Preliminary Sizing of Active Magnetic Bearings for an sCO_2 Waste-Heat Recovery Application

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Power Cycles
Symposium

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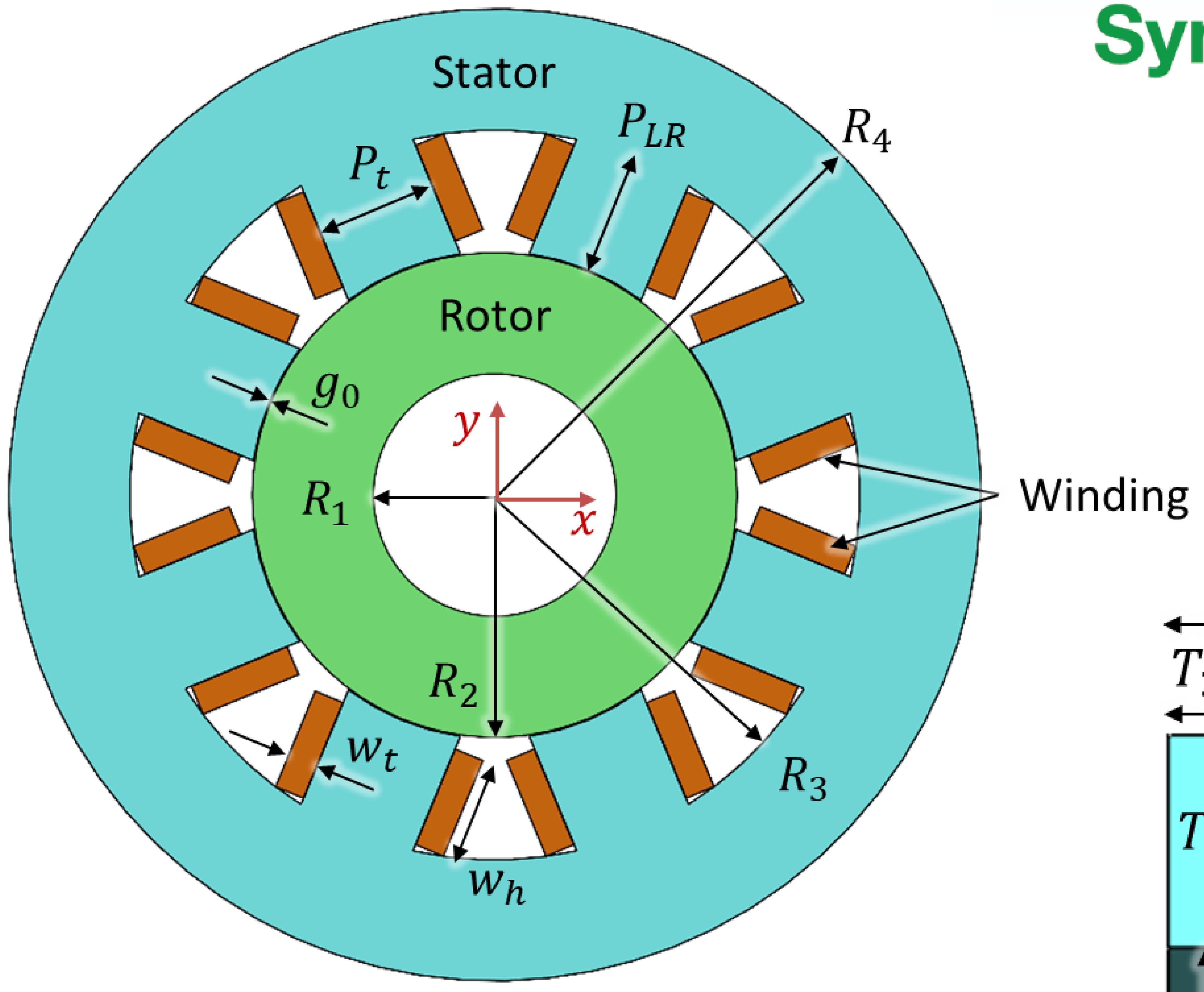

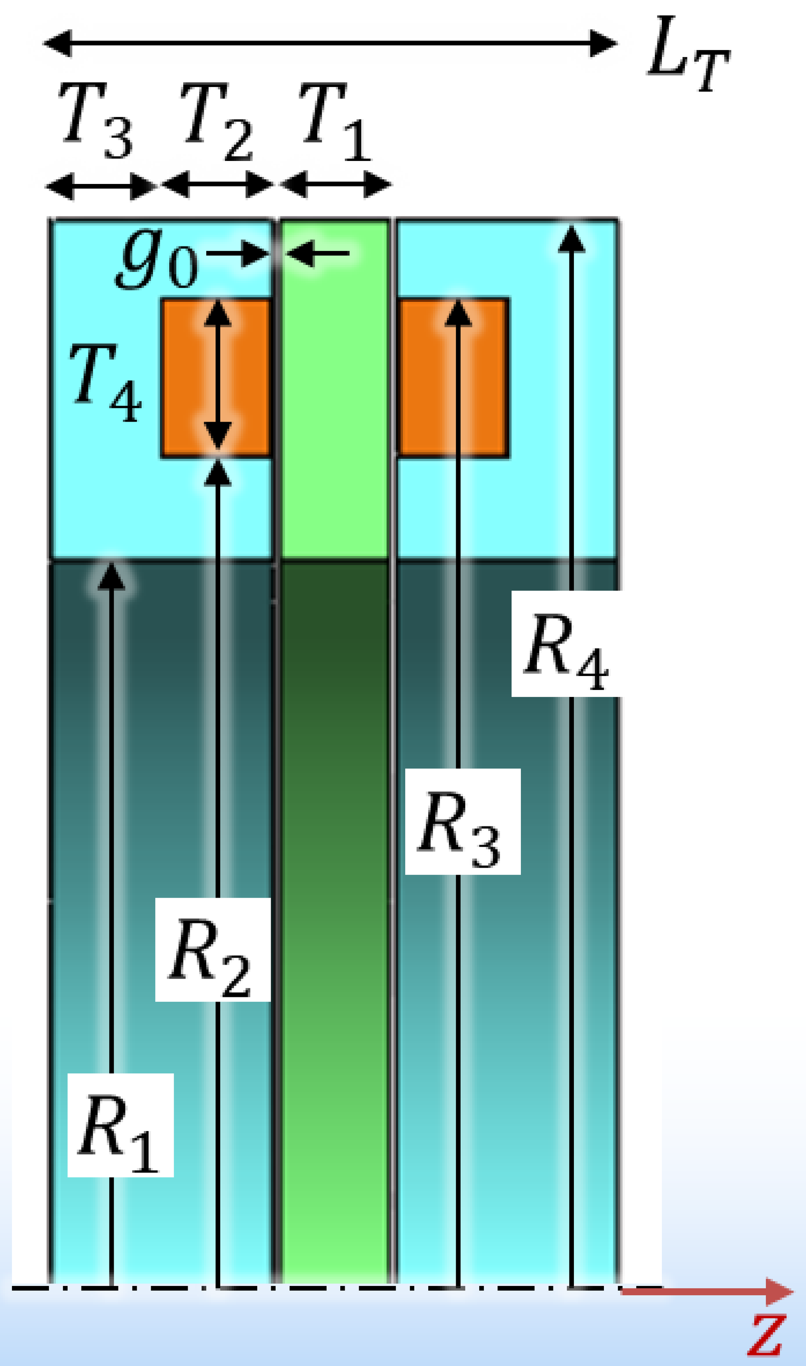

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Conceptual, hermetic sCO_2 WHR machines developed in previous study

WHR machines [12]

- High-speed (27 krpm) machine
  - 3.87 MW compressor
  - 4.83 MW turbine
  - 0.92 MWe starter/generator
- Low-speed (12 krpm) machine
  - 7.95 MW Turbine
  - 7.67 MWe generator

