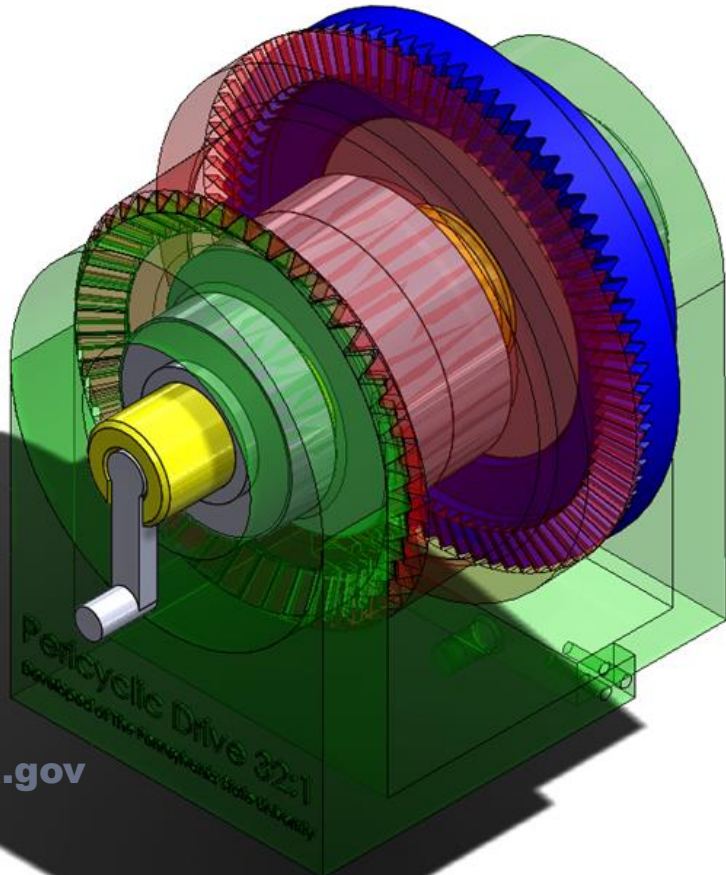


Design Space Exploration of Pericyclic Transmission with Counterbalance and Bearing Load Analysis



Zachary A. Cameron

Research Engineer, NASA GRC

Dr. Edward C. Smith

Professor, Penn State

Dr. Hans DeSmidt

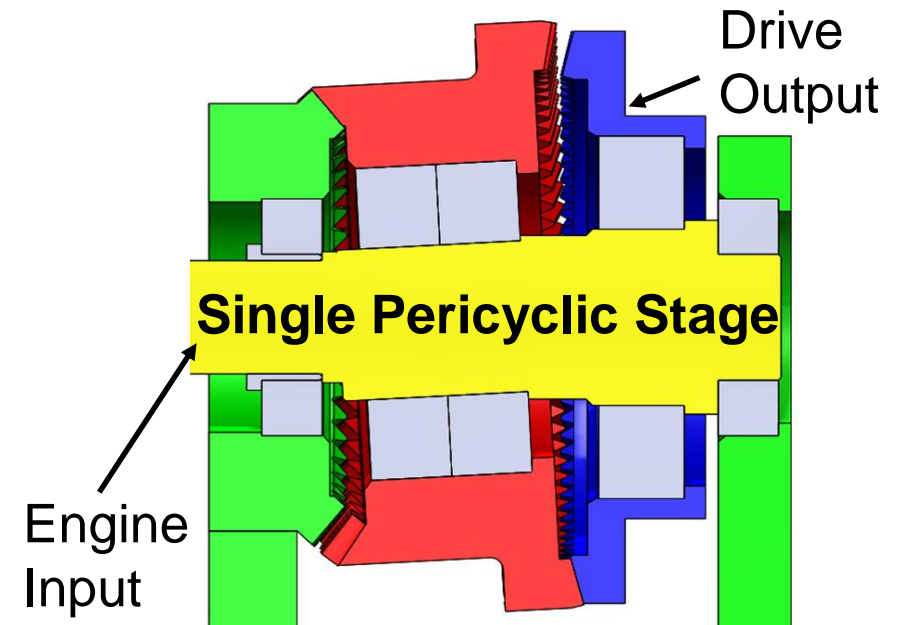
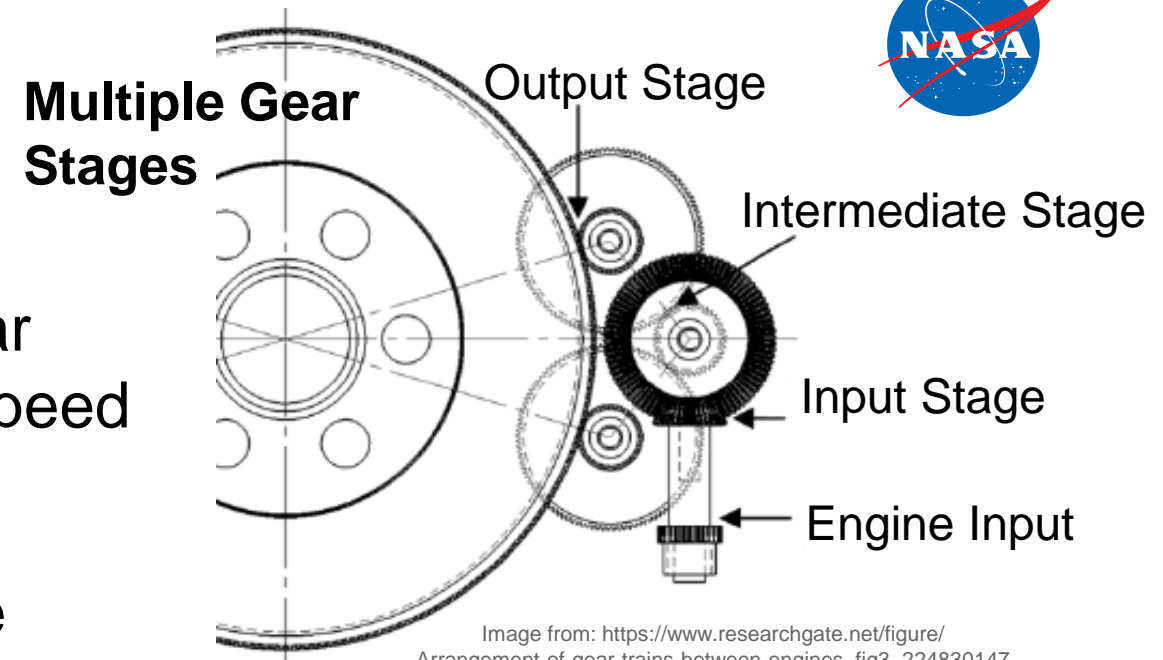
Professor, U Tennessee

Dr. Robert C. Bill

Research Associate, Penn State

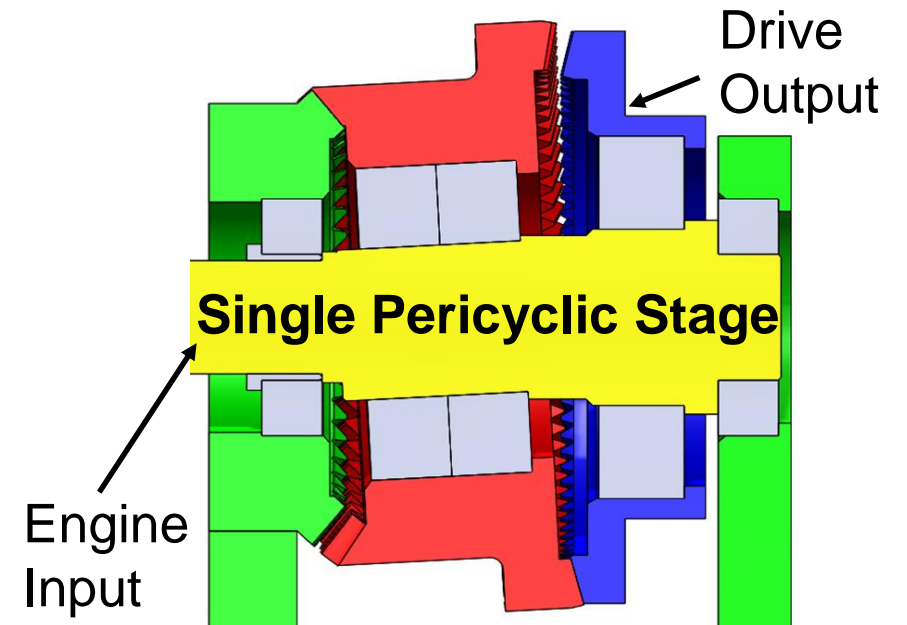
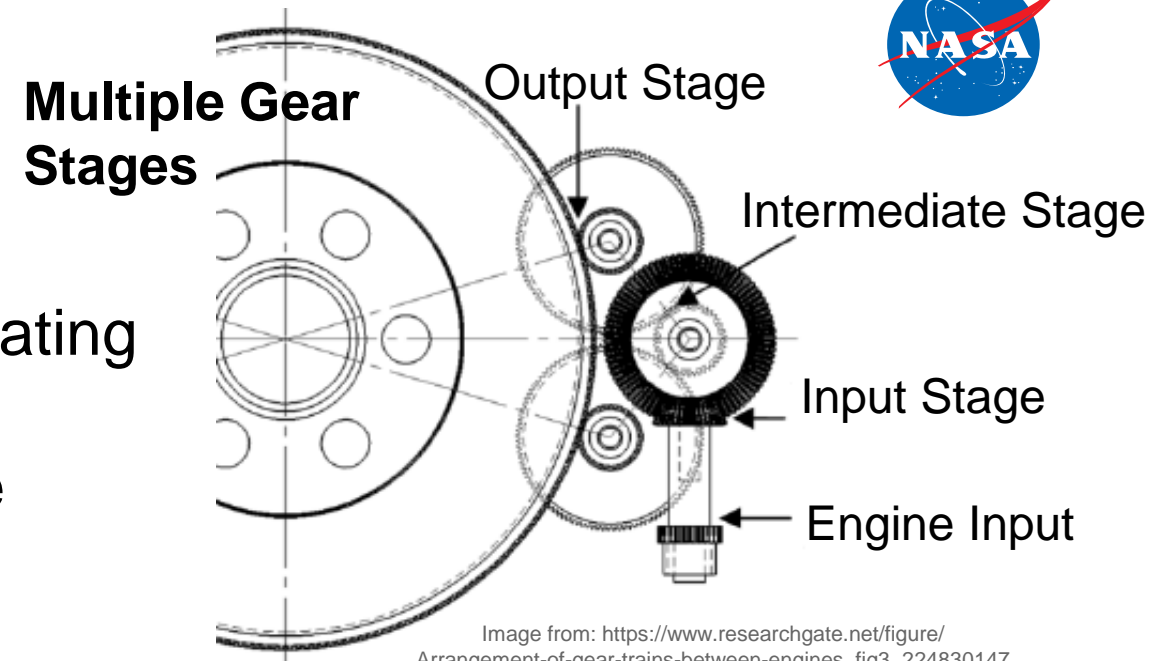
Motivation

