

# High Speed Motor Test Rig

## Design Review 2

Spring 2016

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Sponsor: Danfoss

Liaison: William Sun

Faculty Advisor: Dr. Patrick Hollis

3-15-16

# Presentation Overview

1. Background
2. Motivation
3. Project Description
4. Ideal/Final Design
5. Components selected
6. Base frame design
7. Alignment Positioning
8. Natural frequency analysis
9. Safety Shielding.
10. Scheduling, Conclusion, Future Work

# Sponsor Background

- Client: **Danfoss Turbocor**
  - Market leader in oil-free compressors for commercial air conditioning systems.
  - Combination of magnetic bearings and variable-speed centrifugal compression to achieve higher speeds and higher efficiency than competitors.
- Danfoss needs a system to test compressor motor performances.
  - Their ideal solution: a motor generator system.



Figure 1: Danfoss Turbocor TT500 Compressor

# Project Background

- **Motor-generator systems:** Couples two motors, one working as a motor and the other one as as a motor load (generator)
  - The generator is used to vary a desired load on the motor.
- A coupling conjoins the motor shaft to the generator shaft.
  - Flexible coupling minimizes bending forces between shafts.
- Excessive radial loads can damage the motors and possibly fracture the coupling(s) and shafts.
  - Motor-generator test rigs incorporate shaft alignment features.
  - Vertical and lateral positioning must be adjusted accurately.

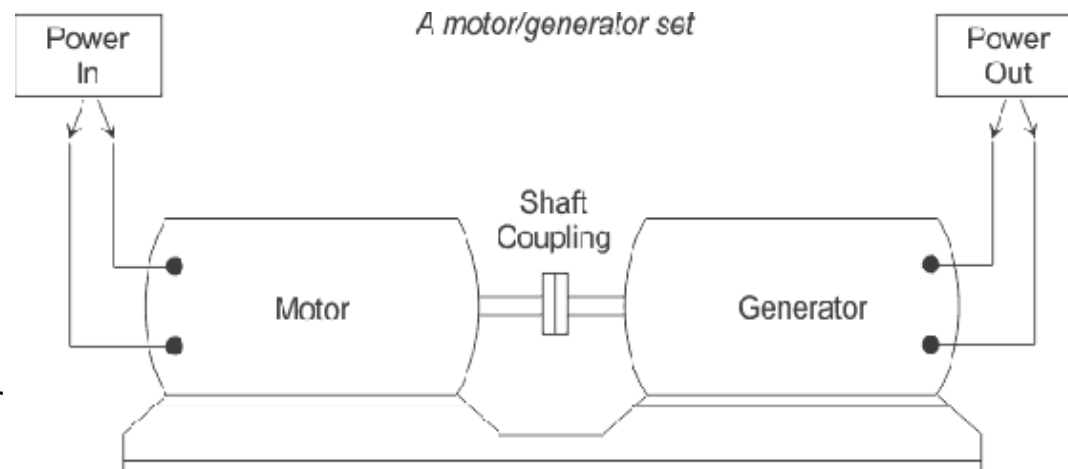


Figure 2. Motor-generator concept

# Motivation

Danfoss Turbocor will use the High Speed Motor Test Rig to test compressor motor performance efficiency.

- By using a transducer, the output torque from the motor can be monitored. These values can be compared to theoretical torque values, calculated from the amount of supplied voltage/current.

Current method for testing is expensive and tedious.

- Requires compressors to be operated in chiller rooms.

Motor Test Rig  
Concept Draft 1  
Dec. 14, 2009  
Lin Sun

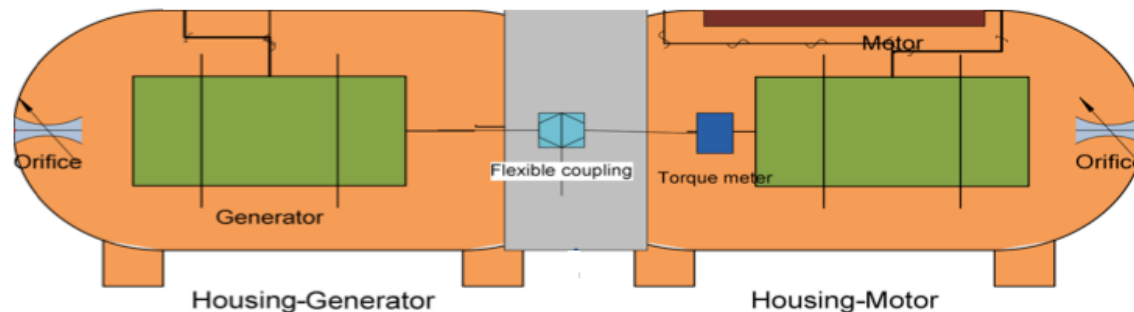


Figure 3. Motor-test rig concept draft

# Project Description

- **Problem Statement:** Danfoss needs a motor-generator system to test compressor motor performances. Past testing methods are unpractical. The solution needs to be simple yet still allowing performance efficiency to be evaluated.
- **Goal aspects:**
  - Design of the base stand and design/selection of all components (couplers, adapters and torque transducer)
  - Alignment system design and qualification
- Test rig needs to be able to qualify all TT-Series compressor motors
  - Torques and angular speeds vary between models