Both machines designed with sCO_2 gas bearings

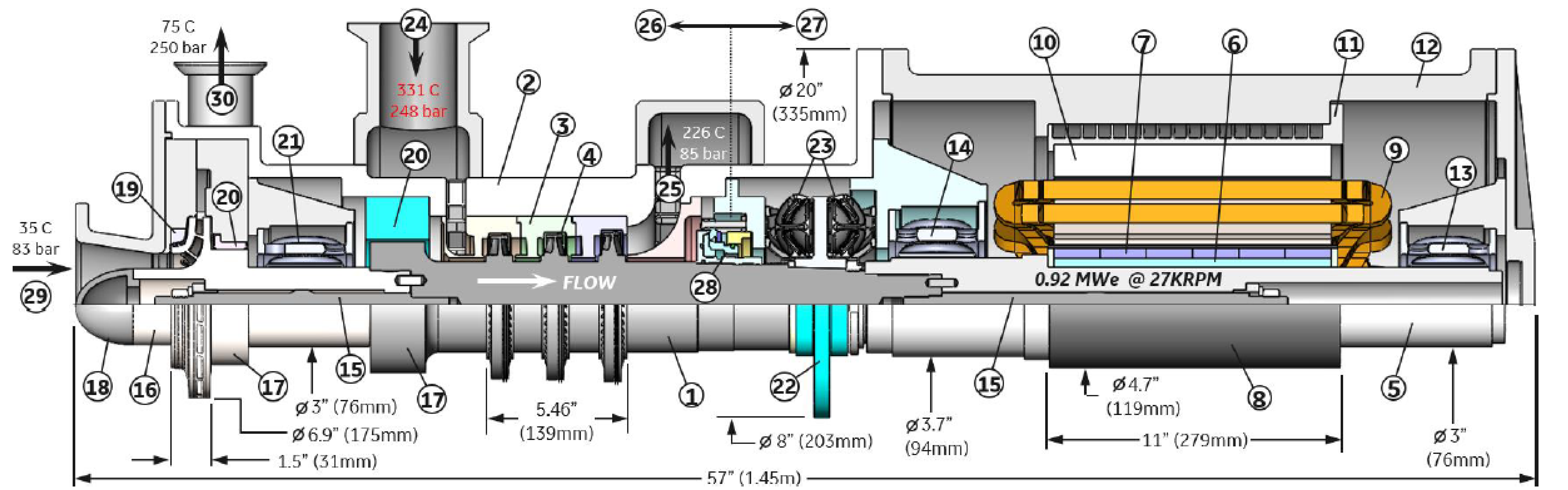
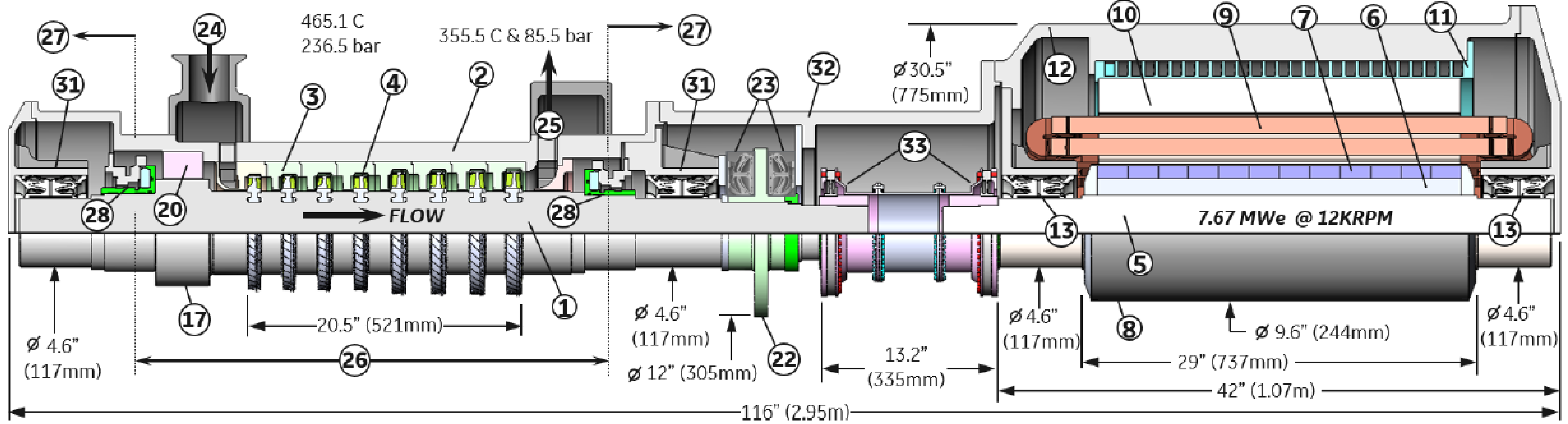


Fig 15. High-speed gas-generator 27krpm: (1) turbine shaft, (2) turbo-compressor casing, (3) turbine nozzle ring, (4) 3 stage shrouded axial turbine, (5) starter-generator (S/G) shaft, (6) laminations, (7) permanent magnet segments, (8) carbon fiber retainment sleeve, (9) armature end windings, (10) armature core, (11) cooling jacket, (12) S/G casing, (13) generator radial bearing, (14) midspan radial bearing, (15) tie rod, (16) shrouded centrifugal compressor impeller, (17) balance piston, (18) spinner cone, (19) impeller eye seal, (20) balance piston seal, (21) compressor-end bearing, (22) thrust runner, (23) thrust bearing system, (24) turbine inlet, (25) turbine exhaust, (26) high pressure zone, (27) lower pressure zone, (28) thin-film riding seal, (29) compressor suction, (30) compressor discharge



[12] Ertas, B, Zierer, J, McClung, A, Torrey, D, Bidkar, RA, Hofer, D, Rallabandi, V, Singh, R, & Zhang, X. "Super-Critical Carbon Dioxide Power Cycle for Waste Heat Recovery Utilizing Hermetic Oil-Free Turbomachinery: Cycle and Conceptual Turbomachinery Design." Proceedings of the ASME Turbo Expo 2023: Turbomachinery Technical Conference and Exposition. Volume 12: Supercritical CO_2. Boston, Massachusetts, USA. June 26–30, 2023. V012T28A033. ASME

Goal: To develop conceptual designs for these machines with active magnetic bearings (AMBs)

Why?

- AMBs allow greater control of rotordynamics
- AMBs can operate at zero speed and zero process-gas pressure

Challenges

- High-temperature performance
- sCO_2 compatibility

Outputs of design process

- Bearing sizing
- AMB dynamic coefficients
- Rotordynamics analysis
- Target AMB closed-loop stiffness and damping values