- Rotorcraft transmission require multiple gear stages to decrease turbine speed to rotor speed
- Pericyclic transmission can replace multiple gear stages through its ability to achieve high reduction ratios (40:1 or greater)
- Additional benefits shown by Mathur were fewer total components, reduced weight, and decreased noise due to many teeth in contact



Motivation

- Previous work examining dynamics of nutating plate transmission by Anderson showed dynamic moment as a speed limiter to the drive
- Further work by Saribay also made note of this dynamic moment or “overturning moment”
- Neither works explored a method to manage the dynamic moment in high speed operation or reduce resulting bearing loads



Objectives

- Determine design aspects that impact transmission loading
- Gain firm grasp on dynamics of the transmission and magnitudes of moments for operating speeds relative to rotorcraft
- Explore methods to reduce generation of high dynamic loads
- Resolve bearing loads for entire transmission, while utilizing strategies to limit dynamic loads generated

Outline

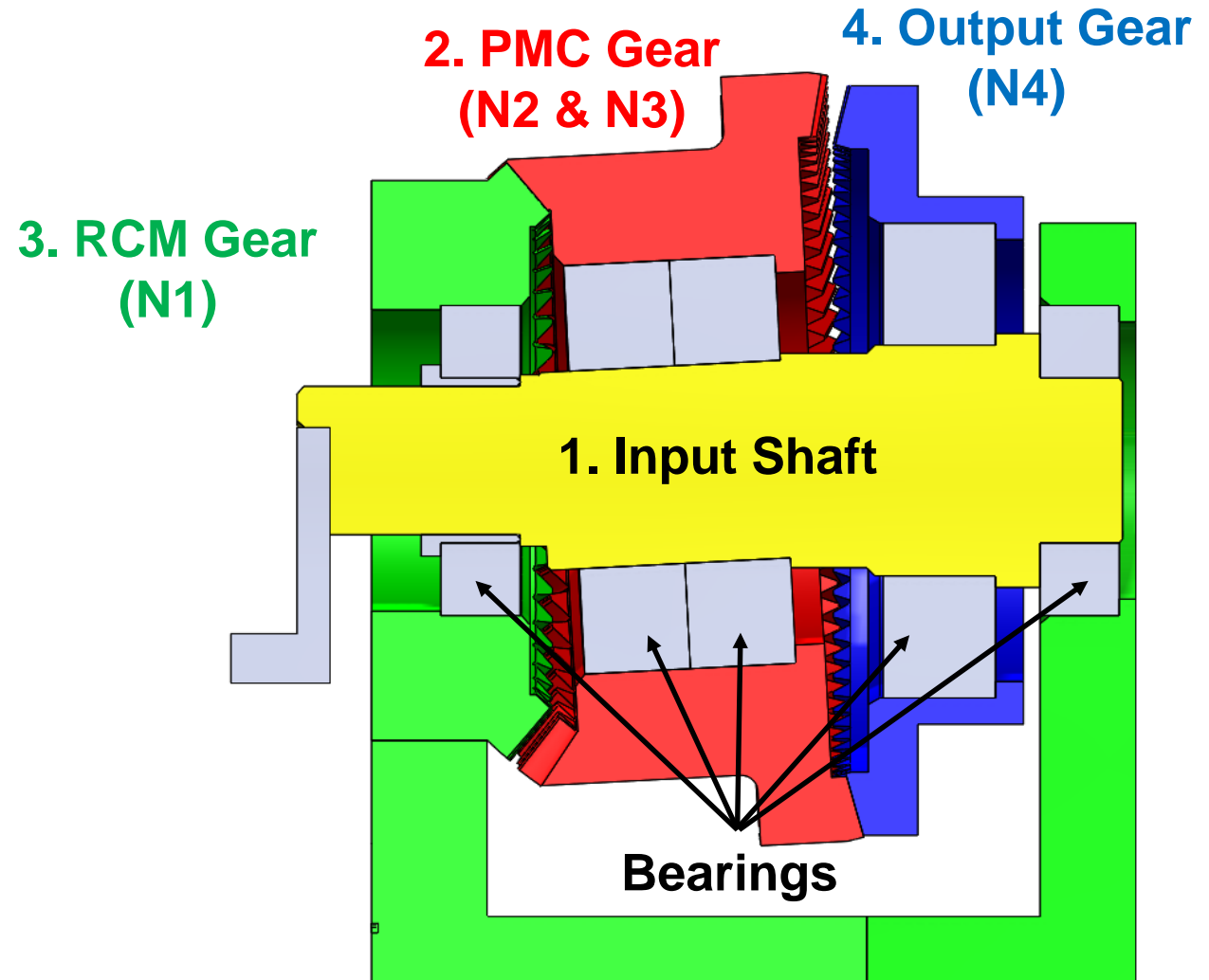
1. Pericyclic Transmission Geometry, Kinematics, and Power Flow
2. Pericyclic Dynamics & Methods to Limit Dynamic Loads
3. Static Model of Dual Pericyclic Motion Converter Drive
4. Conclusions

Pericyclic Transmission Geometry, Kinematics, and Power Flow

Components of Pericyclic Transmission

Four Major Components:

1. Input Shaft
2. Pericyclic Motion Converter (PMC) Gear
3. Reaction Control Member (RCM) Gear
4. Output Gear



PMC Gears in Motion

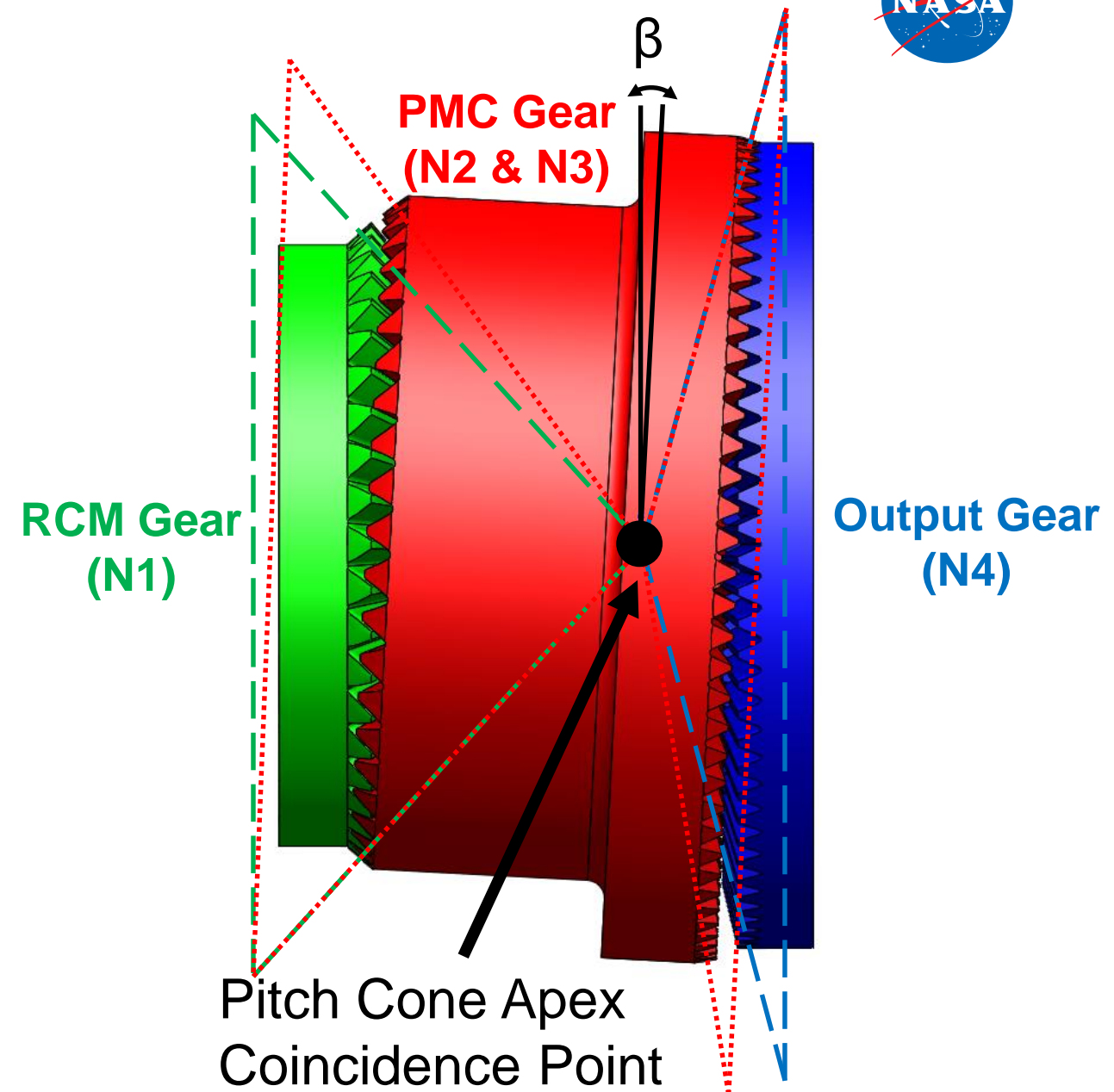
Pericyclic transmission makes use of rotational and nutational motion to achieve high reduction ratios