Compressor	Max Torque (Nm)	Max Speed (RPM)
TT300	22.8	37,762
TT350	38.0	30,598
TT400	37.2	25,091
TT700	73	17,000

Table 1: Danfoss TT-series compressor specifications

# Ideal Design

- 4 rigid couplers, 25.4 mm diameter steel dowels, 2 flexible bellows couplers, 1 torque transducer (Magtrol 308/311), ¼ inch thick 2x2 inch steel tubing (frame), transducer stand to be welded to frame, steel tubing to be fastened with ½ inch hex bolts, 2 shaft extenders
- Cost of each transducer: \$8,000. Client has requested an alternative ..

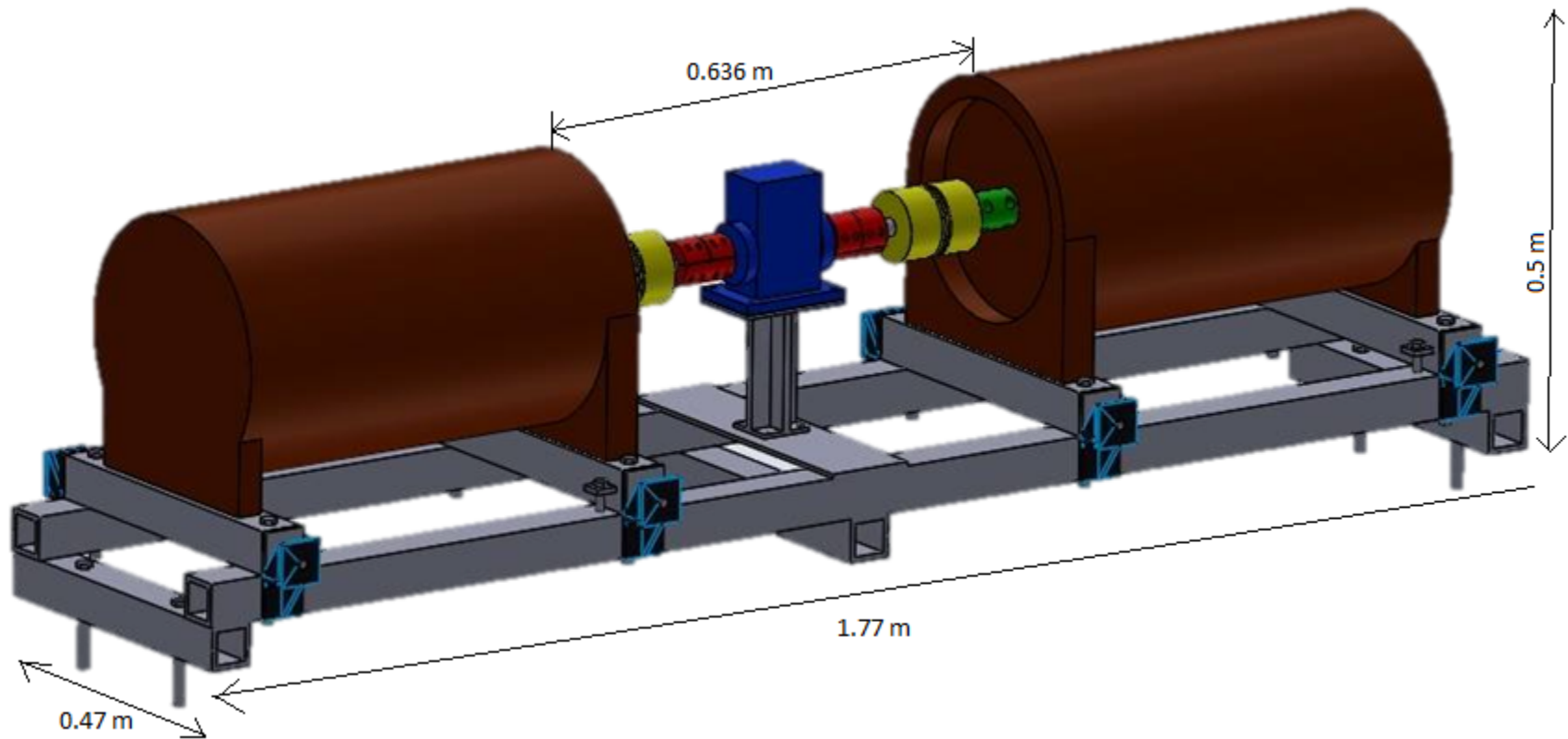


Figure 4: Ideal test rig design view

# Final Design

- A. Flexible coupler
- B. Shaft
- C. Rigid coupler
- D. Compressor
- E. Set screw bracket (lateral alignment)
- F. Frame
- G. Screw jack

