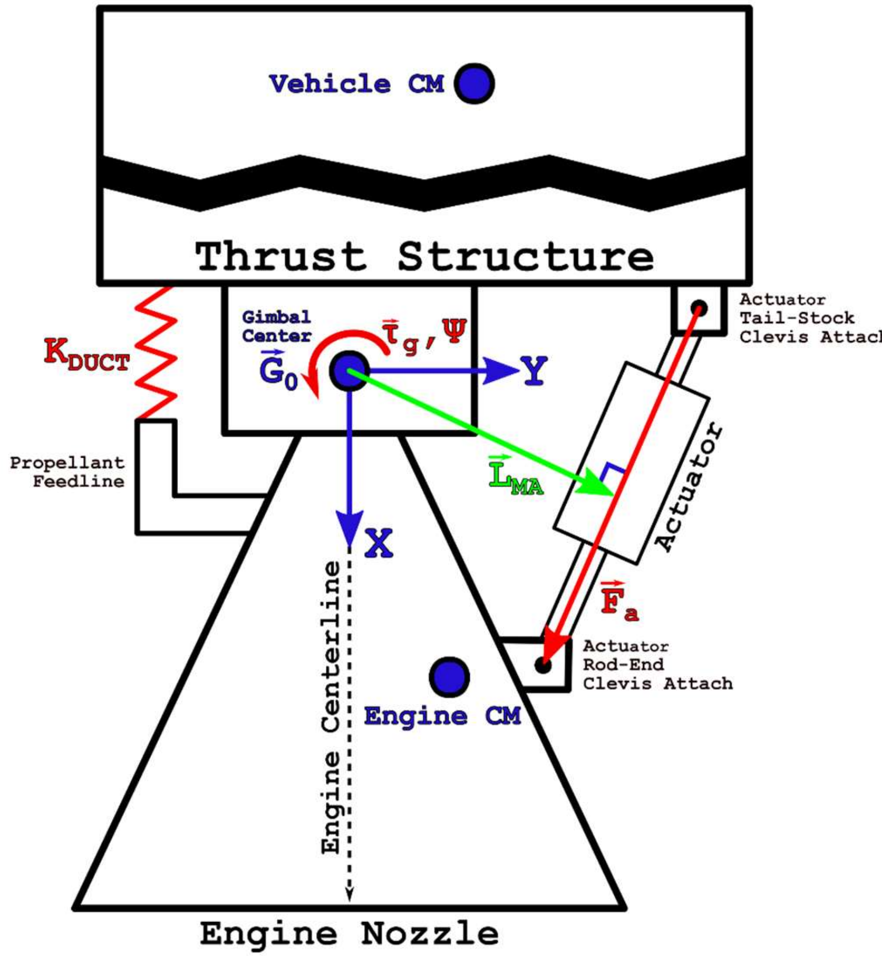
- Likewise, the calculated gimbaled engine torques in the vehicle fixed coordinate system frame, about the gimbal center-of-rotation can be converted to actuator forces by either of the methods described below:

$$\left|\vec{\boldsymbol{F}}_a\right| = \frac{\left|\vec{\boldsymbol{\tau}}_g\right|}{\left|\vec{\boldsymbol{L}}_{MA}\right|} \text{ (ref. 1)}$$

OR

$$\vec{\boldsymbol{\tau}}_g = \boldsymbol{T} * \vec{\boldsymbol{F}}_a \leftrightarrow \vec{\boldsymbol{F}}_a = \boldsymbol{T}^{-1} * \vec{\boldsymbol{\tau}}_g \text{ (ref. 2)}$$

$\boldsymbol{R}$	≡	Rotation matrix from gimbaled engine coordinate system frame to fixed vehicle coordinate system frame
ψ	≡	Net gimbal angular displacement
$\vec{\boldsymbol{F}}_a$	≡	TVC actuator force vector
$\vec{\boldsymbol{\tau}}_g$	≡	Net gimbal torque about gimbal center-of-rotation
$\vec{\boldsymbol{L}}_{MA}$	≡	TVC actuator moment arm position vector
$\boldsymbol{T}$	≡	Gimbal torque / actuator force transformation matrix



(ref. 1): Refer to ER63 Technical Bulletin (***Derivation of Thrust Vector Control (TVC) Moment Arm***) regarding equation explanation, derivation, and application (*useful for **2D** analysis*).