Gear Pitch Cones

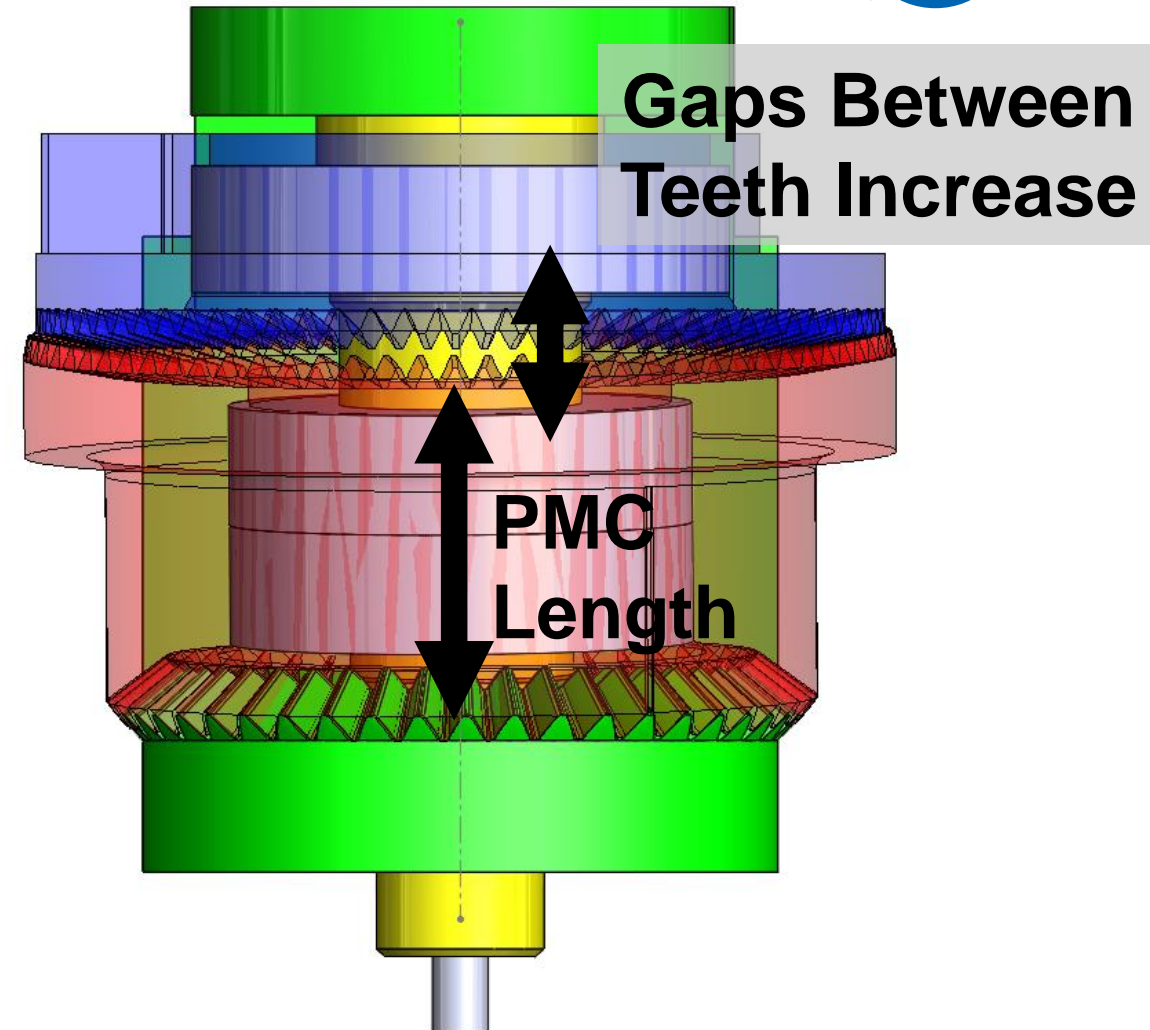
- All pitch cone apexes must be coincident for gears to mesh
- Results in reduction ratio that is independent of nutation angle

$$\frac{\omega_{in}}{\omega_{out}} = \frac{1}{\left(1 - \frac{N1}{N2} * \frac{N3}{N4}\right)}$$



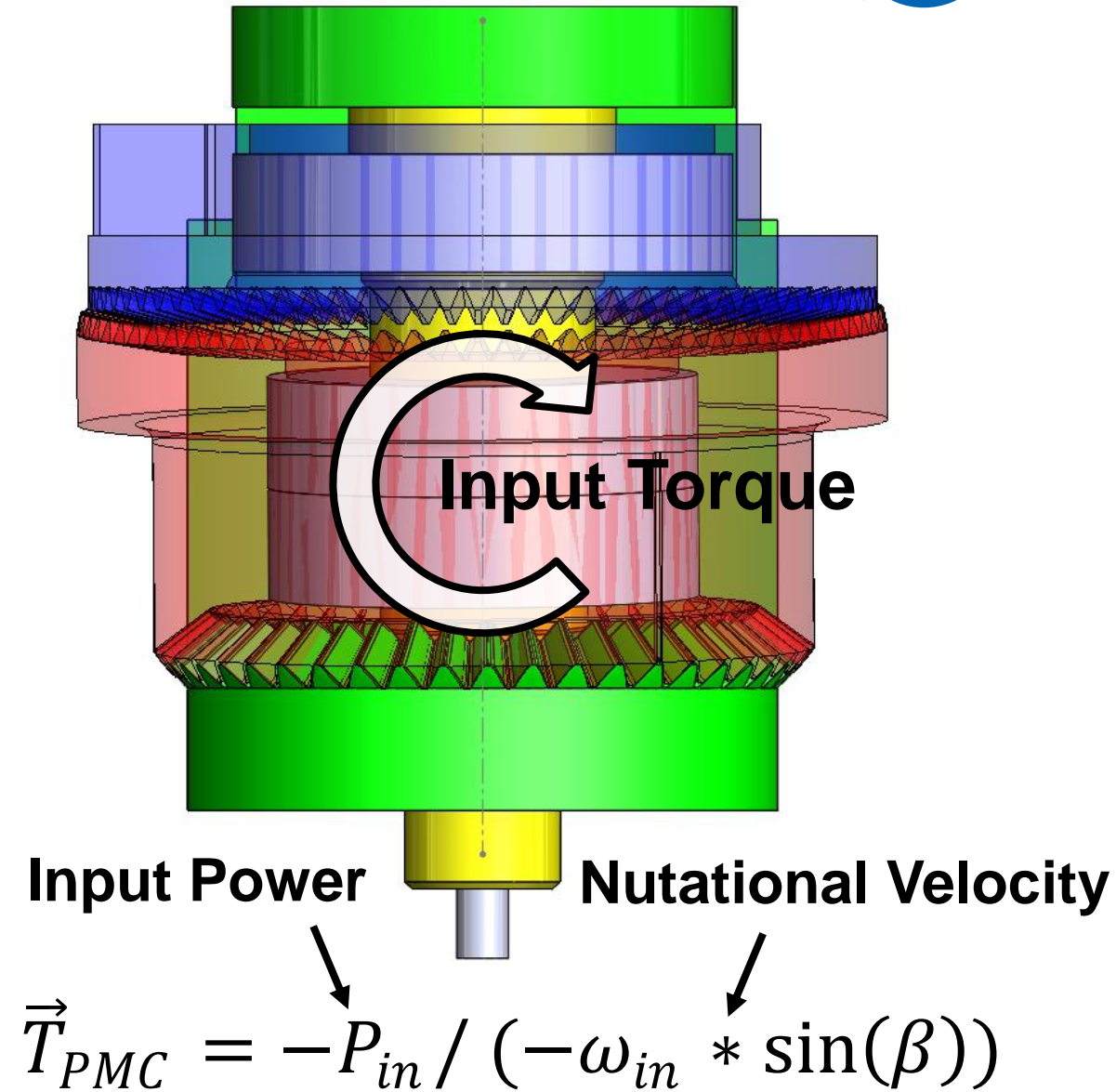
Increasing Nutation Angle

- Less conformal pitch cones increase gear loads
- Transmission shortens axially; decreases mass but removes available space for bearings



Increasing Nutation Angle

- Less conformal pitch cones increase gear loads
- Transmission shortens axially; decreases mass but removes available space for bearings
- Increased nutational velocity decreases static input torque and bearing loads