The AMB design process is iterative

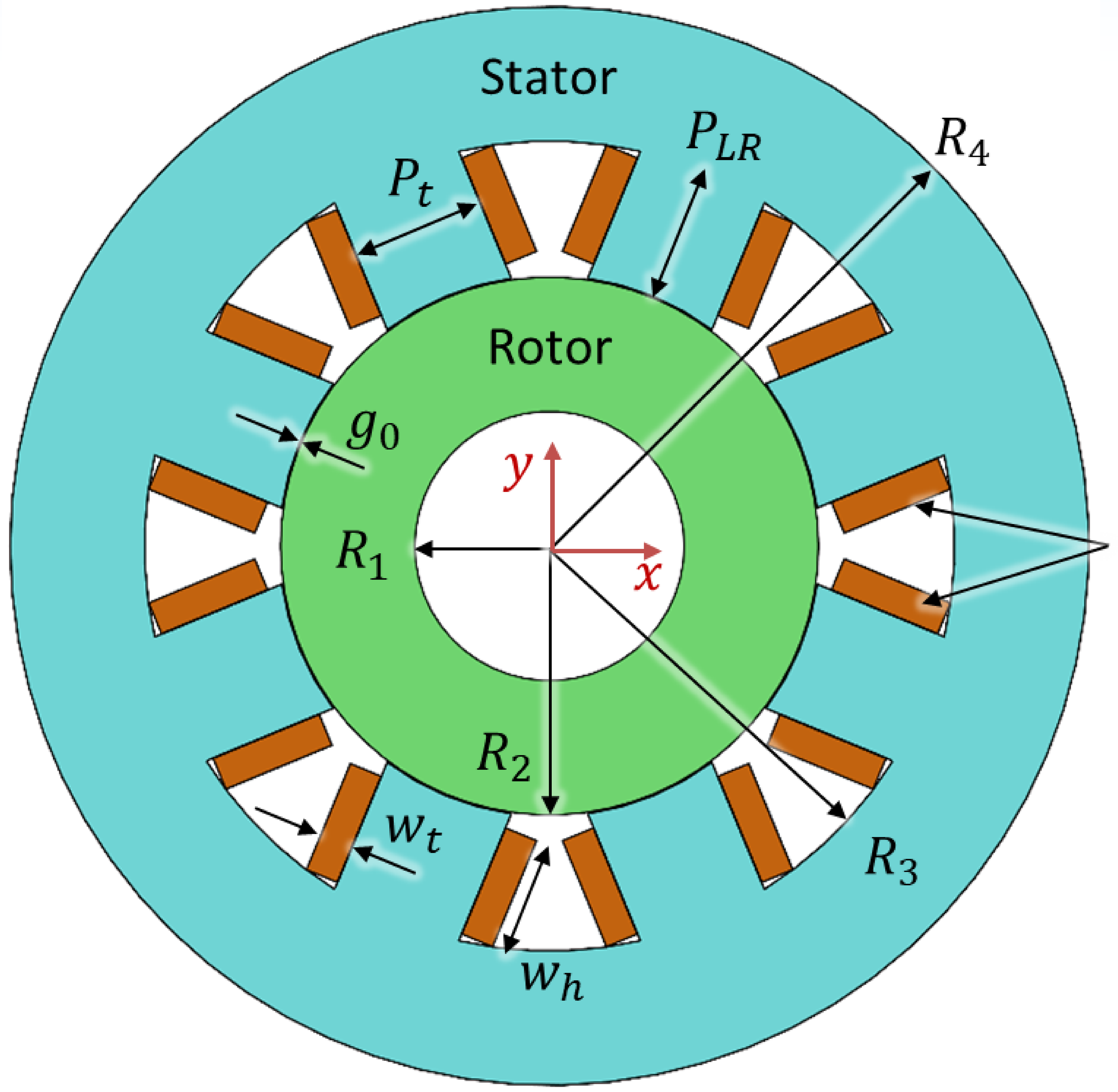
AMB load requirements

$$F_{Total} = F_{Static} + F_{Dynamic}$$

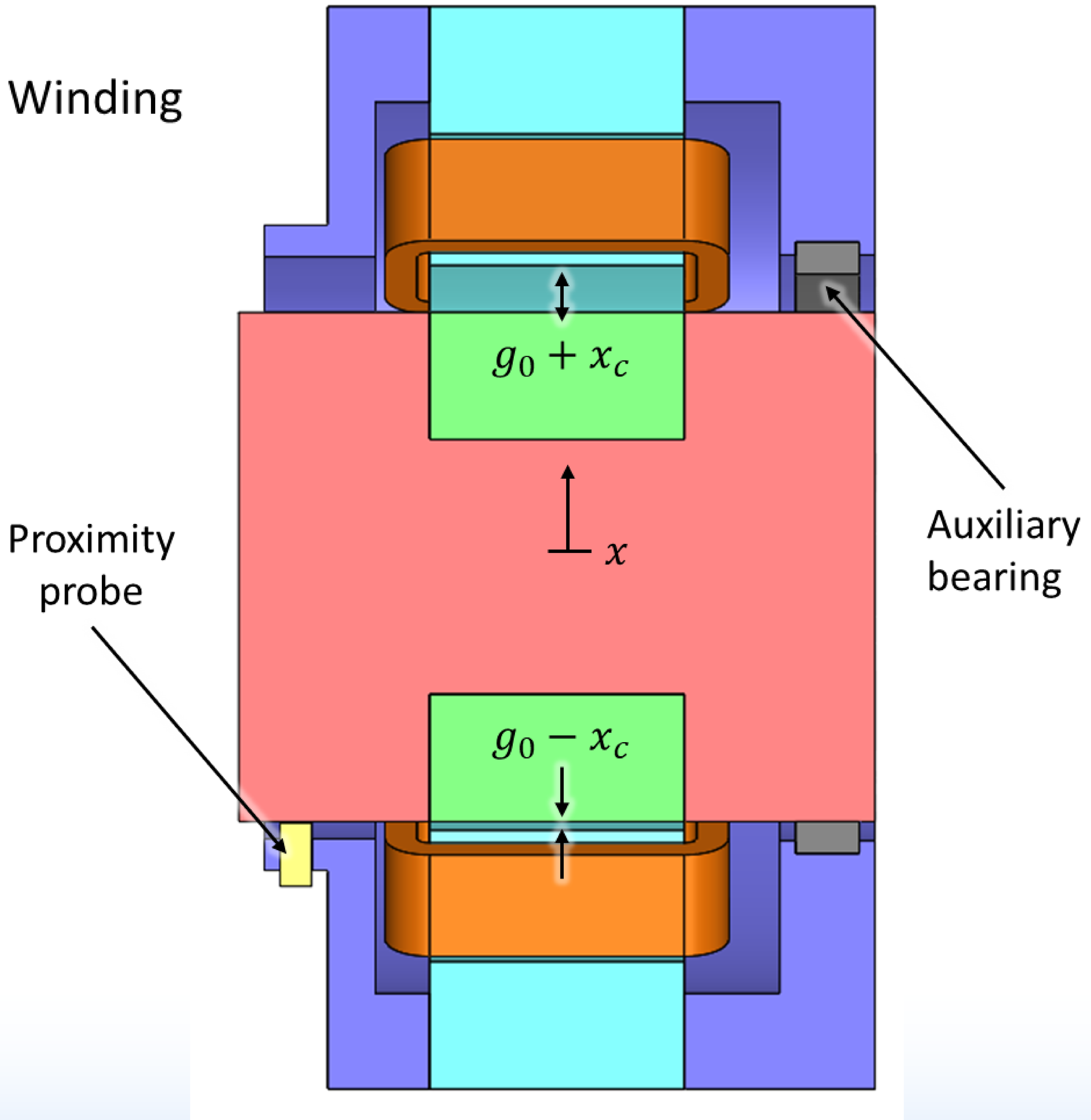
AMB	F_{Static}	$F_{Dynamic}$
Radial	System Req.	F_{static}
Thrust		0

Machine	Bearing	Load Requirement	
		Static [lbf]	Total [lbf]
High-speed machine (27 krpm)	HS compressor	69	138
	HS thrust	2000	2000
	HS midspan	73	146
	HS generator	39	78