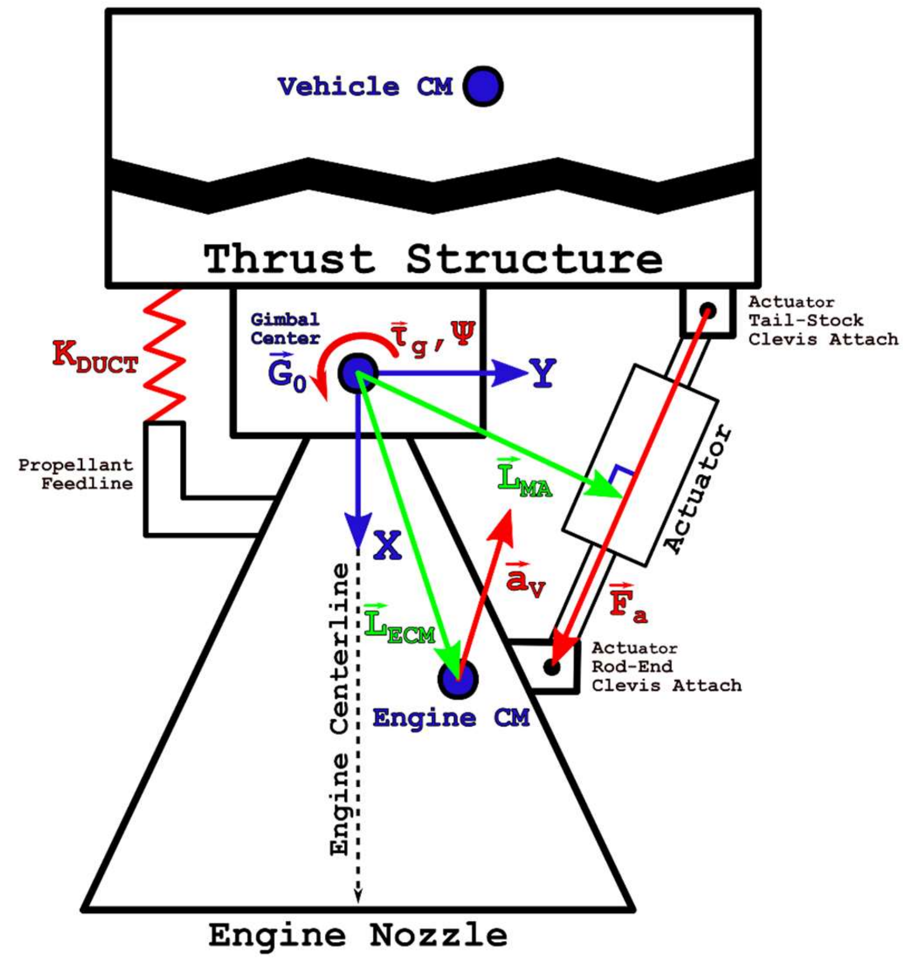
(ref. 2): Refer to ER63 Technical Bulletin (***Derivation of Thrust Vector Control (TVC) Gimbal Torque / Actuator Force Transformation Matrix***) regarding equation explanation, derivation, and application (*useful for **3D** analysis*).

Actuator Reaction Loads Due to Vehicle Translational Accelerations Acting On Engine CM

- Gimbal torques due to translational vehicle accelerations are found via the cross product of the 3D position vector of the engine's center-of-mass with respect to the engine's gimbal center and the 3D force vector acting on the center-of-mass due to vehicle translational accelerations:

$$\vec{\boldsymbol{\tau}}_g = (\boldsymbol{R} * \vec{\boldsymbol{r}}_{ECM}) \times m_e \vec{\boldsymbol{a}}_v$$

$\vec{\boldsymbol{\tau}}_g$	≡	Net torque vector about gimbal center-of-rotation
$\vec{\boldsymbol{r}}_{ECM}$	≡	Position vector for engine CM relative to gimbal center
$\boldsymbol{m}_e$	≡	Engine mass
$\vec{\boldsymbol{a}}_v$	≡	Translational acceleration vector of vehicle



NOTE: This same calculation can be used to evaluate other actuator loads due to acceleration environments besides operation vehicle accelerations (e.g. gravitational or stage-boost (launch) accelerations acting on the Engine CM) by substituting the quantity used for $\vec{a}_v$.