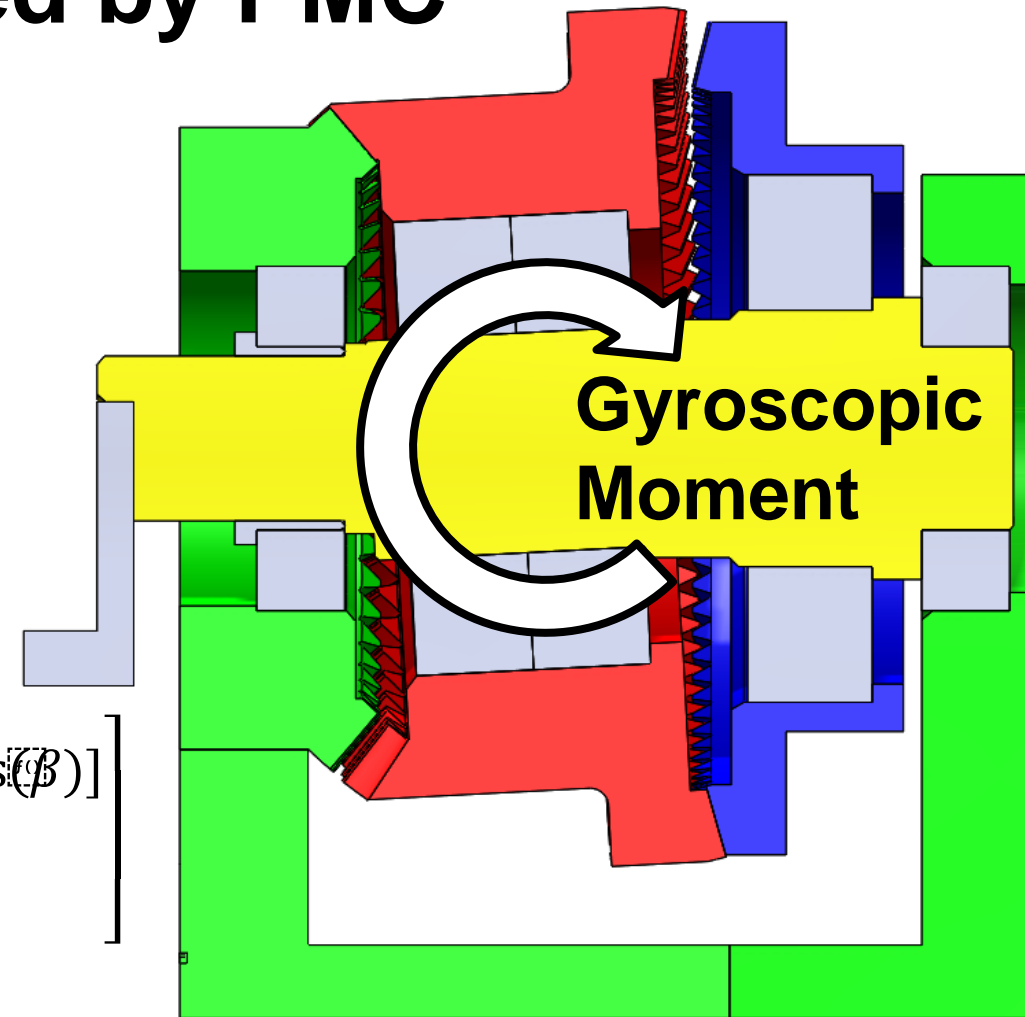


PMC Dynamics & Methods to Limit Dynamic Loads

Dynamic Moment Generated by PMC

- Gyroscopic moment from combination of rotation and nutational velocities acting about x axis (out of page) provides additional PMC bearing load

$$\frac{D\vec{H}_{PMC}}{Dt} = \begin{bmatrix} -\omega_{in}^2 * \sin(\beta) * \left[I_{pzz} * \left(\cos(\beta) - \left(\frac{N1}{N2} \right) \right) - I_{pyy} * \cos(\beta) \right] \\ 0 \\ 0 \end{bmatrix}$$

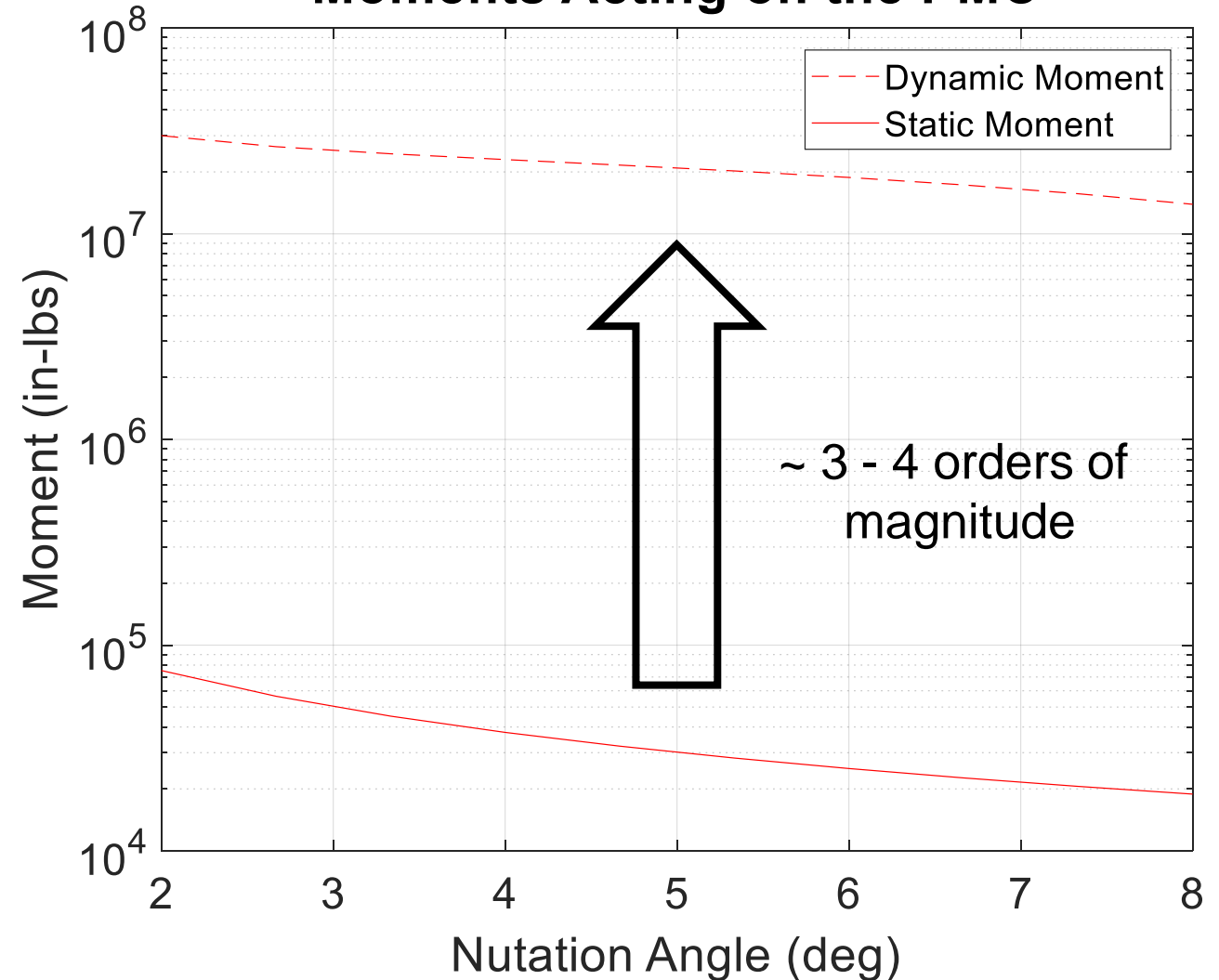


Dynamic Moment Versus Static Moment

Design Variable	
Reduction Ratio	40:1
N1	52
N2	54
N3	81
N4	80
Input Power	1,000 HP
Input Speed	12,000 RPM