Low-speed machine (12 krpm)	LS turbine NDE	179	358
	LS turbine DE	289	578
	LS thrust	3500	3500
	LS generator DE	354	708
	LS generator NDE	320	640

Radial AMB design is focused on center and liftoff forces



$$F_x = \frac{\mu_0 A_R N^2 \cos(\theta)}{4}\left(\frac{(I_b + I_c)^2}{(g_0 - x\cos(\theta))^2} - \frac{(I_b - I_c)^2}{(g_0 + x\cos(\theta))^2}\right)$$



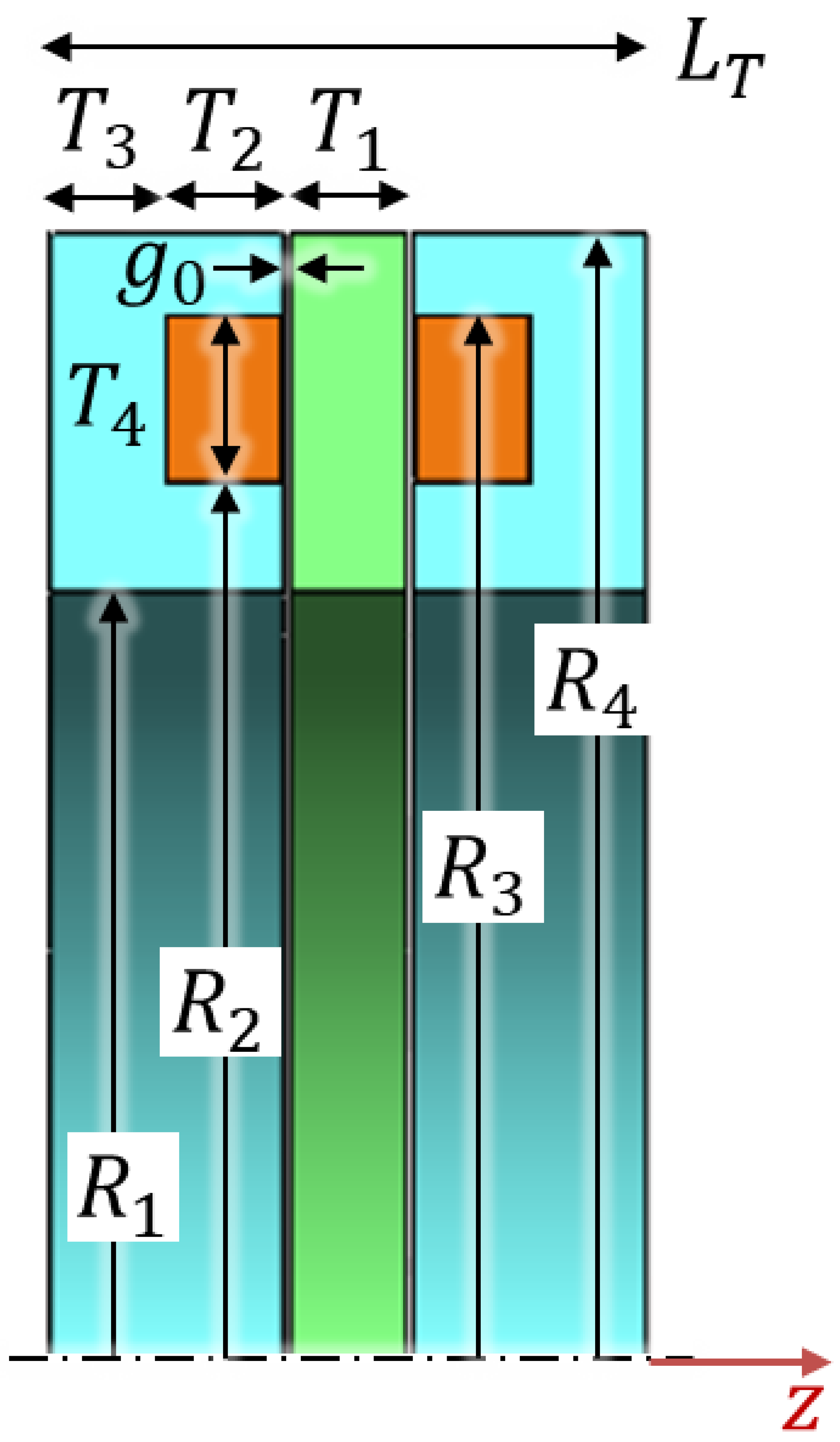
$$I_{max} \triangleq \frac{2 g_0 B_{sat}}{\mu_0 N}$$