Actuator Reaction Loads Due to Vehicle Angular Accelerations Acting On Engine CM

- Gimbal torques due to angular vehicle accelerations are found via the cross product of the 3D position vector of the engine's center-of-mass with respect to the engine's gimbal center and the 3D force vector acting on the center-of-mass due to vehicle angular accelerations:

$$\vec{\tau}_g = (\boldsymbol{R} * \vec{\boldsymbol{r}}_{ECM}) \times m_e \left(\vec{\alpha}_v \times \left((\boldsymbol{R} * \vec{\boldsymbol{r}}_{ECM}) - \vec{\boldsymbol{r}}_{VCM}\right)\right)$$

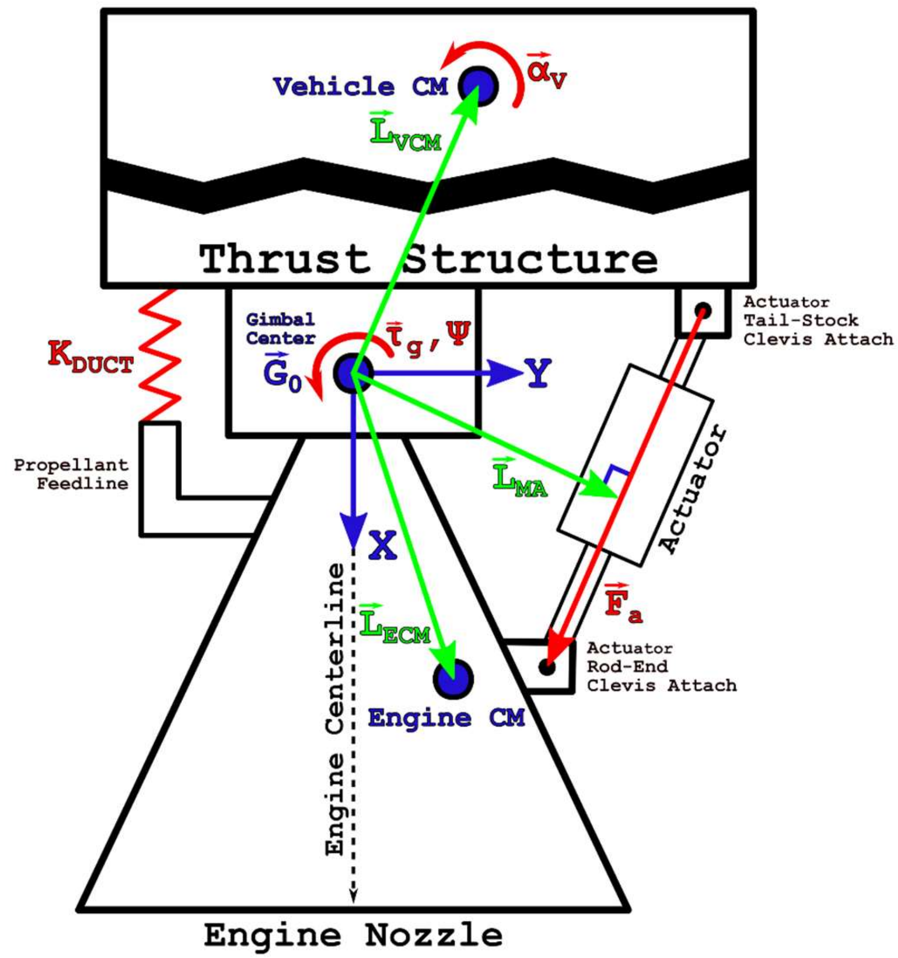
$\vec{\tau}_g$ ≡ Net torque vector about gimbal center-of-rotation