At high input speeds dynamic moment is unreasonable

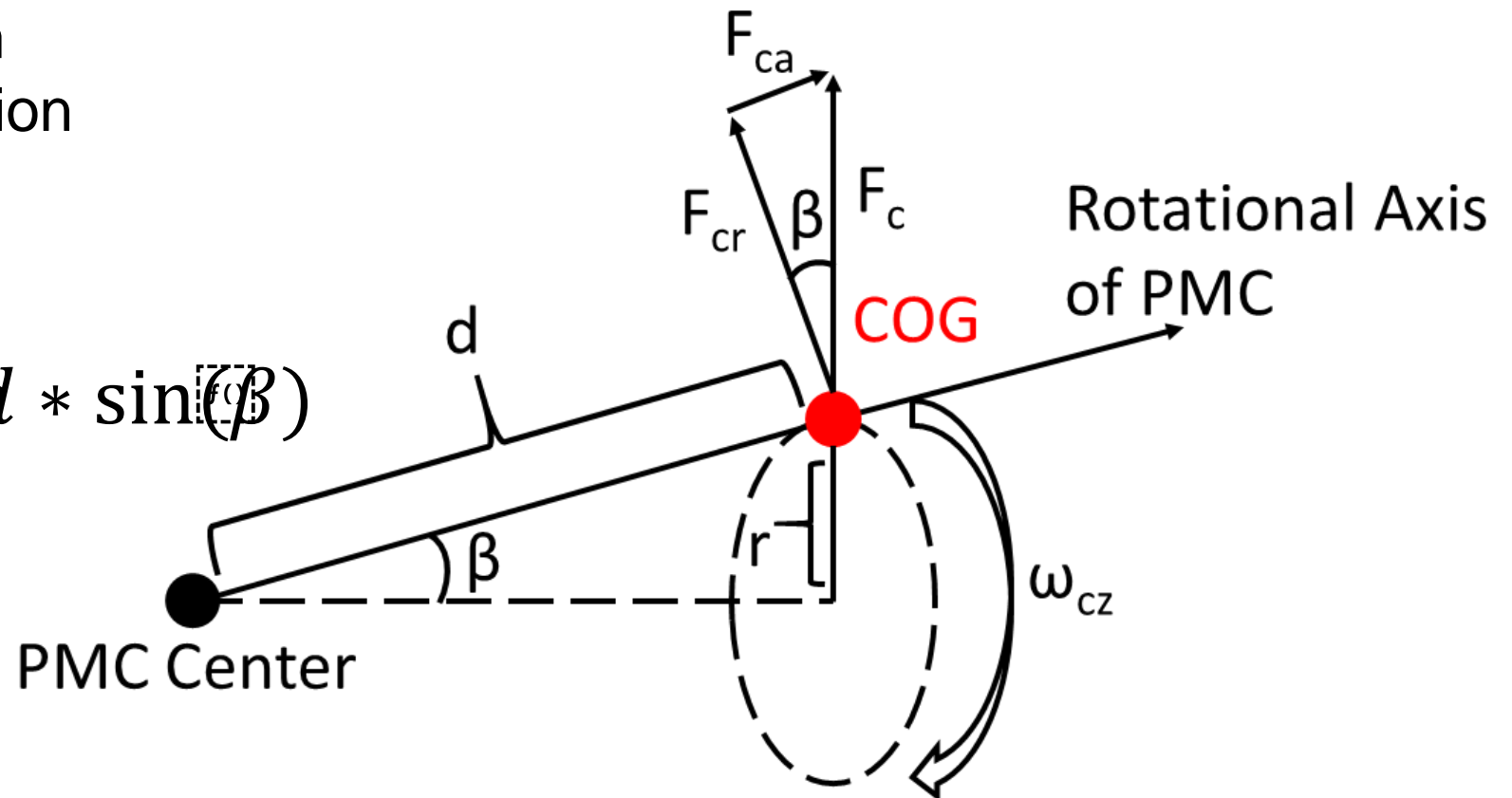
Moments Acting on the PMC



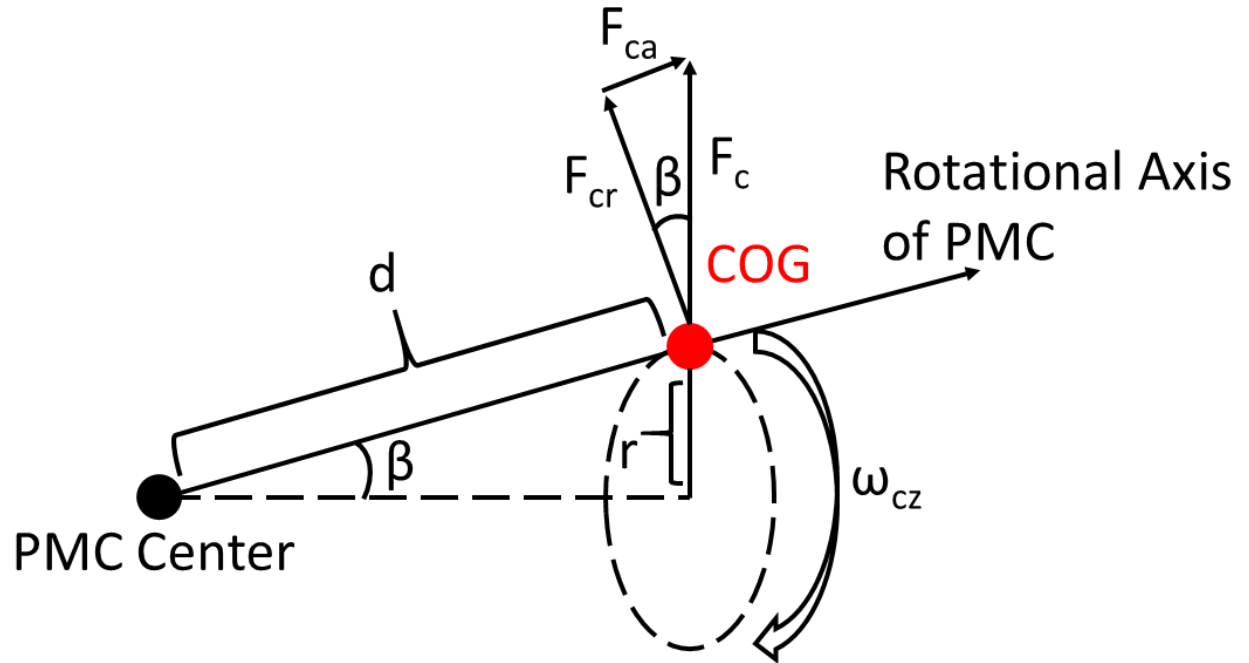
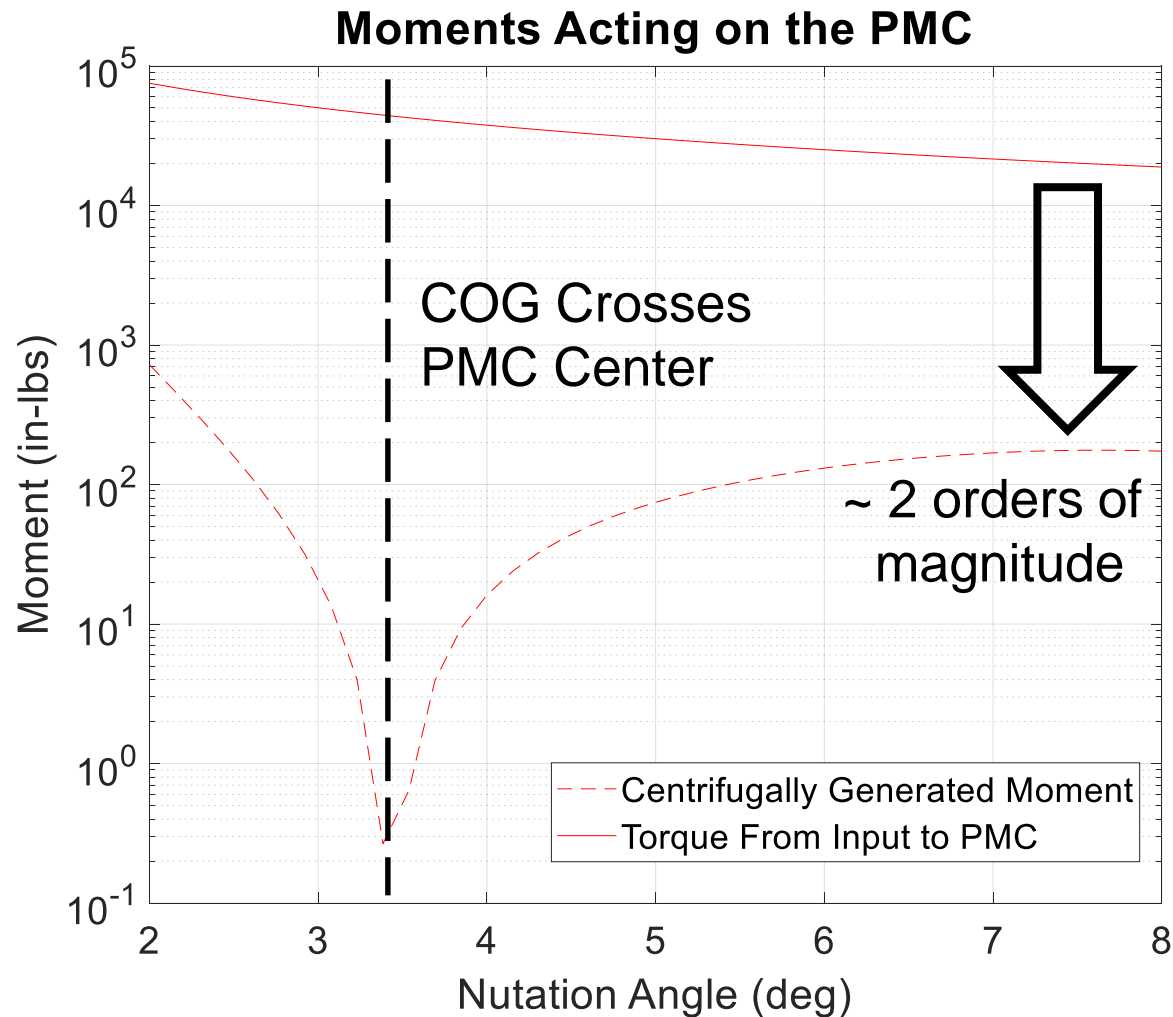
Centrifugal Force and Resulting Loads