$$I_b \triangleq \frac{1}{2} I_{max}$$

$$F_{x,c} = \frac{\mu_0 A_R N^2 I_{max}^2 \cos(\theta)}{4 g_0^2}$$

$$F_{x,L} = \frac{\mu_0 A_R N^2 I_{max}^2 \cos(\theta)}{4(g_0 + x_c \cos(\theta))^2}$$

Thrust AMB design is focused on center force



$$F_z = \frac{\mu_0 A_T N^2}{4}\left(\frac{(I_b + I_c)^2}{(g_0 - z)^2} - \frac{(I_b - I_c)^2}{(g_0 + z)^2}\right)$$

$$I_{max} \triangleq \frac{2 g_0 B_{sat}}{\mu_0 N}$$

$$I_b \triangleq \frac{1}{2} I_{max}$$

$$F_{z,c} = \frac{\mu_0 A_T N^2 I_{max}^2}{4 g_0^2}$$

AMB dynamic components drive controller development

$$F_x \cong K_p \mathrm{x} + K_I I_c$$

$$V = L\frac{dI_c}{dt} + R(I_b + I_c)$$

AMB	K_p	K_I	L
Radial	$\frac{\mu_0 A_R N^2 I_b^2 \cos^2(\theta)}{g_0^3}$	$\frac{\mu_0 A_R N^2 \cos(\theta) I_b}{g_0^2}$	$\frac{\mu_0 A_R N^2}{2g}$
Thrust	$\frac{\mu_0 A_T N^2 I_b^2}{g_0^3}$	$\frac{\mu_0 A_T N^2 I_b}{g_0^2}$	$\frac{\mu_0 A_T N^2}{2g_0}$

AMB load requirements drive sizing

$$F_{x,c} = \frac{\mu_0 A_R N^2 I_{max}^2 \cos(\theta)}{4g_0^2}$$

$$F_{x,L} = \frac{\mu_0 A_R N^2 I_{max}^2 \cos(\theta)}{4(g_0 + x_c \cos(\theta))^2}$$

$$F_{z,c} = \frac{\mu_0 A_T N^2 I_{max}^2}{4g_0^2}$$

AMB Type	Load requirement
Radial	$F_{x,c} > F_{Total}$
	$F_{x,L} > F_{Static}$
Thrust	$F_{z,c} > F_{Total}$

Hiperco® 50 selected for AMB magnetic materials

Need good magnetic properties at 1000 °F

Hiperco® 50

- FeCoVn alloy
- Curie point: ~1700 °F
- Maintains good saturation flux density and permeability at 1000 °F

Properties do change with temperature

Saturation flux density

- 2.3 T @ 73 °F
- 1.9 T @ 1000 °F

$$F \propto B_{sat}^2$$

∴ 17% decrease in B_{sat} → 32% decrease in Force

AMB sizing efforts provide shaft geometry requirements

Machine	Bearing	Static			Total		
		Req [lbf]	F_L [lbf]	SF	Req [lbf]	F_c [lbf]	SF
High-speed machine (27 krpm)	HS compressor	69	154	**2.2**	138	236	**1.7**
	HS thrust	N/A	N/A	**N/A**	2000	2,670	**1.3**
	HS midspan	73	193	**2.6**	146	295	**2.0**
	HS generator	39	154	**4.0**	78	236	**3.0**
Low-speed machine (12 krpm)	LS turbine NDE	179	289	**1.6**	358	442	**1.2**
	LS turbine DE	289	382	**1.3**	578	583	**1.0**
	LS thrust	N/A	N/A	**N/A**	3500	3,640	**1.0**
	LS generator DE	354	475	**1.3**	708	725	**1.0**
	LS generator NDE	320	475	**1.5**	640	725	**1.1**

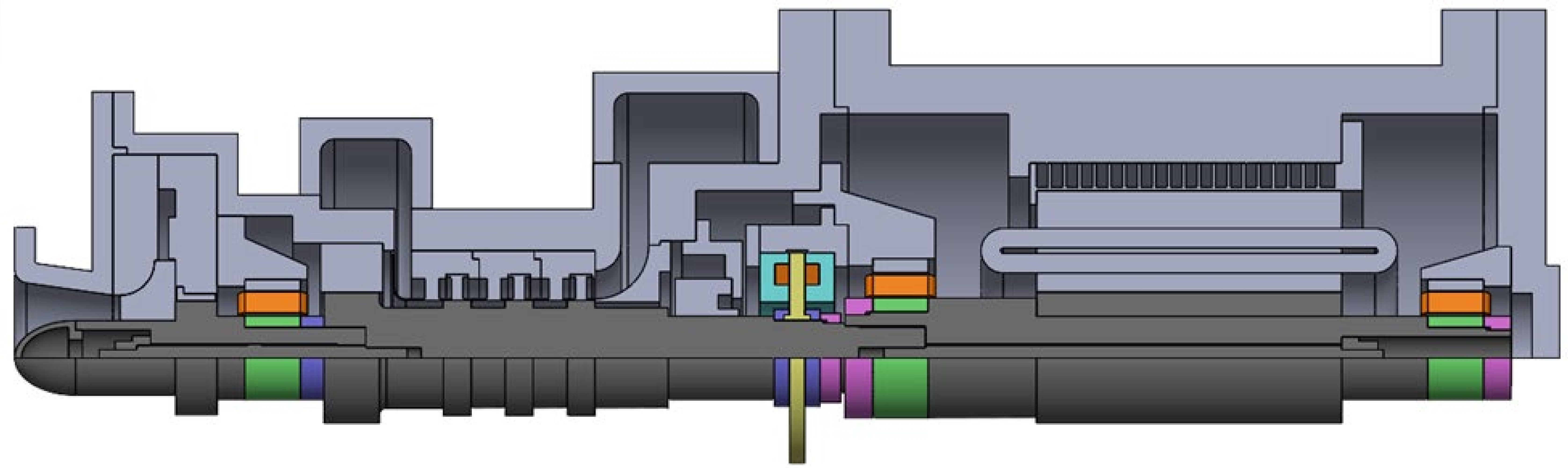
AMB dynamic coefficients show room for further optimization

Machine	Bearing	K_p [lbf/in]	K_I [lbf/A]	I_b [A]	L [mH]
High-speed machine (27 krpm)	HS compressor	11,100	49.1	4.8	12.3
	HS thrust	134,000	506	5.3	108
	HS midspan	13,900	61.4	4.8	15.3
	HS generator	11,100	49.1	4.8	12.3
Low-speed machine (12 krpm)	LS turbine NDE	20,800	138	3.2	51.7
	LS turbine DE	27,500	182	3.2	68.3
	LS thrust	182,000	689	5.3	147
	LS generator DE	34,200	226	3.2	84.8
	LS generator NDE	34,200	226	3.2	84.8

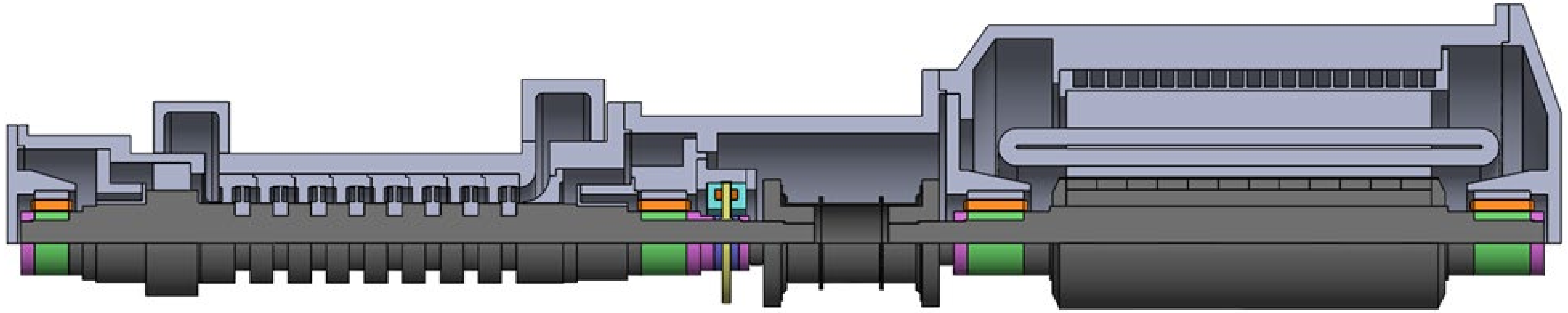
Preliminary rotordynamics models developed to validate shaft geometry