$\vec{r}_{ECM}$ ≡ Position vector for engine CM relative to gimbal center

m_e ≡ Engine mass

$\vec{\alpha}_v$ ≡ Angular acceleration vector of vehicle about vehicle CM

$\vec{r}_{VCM}$ ≡ Position vector for vehicle CM relative to gimbal center

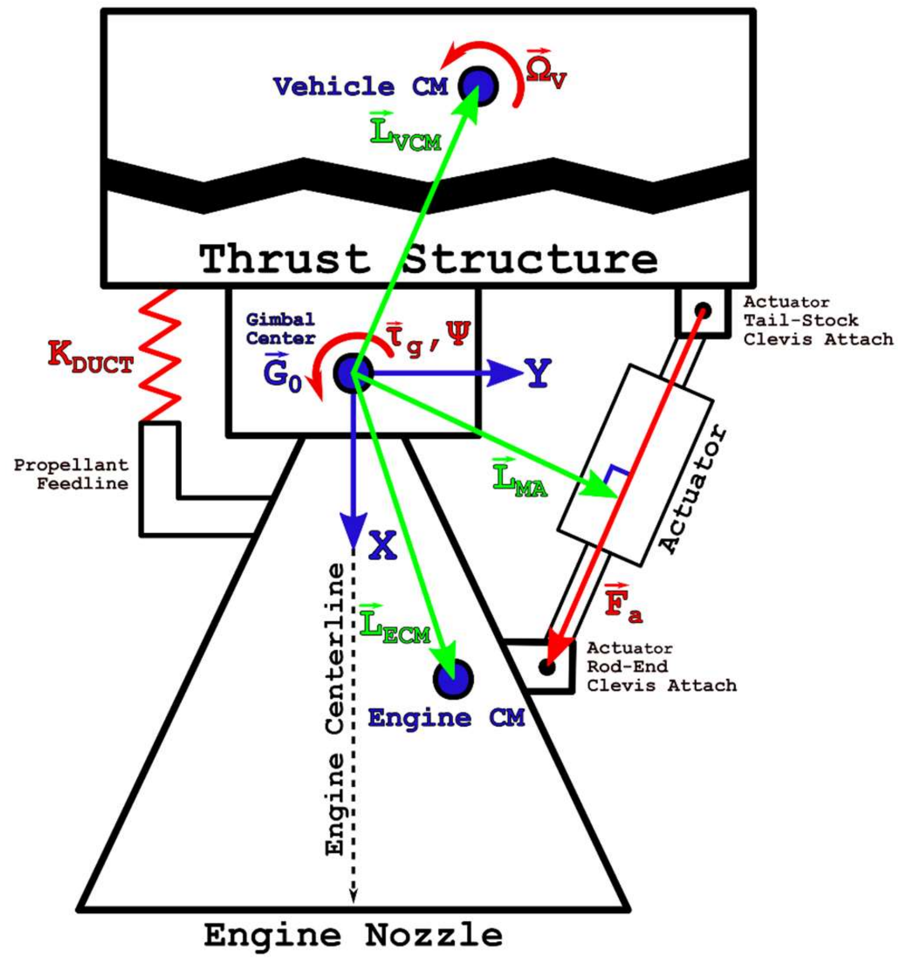


Actuator Reaction Loads Due to Vehicle Angular Velocities

- Gimbal torques due to angular vehicle accelerations are found via the cross product of the 3D position vector of the engine's center-of-mass with respect to the engine's gimbal center and the 3D force vector acting on the center-of-mass due to vehicle angular velocities:

$$\vec{\tau}_g = (\boldsymbol{R} * \vec{\boldsymbol{r}}_{ECM}) \times m_e \left(\vec{\boldsymbol{\Omega}}_v \times \left(\vec{\boldsymbol{\Omega}}_v \times \left((\boldsymbol{R} * \vec{\boldsymbol{r}}_{ECM}) - \vec{\boldsymbol{r}}_{VCM} \right) \right) \right)$$