Center of gravity offset from
PMC center has orbital motion
generating centrifugal force

$$F_c = M_{PMC} * \omega_{cz}^2 * d * \sin(\beta)$$



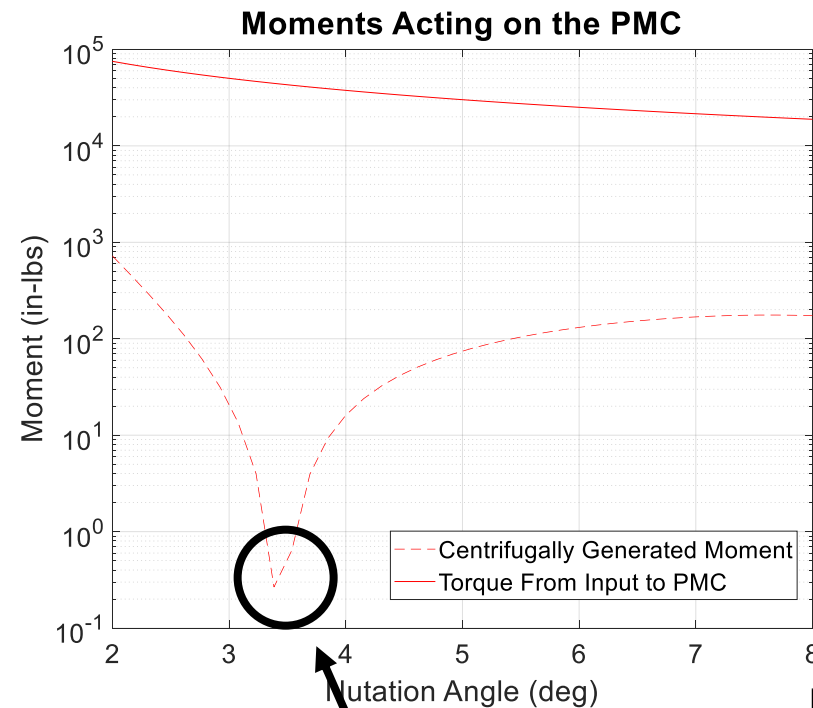
Centrifugal Force and Resulting Loads



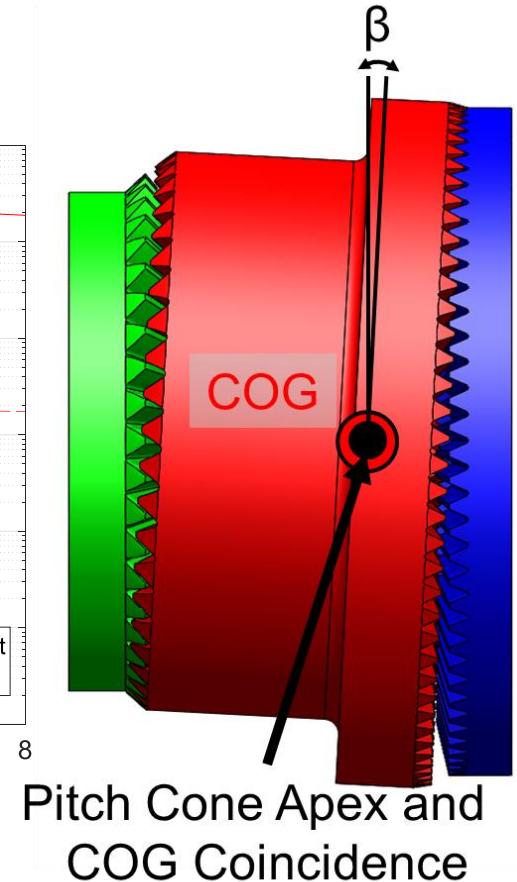
Centrifugal load in this design case is lower but should not be ignored

Limiting Centrifugal Moment

- Limiting the centrifugal loads developed can be accomplished by making the two sides of the PMC teeth numbers close in value (symmetrical)
- Altering mass of either side to center COG over pitch cone apex center
- Selection of nutation angle where COG crosses from one side of PMC to the other



Operate Here



Eliminating Gyroscopic Moment

Setting Dynamic Moment to Zero

$$0 = \begin{bmatrix} -\omega_{in}^2 * \sin(\beta) * [I_{pzz} * \left(\cos(\beta) - \left(\frac{N1}{N2} \right) \right) - I_{pyy} * \cos(\beta)] \\ 0 \\ 0 \end{bmatrix}$$

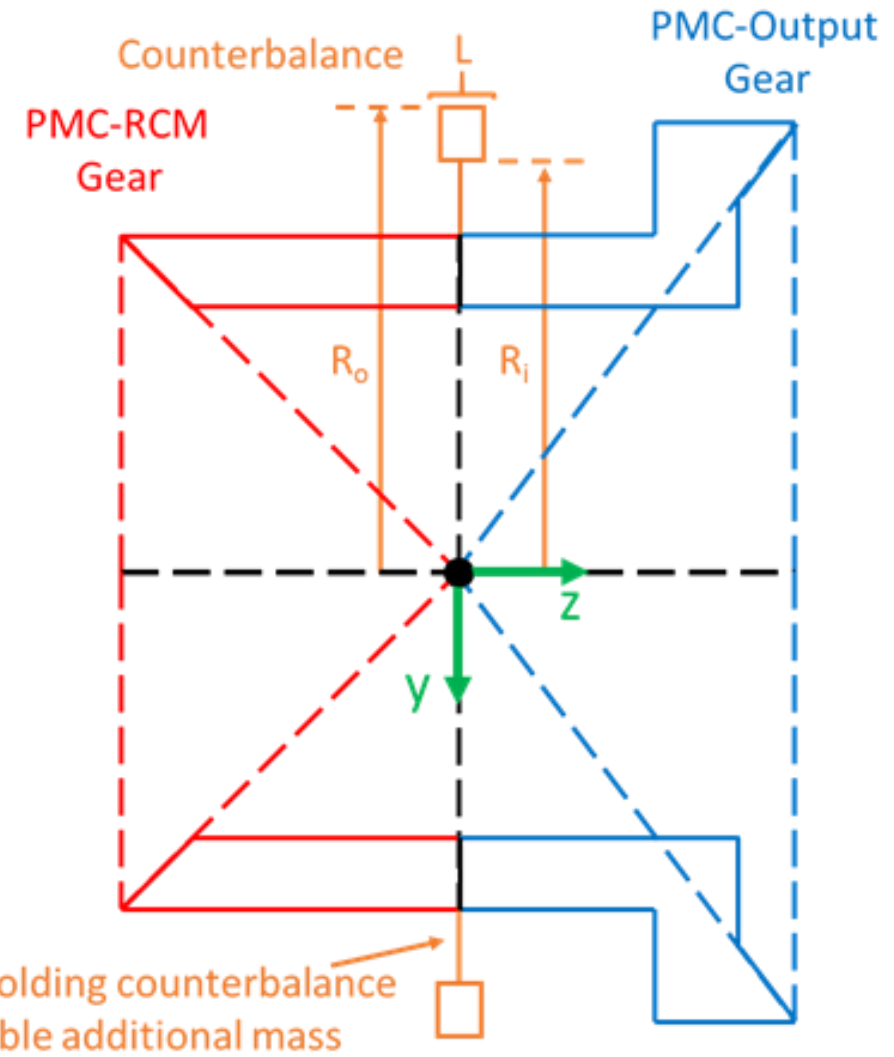
Requirements

$$(R_o^2 + R_i^2) \gg L^2$$

$$\cos(\beta) \geq \frac{1}{2}$$

$$\frac{N1}{N2} \leq \frac{1}{2}$$

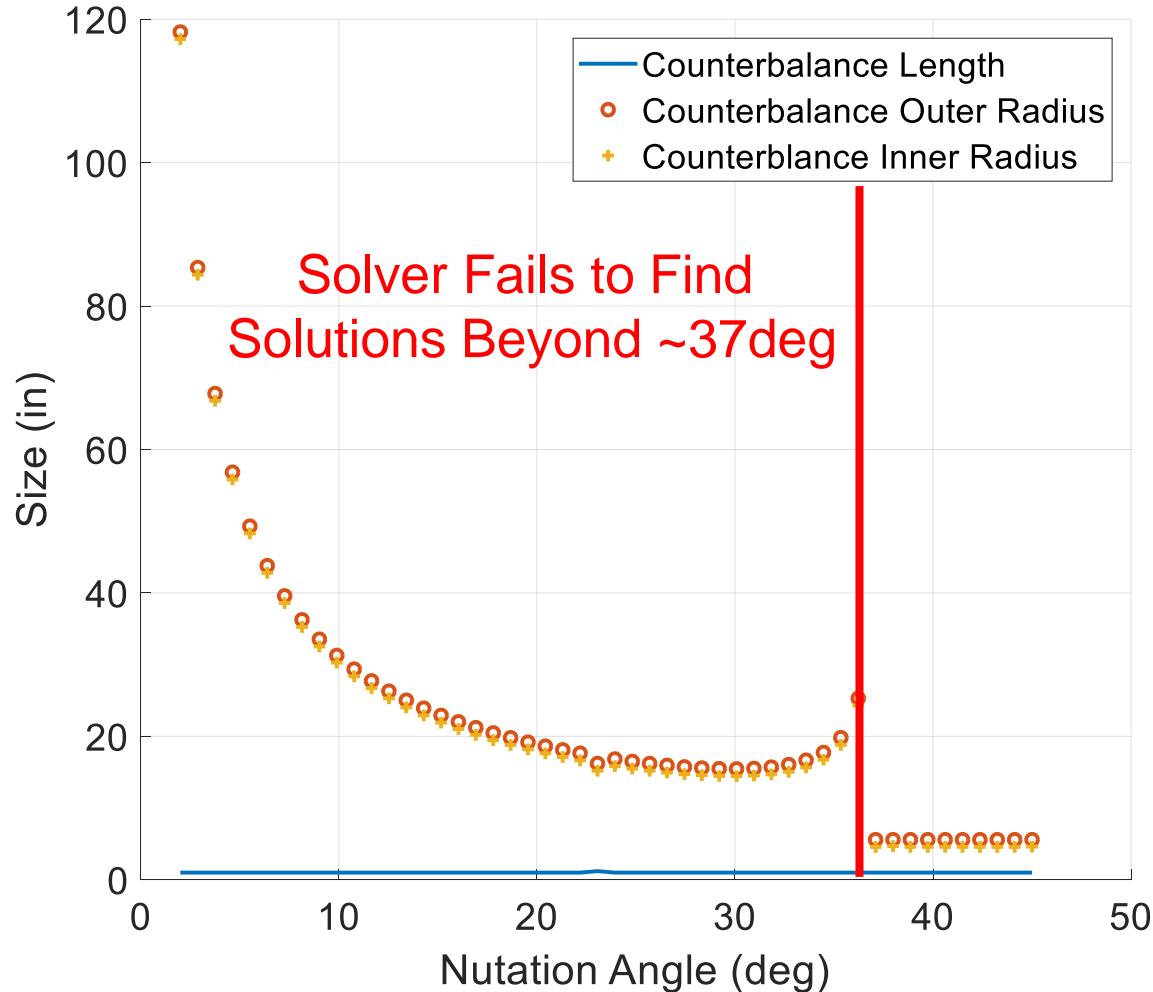
Design Variable	
Reduction Ratio	40:1
N1	30
N2	75
N3	78
N4	32
N1 / N2	0.40