	Mode	Freq. [cpm]	Target Freq. [cpm]	Percent Difference	Mode Type
High-speed machine (27 krpm)	1	6,962.3	7,041.9	–1.1%	Cylindrical
	2	8,956.9	9,047.9	–1.0%	Conical
	3	15,233.4	17,122.9	–11%	1st Bending
	4	35,821.1	3,5841.4	–0.1%	2nd Bending
Low-speed turbine (12 krpm)	1	5,690.8	5,661.9	0.5%	Cylindrical
	2	7,769.0	7,332.3	0.5%	Conical
	3	15,311.6	15,240.6	0.5%	1st Bending
Low-speed generator (12 krpm)	1	4,034	4,020	–0.3%	Cylindrical
	2	7,193	7,593	5.6%	Conical
	3	23,029	24,581	6.7%	1st Bending

WHR machine designs modified for AMBs

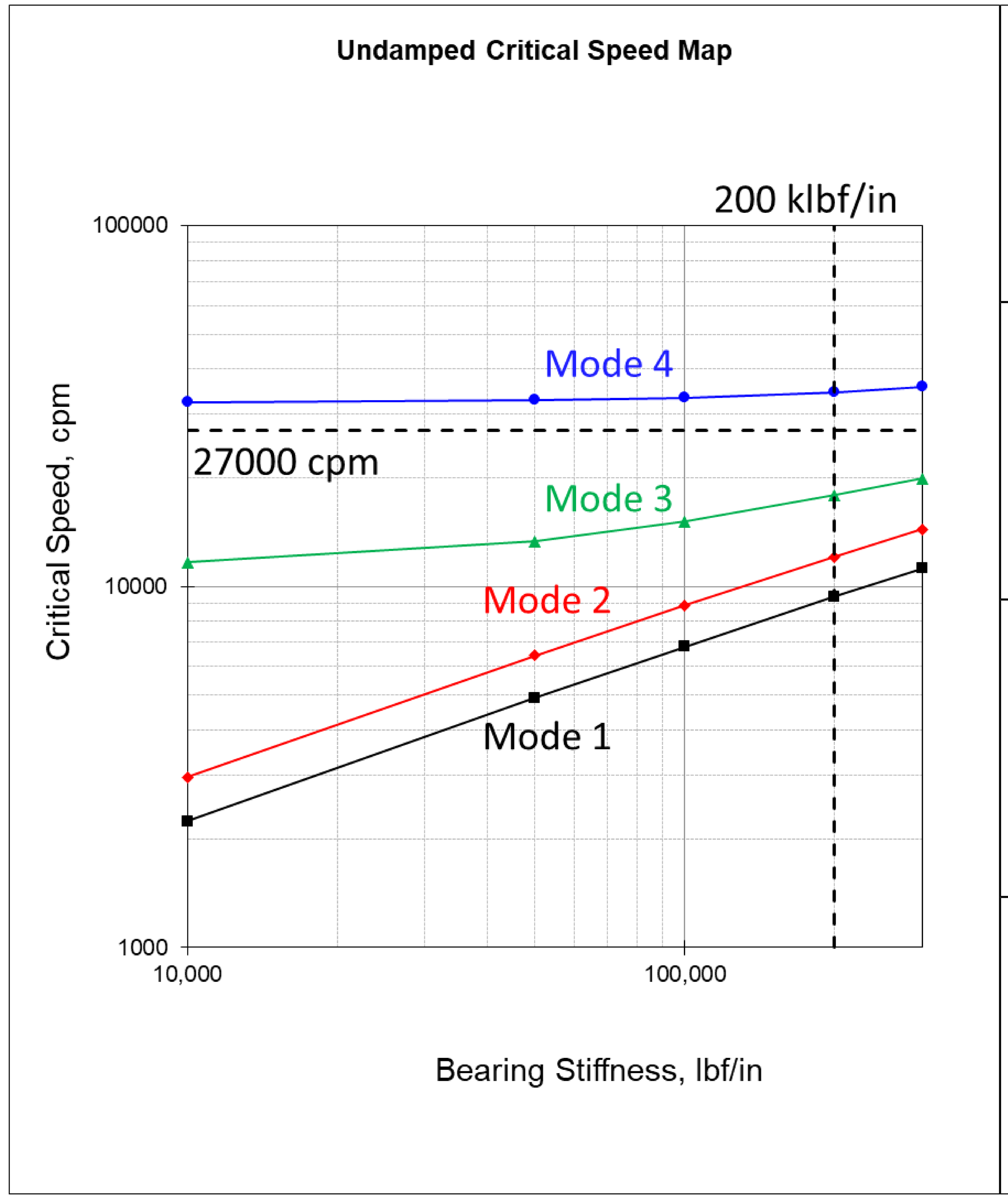


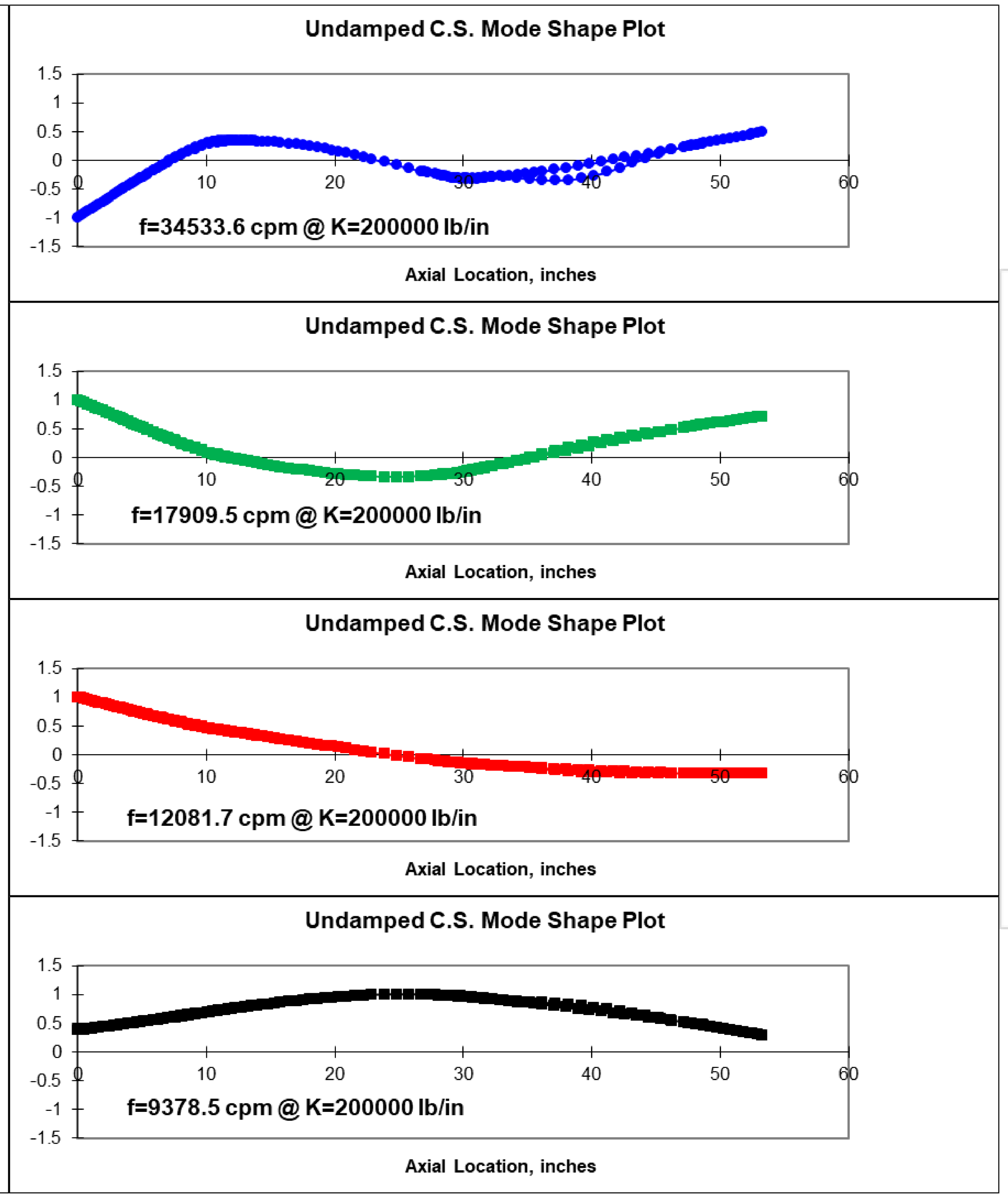
High-speed machine (27 krpm) with AMBs

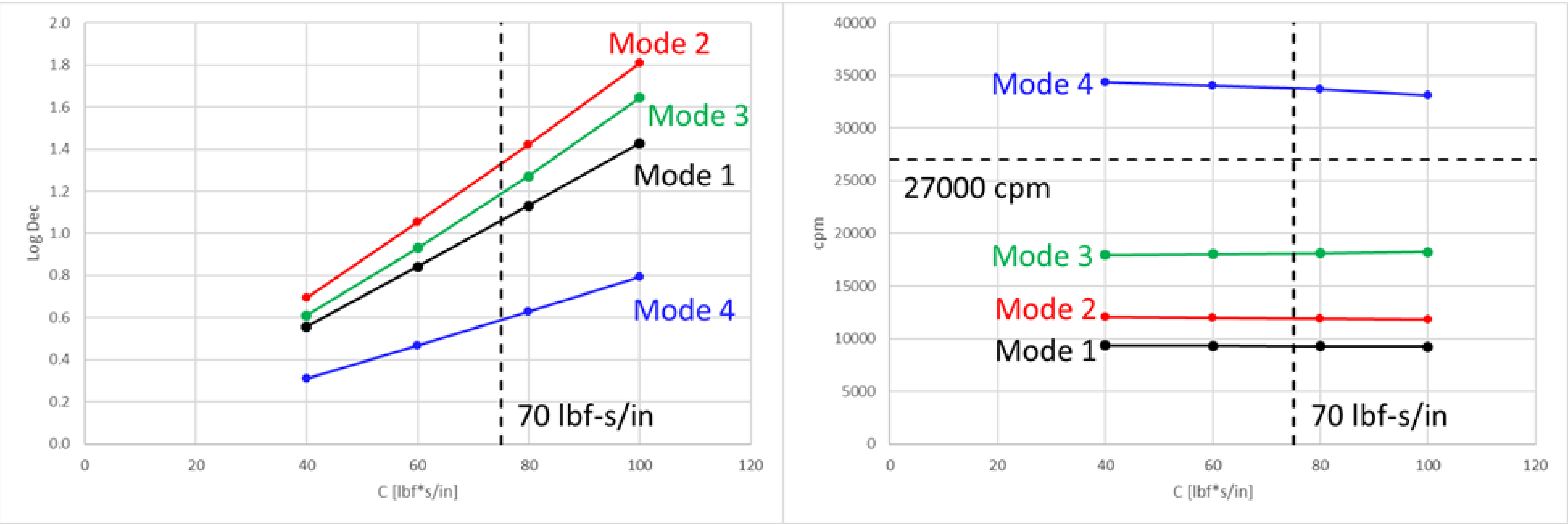


Low-speed machine (12 krpm) with AMBs

AMB rotordynamics: High-speed machine (27 krpm)