$\vec{\boldsymbol{\tau}}_g$	≡	Net torque vector about gimbal center-of-rotation
$\vec{\boldsymbol{r}}_{ECM}$	≡	Position vector for engine CM relative to gimbal center
$\boldsymbol{m_e}$	≡	Engine mass
$\vec{\boldsymbol{\Omega}}_v$	≡	Angular velocity vector of vehicle about vehicle CM
$\vec{\boldsymbol{r}}_{VCM}$	≡	Position vector for vehicle CM relative to gimbal center



Actuator Reaction Loads Due to Radial Thrust Offset

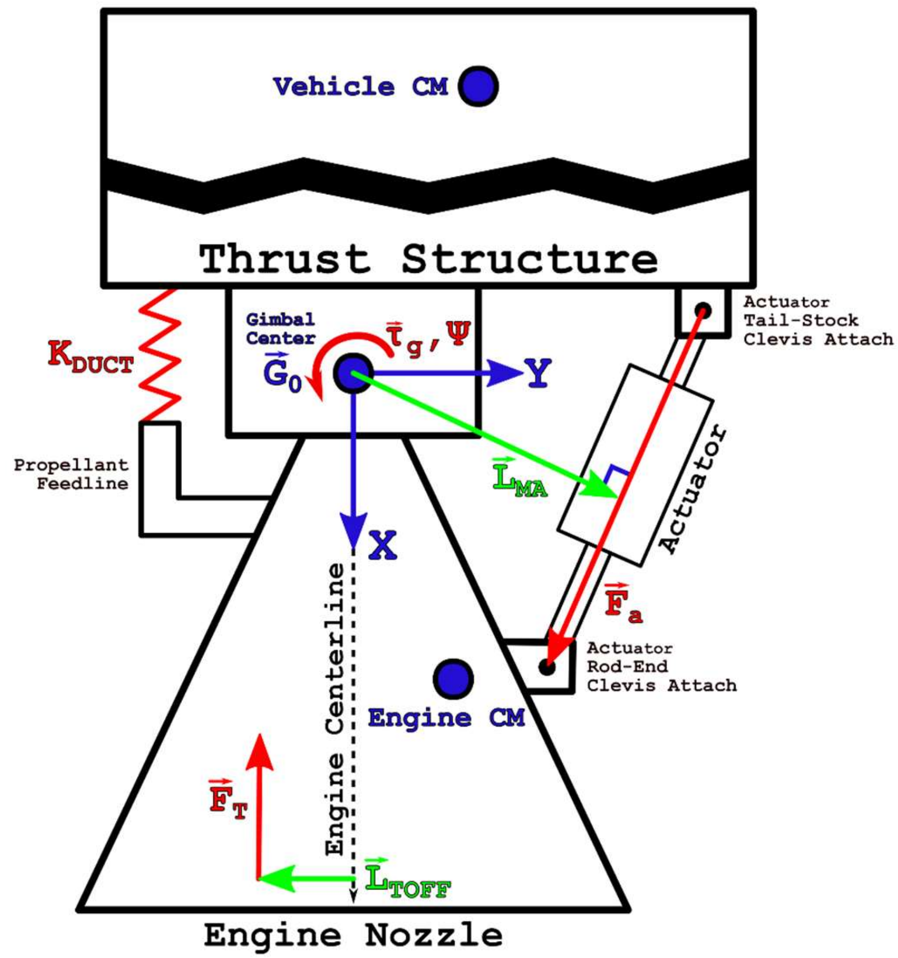
- Gimbal torques due to radial thrust vector offset are found via the cross product of the 3D position vector of the thrust vector radial offset and the 3D force vector representing the max axial thrust of the rocket engine:

$$\vec{\boldsymbol{\tau}}_g = \boldsymbol{R} * \left(\vec{\boldsymbol{r}}_{TOFF} \times \vec{\boldsymbol{F}}_T\right)$$