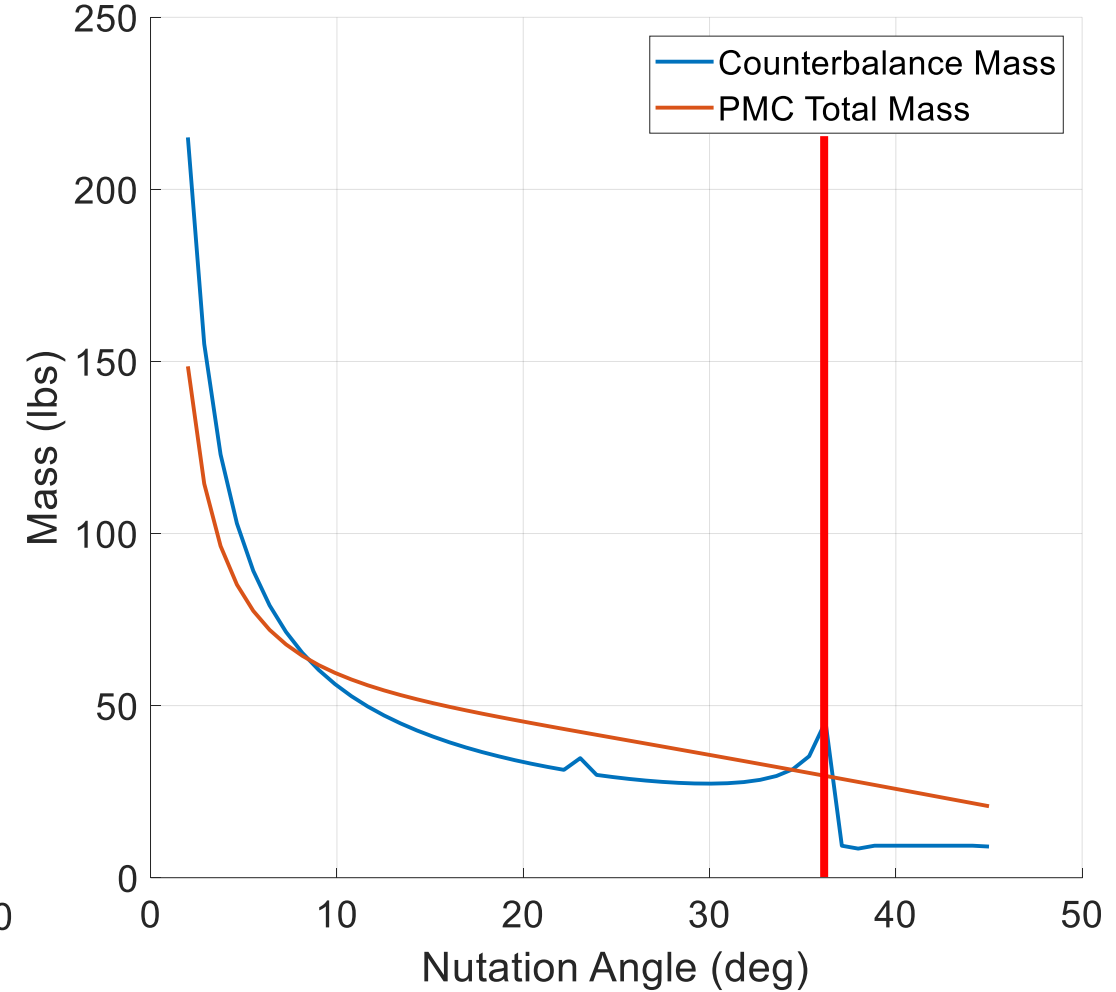
Thin support holding counterbalance with negligible additional mass

Eliminating Gyroscopic Moment

Counterbalance Dimensions



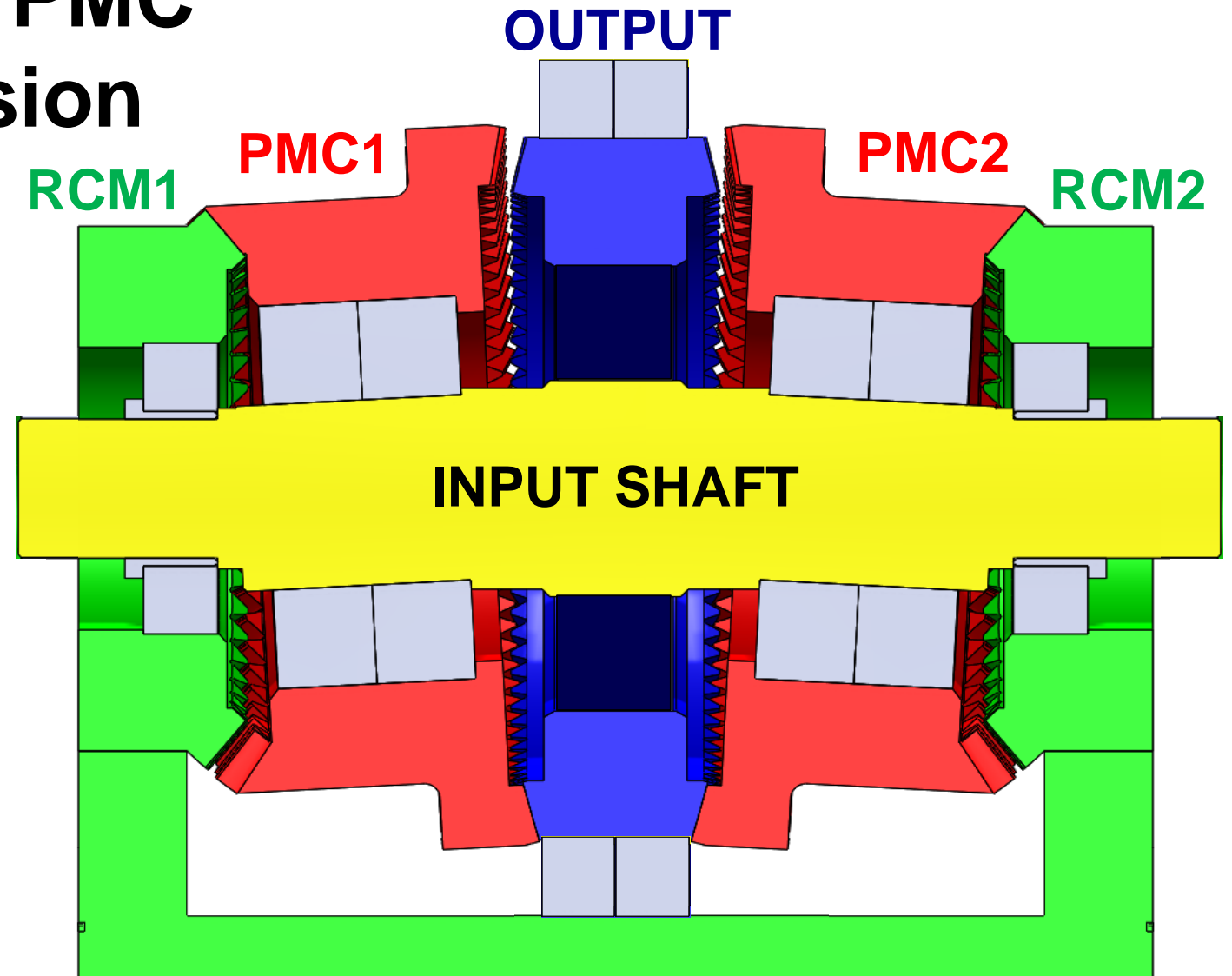
Mass of PMC and Counterbalance



Static Model of Dual Pericyclic Motion Converter Drive

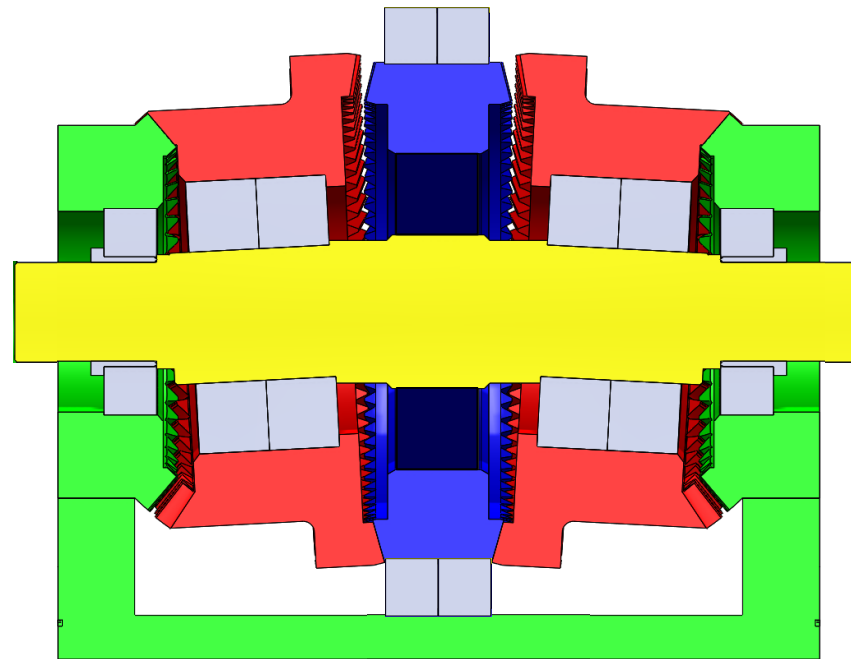
Static Model of Dual PMC Pericyclic Transmission