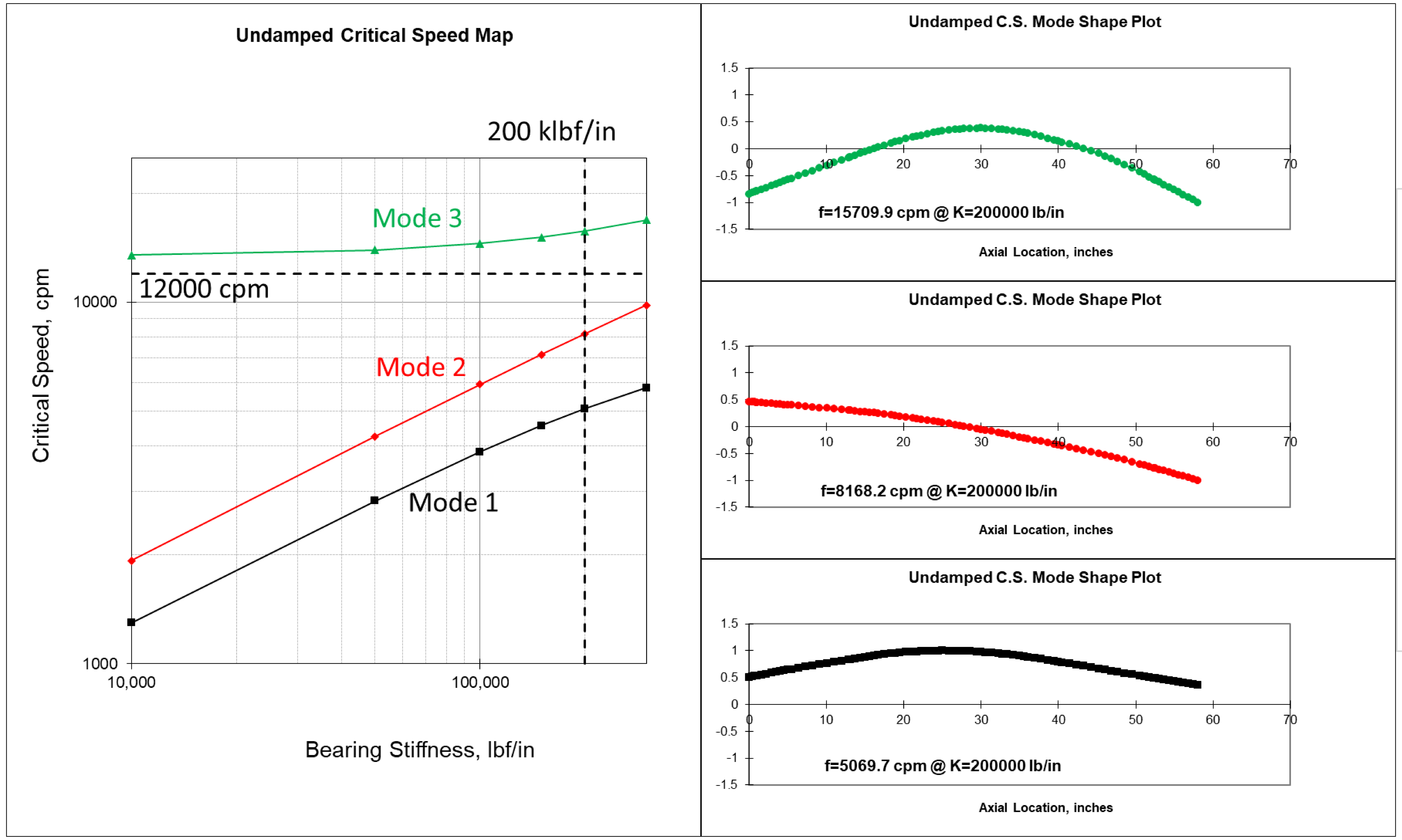


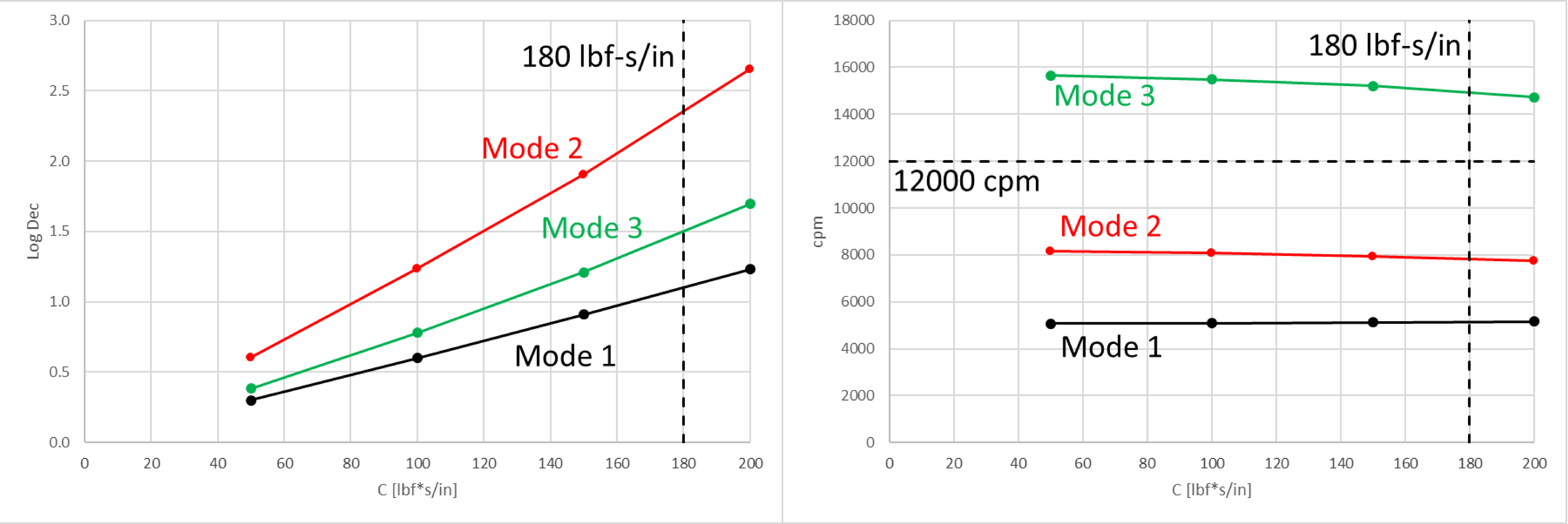




CL Stiffness	CL Damping	Damped SM
200,000 lbf/in	70 lbf-s/in	25.0%

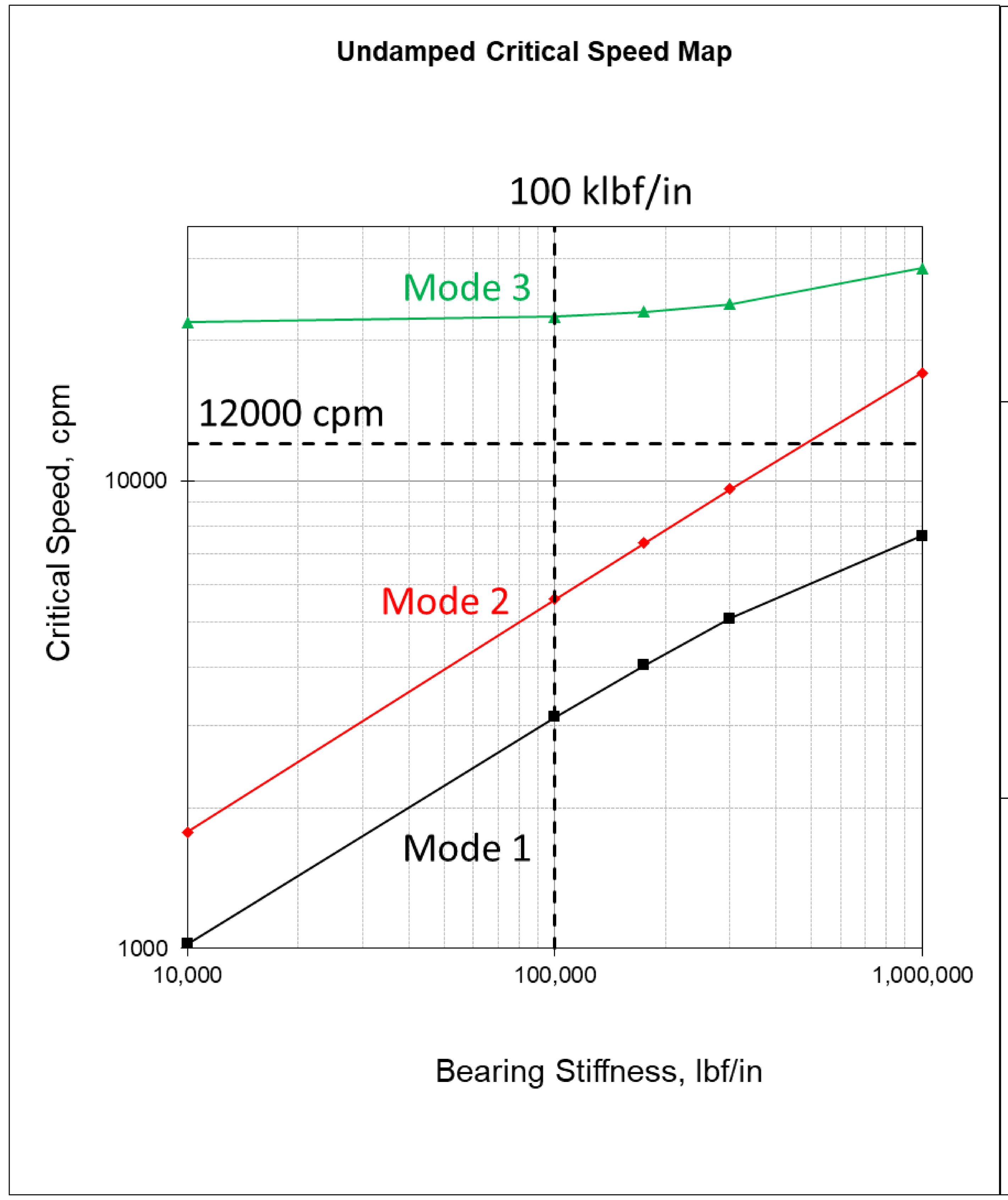
AMB rotordynamics: Low-speed turbine (12 krpm)