$\vec{\boldsymbol{\tau}}_g$ ≡ Net torque vector about gimbal center-of-rotation

$\vec{\boldsymbol{r}}_{TOFF}$ ≡ Thrust vector radial offset position vector

$\vec{\boldsymbol{F}}_T$ ≡ Force vector for engine thrust

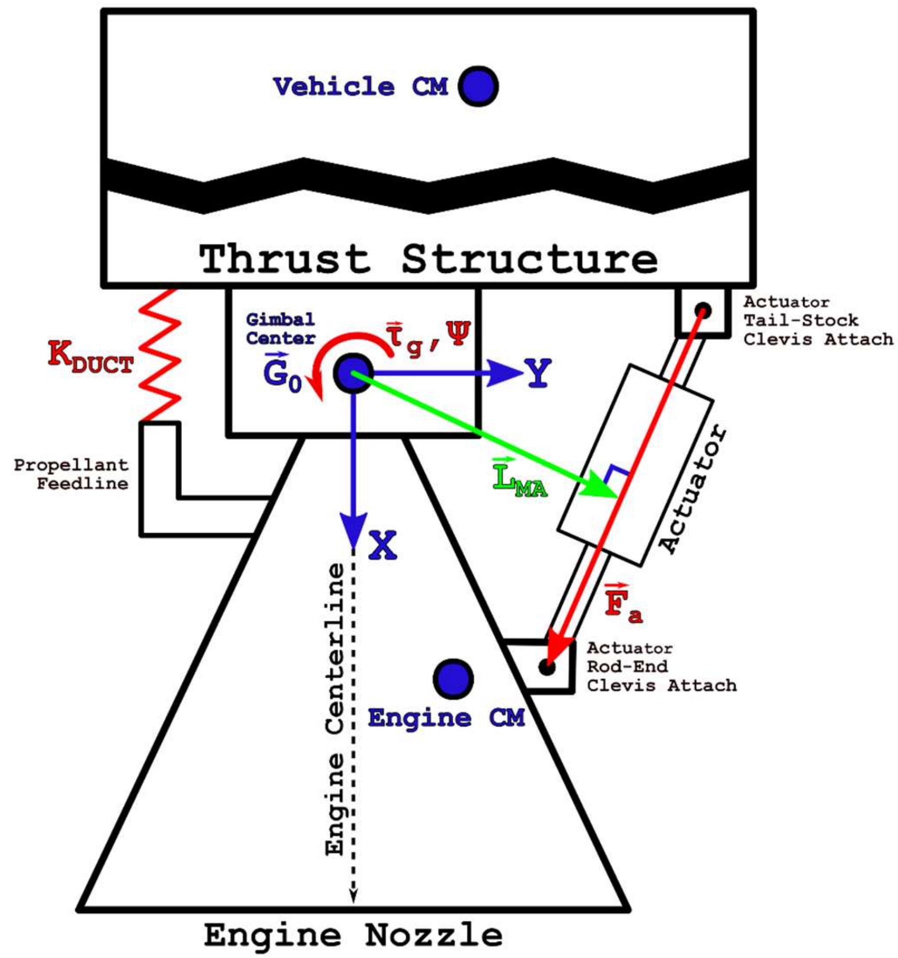


Actuator Reaction Loads Due to Feedline Duct Displacement

- Gimbal torques due to feedline duct displacements are found via the product of the feedline duct rotational stiffness matrix about the engine's gimbal center and the 3D angular displacement vector about the gimbal center:

$$\vec{\tau}_g = K_{DUCT} * \vec{\varphi}$$

$\vec{\tau}_g$	≡	Net torque vector about gimbal center-of-rotation
K_{DUCT}	≡	Flex duct (bellows) interface stiffness matrix
$\vec{\varphi}$	≡	Engine gimbal angular position vector