- Dual pericyclic mirrors components
- Splits power between two PMCs
- Each PMC has counterbalance
- PMCs designed to place COG at center



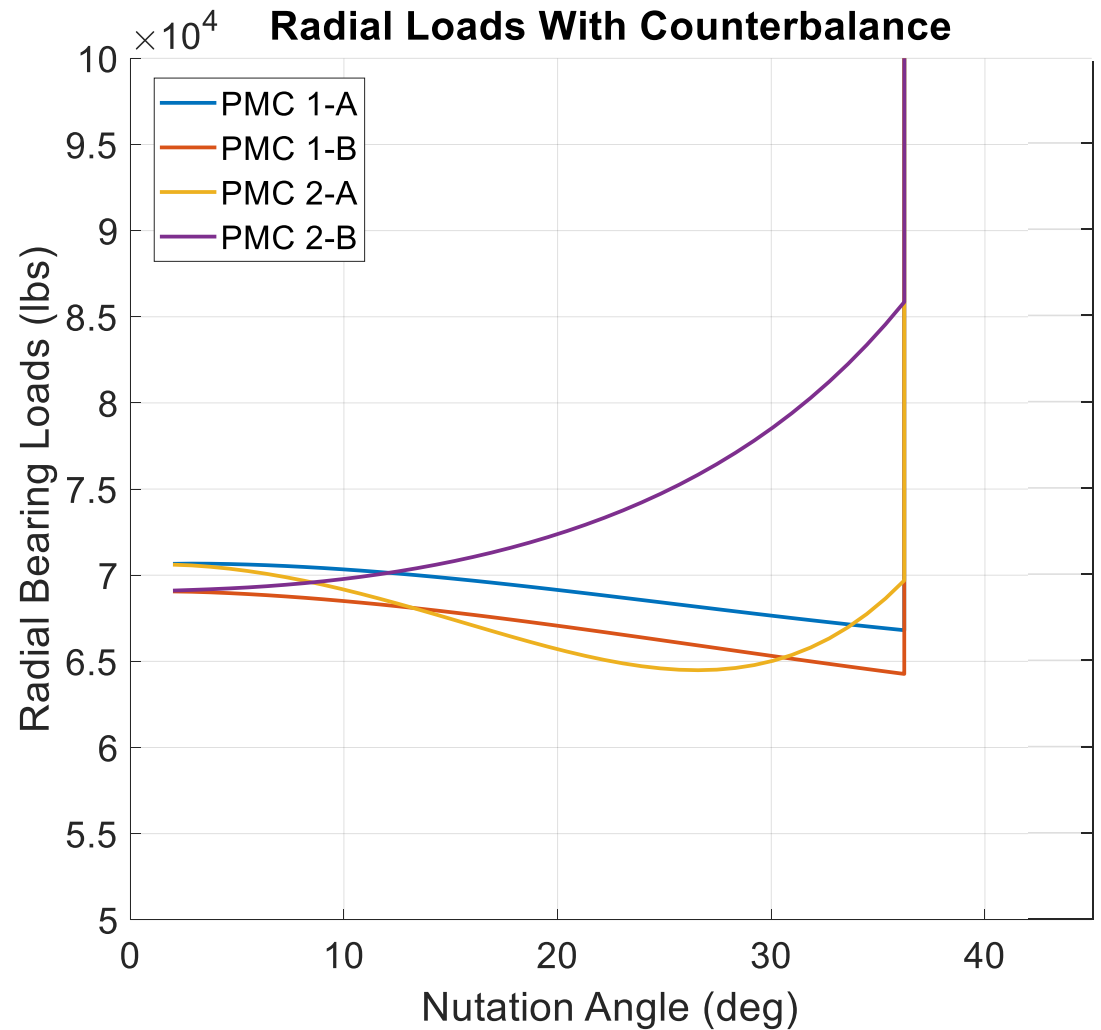
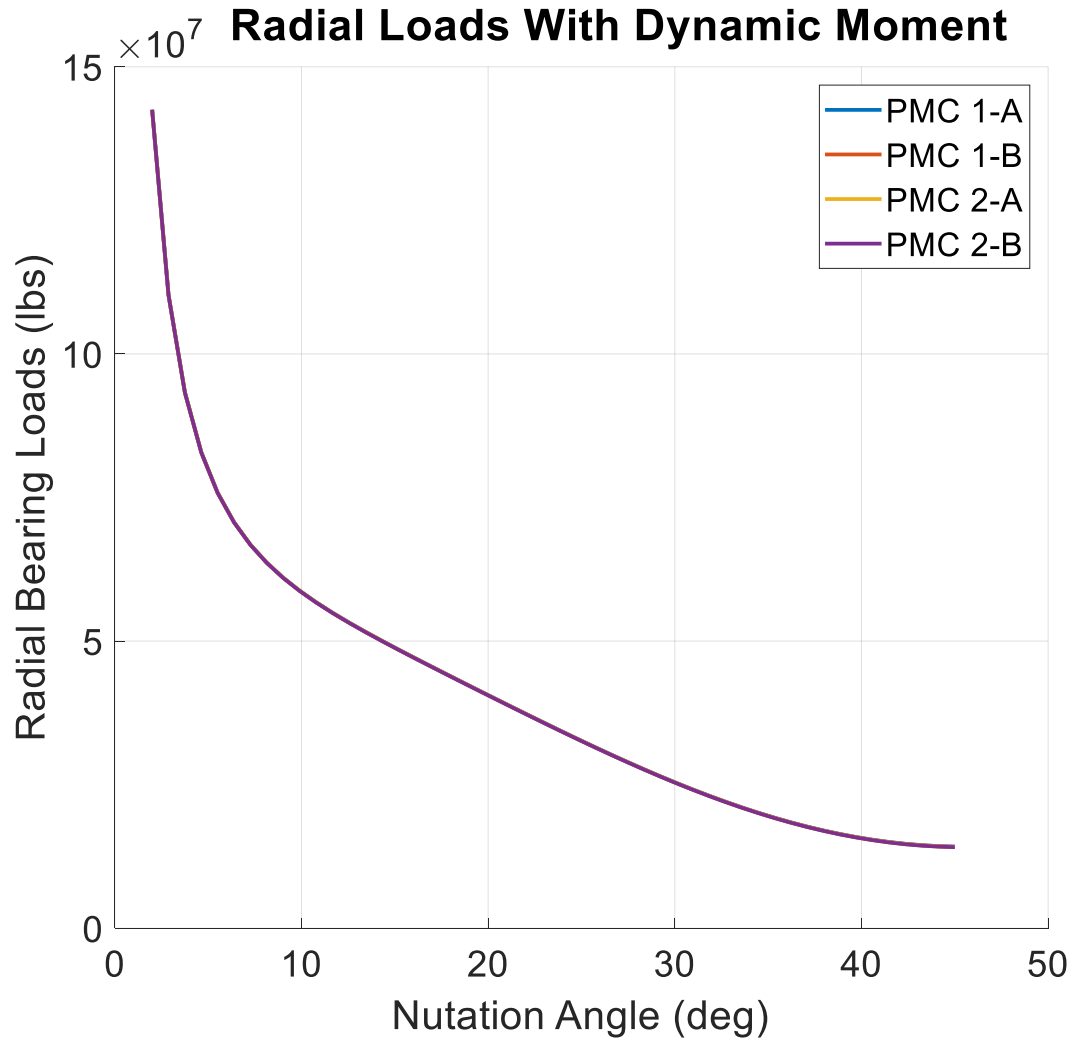
Dual PMC Model

Bearing Name	Loads Reacted	Unknowns
Input 1	Radial	2
Input 2	Radial & Axial	3
PMC 1-A	Radial	2
PMC 1-B	Radial & Axial	3
PMC 2-A	Radial	2
PMC 2-B	Radial & Axial	3
Output 1	Radial	2
Output 2	Radial	2
TOTAL		19



Design Variable	
Reduction Ratio	40:1
N1	30
N2	75
N3	78
N4	32
Input Power	1,000 HP
Input Speed	12,000 RPM

Sample Output From Static Model



Conclusions

Conclusions

- Tradeoff with increased nutation angle is decreased PMC bearing static loads for increased gear tooth loads
- Intelligent PMC design can effectively negate the PMC centrifugal loads
- The high gyroscopic moment, given **certain tooth numbers and nutation angles**, can be counterbalanced, in the case shown for as little as 60% additional mass to the PMC
- Static model of dual pericyclic developed to find loads across entire transmission and showed drop of radial loads of three orders of magnitude in the PMC bearings when counterbalanced

Questions