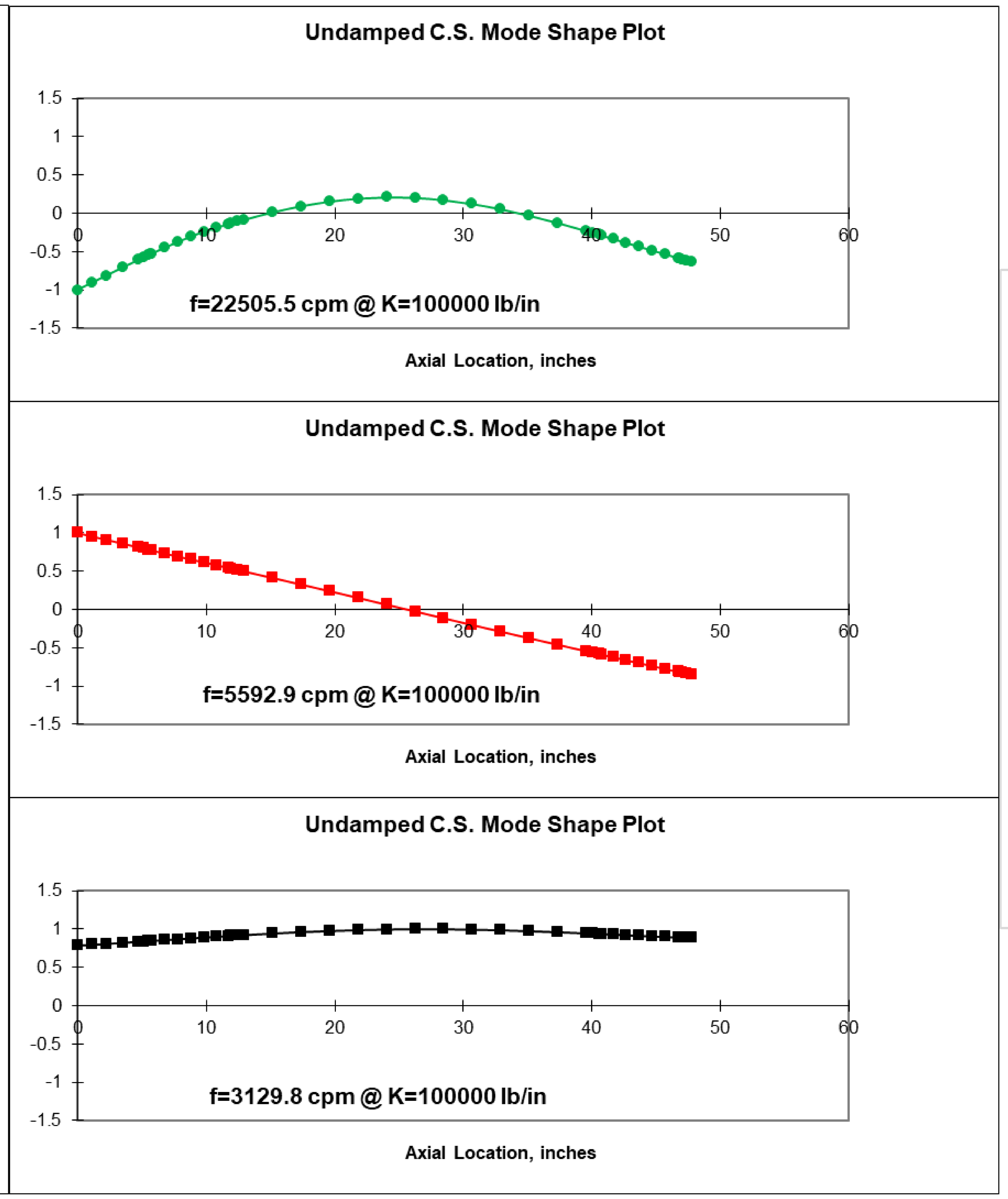


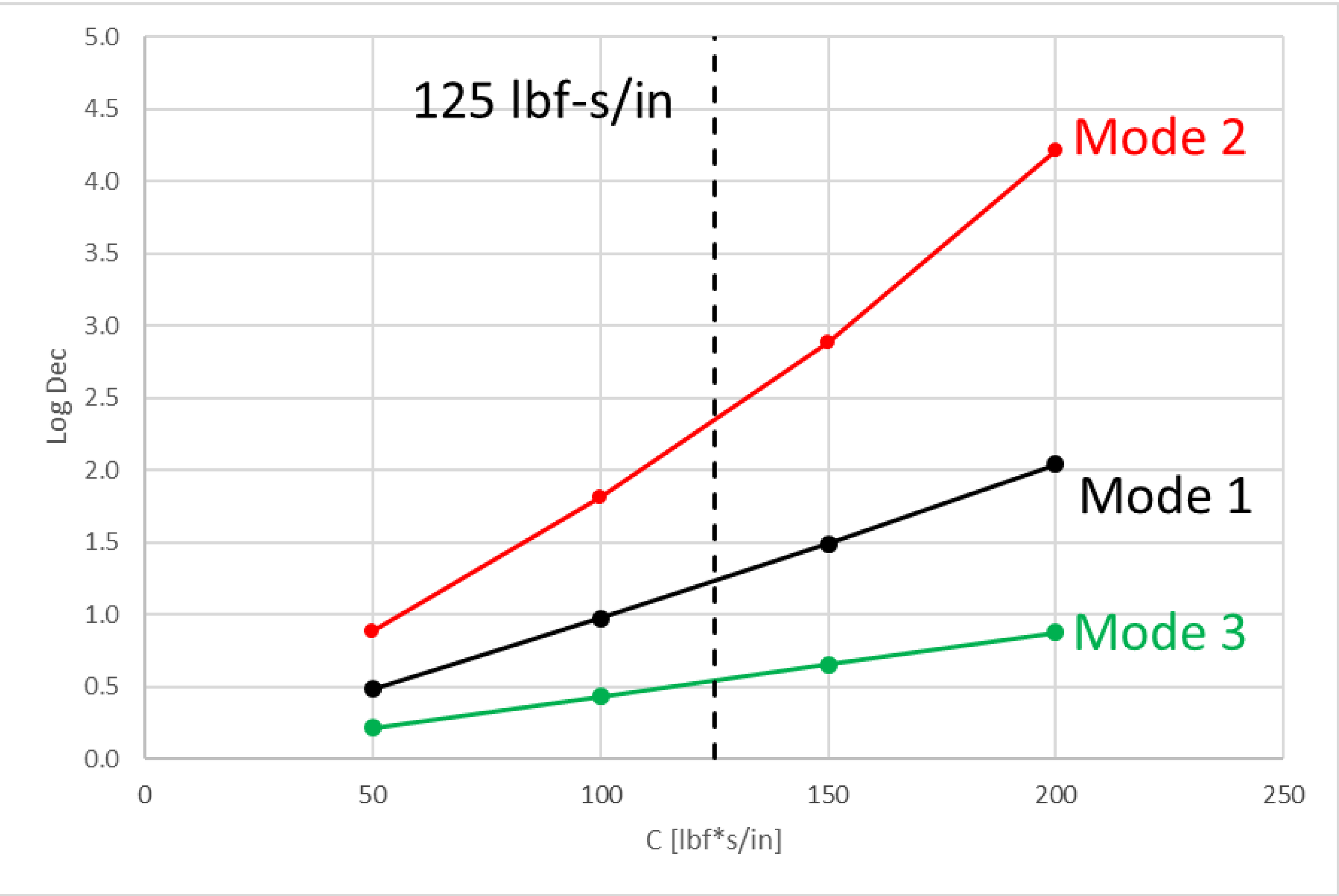


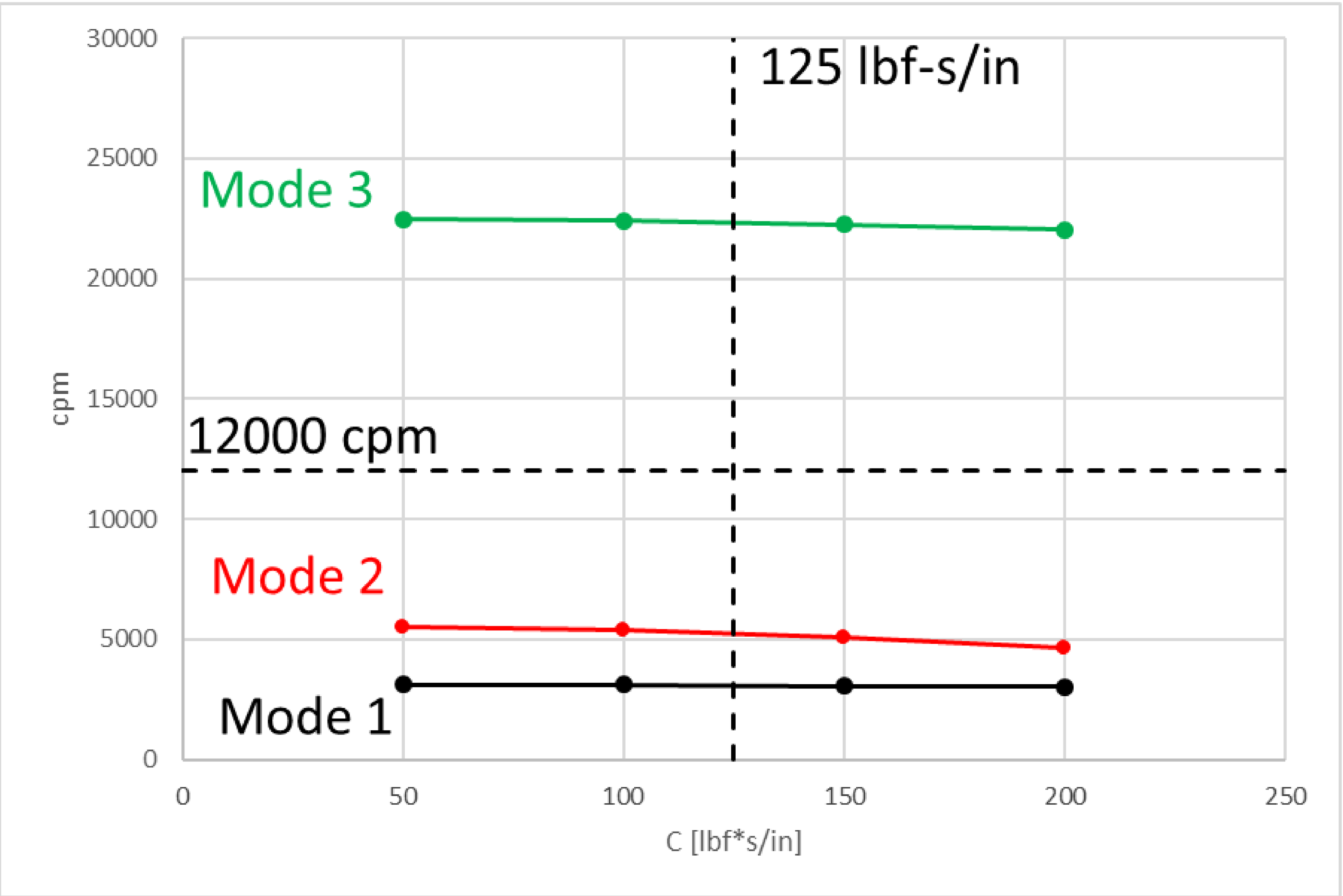
CL Stiffness	CL Damping	Damped SM
200,000 lbf/in	180 lbf-s/in	25.2%

AMB rotordynamics: Low-speed generator (12 krpm)









CL Stiffness	CL Damping	Damped SM
100,000 lbf/in	125 lbf-s/in	86.0%

Rotordynamics results provide closed-loop stiffness and damping targets for controller development

Rotor	Radial Bearing	Required Closed-Loop Stiffness [lbf/in]	Required Closed-Loop Damping [lbf-s/in]	Damped Separation Margin
High-speed machine (27 krpm)	HS compressor	200,000	70.0	25.0%
	HS midspan			
	HS generator			
Low-speed turbine (12 krpm)	LS turbine NDE	200,000	180	25.2%
	LS turbine DE			
Low-speed generator (12 krpm)	LS generator DE	100,000	125	86.0%
	LS generator NDE			

Conclusions

Calculations performed

- Bearing sizing
- AMB dynamic coefficients
- Rotordynamics analysis
- Target AMB closed-loop stiffness and damping values