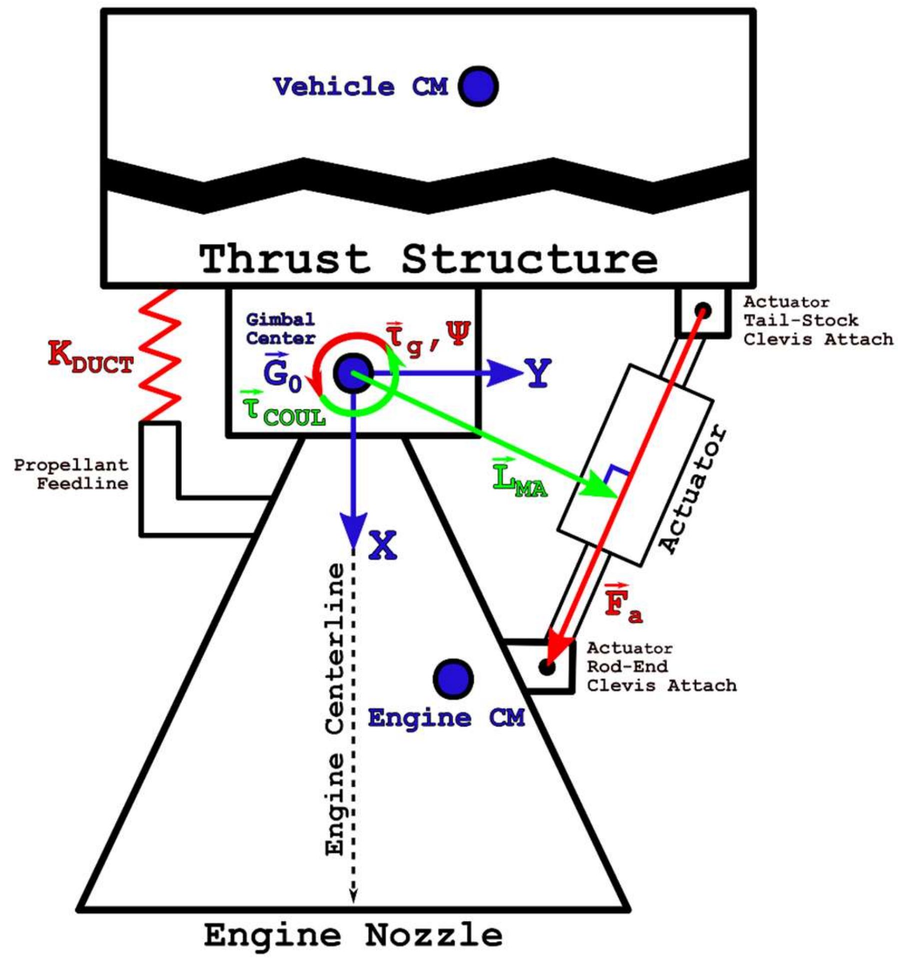
Actuator Reaction Loads Due to Engine Gimbal Bearing Coulomb Friction

- Gimbal torques due to engine gimbal bearing coulomb friction are found via that application of the constant coulomb friction torque:

$$\vec{\tau}_g = R * (\vec{\tau}_{COUL})$$

$\vec{\tau}_g$ ≡ Net torque vector about gimbal center-of-rotation

$\vec{\tau}_{COUL}$ ≡ Columb torque vector



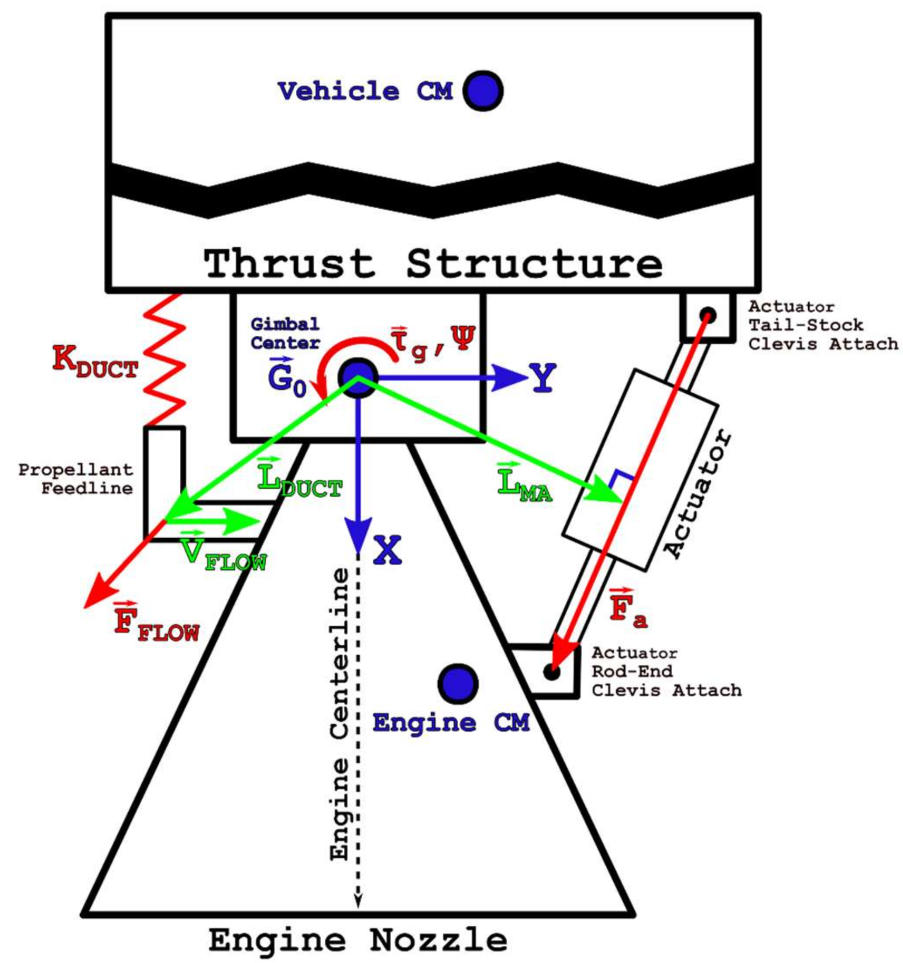
Actuator Reaction Loads Due to Propellant Momentum Change

- Gimbal torques due to the momentum change of propellant flow at the engine propellant inlet are found via the cross product of the 3D position vector of the engine propellant inlet with respect to the engine's gimbal center and the 3D force vector acting at the engine propellant inlet due to the momentum change of the propellant flow:

$$\vec{\tau}_g = R * (\vec{r}_{DUCT} \times \vec{F}_{FLOW})$$

$$\vec{F}_{FLOW} = \dot{m}_{FLOW} * \vec{V}_{FLOW}$$

$\vec{\tau}_g$	≡	Net torque vector about gimbal center-of-rotation
$\vec{r}_{DUCT}$	≡	Position vector of propellant duct-to-engine interface
$\vec{F}_{FLOW}$	≡	Force vector due to momentum change of fluid flow
$\dot{m}_{FLOW}$	≡	Mass flowrate of propellant fluid flow
$\vec{V}_{FLOW}$	≡	Velocity vector of propellant fluid flow



Actuator Reaction Loads Due to Turbopump Gyroscopic Rotation

- Gimbal torques due to gyroscopic forces imparted by the spinning turbopump while the engine is subject to some gimbal angular velocity is found via multiplication of the turbopump mass moment of inertia about its spinning axis, the angular velocity of the turbopump, and the gimbaled engine's 3D angular velocity vector:

$$\vec{\tau}_g = \boldsymbol{R} * \left(\vec{\boldsymbol{H}}_{\boldsymbol{TP}} \times \vec{\boldsymbol{\Omega}}\right)$$

$$\vec{\boldsymbol{H}}_{\boldsymbol{TP}} = I_{TP} * \vec{\boldsymbol{\Omega}}_{TP}$$

$\vec{\tau}_g$ ≡ Net torque vector about gimbal center-of-rotation

$\vec{H}_{TP}$ ≡ Angular momentum vector of turbopump

I_{TP} ≡ Turbopump mass moment of inertia about rotation axis

Ω_{TP} ≡ Angular velocity of turbopump about rotation axis

$\vec{\Omega}$ ≡ Engine gimbal angular velocity vector