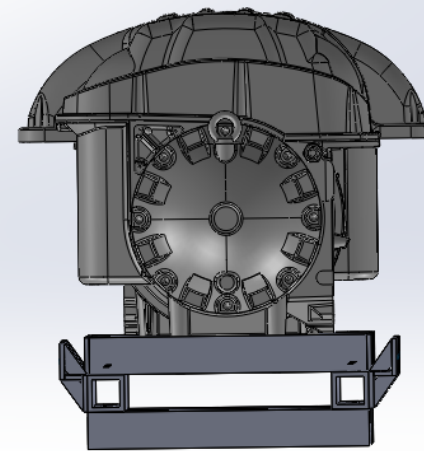


Figure 5. Side view, final design

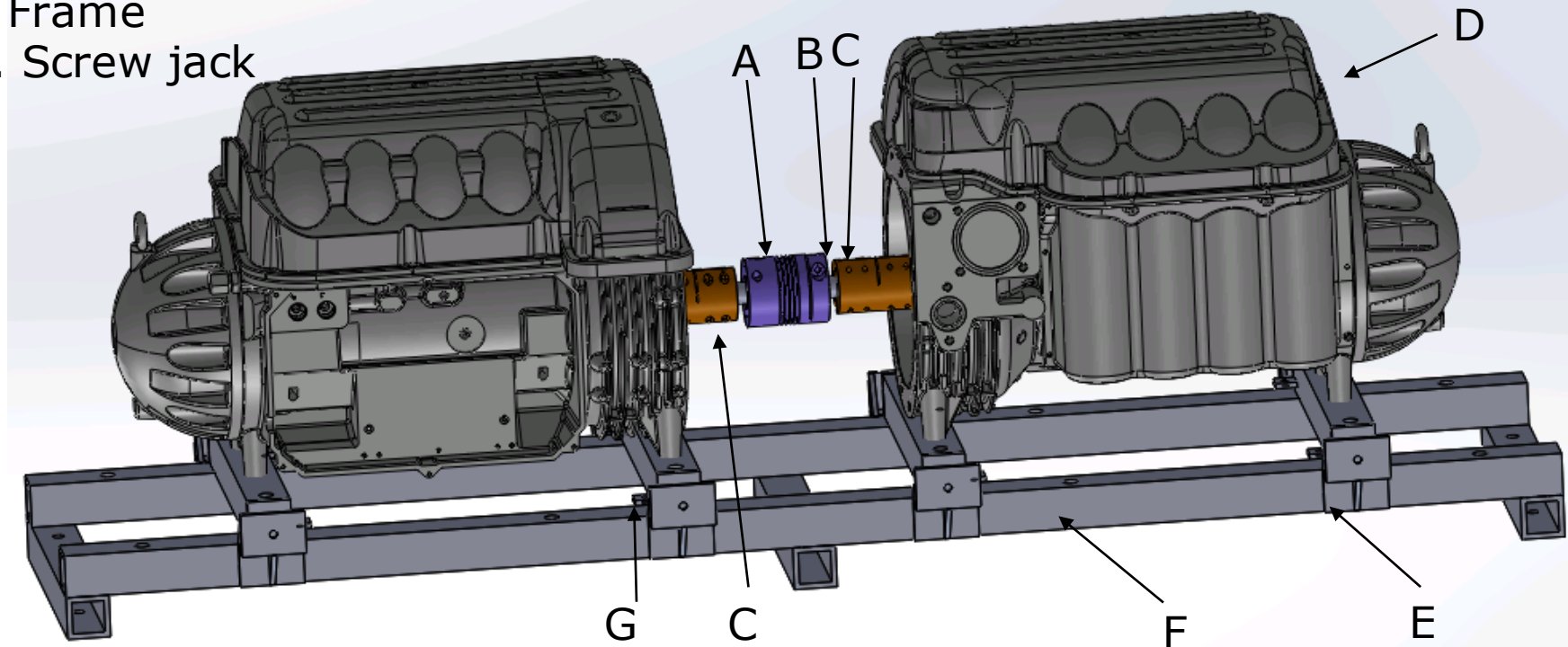


Figure 6: Final design assembly



# Components Selected

- **Re-Machinable Rigid Couplers (2)**

- Re-machinable: Will be balanced and bored by Danfoss (supplied by McMaster-Carr).

- ID<sub>1</sub>: 22mm (Compressor shaft)

- ID<sub>2</sub>: 25.4mm

- **Current Status:** Components received, awaiting final machining.

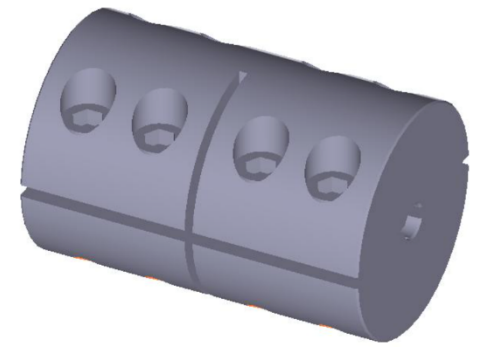


Figure 7. Rigid Coupler

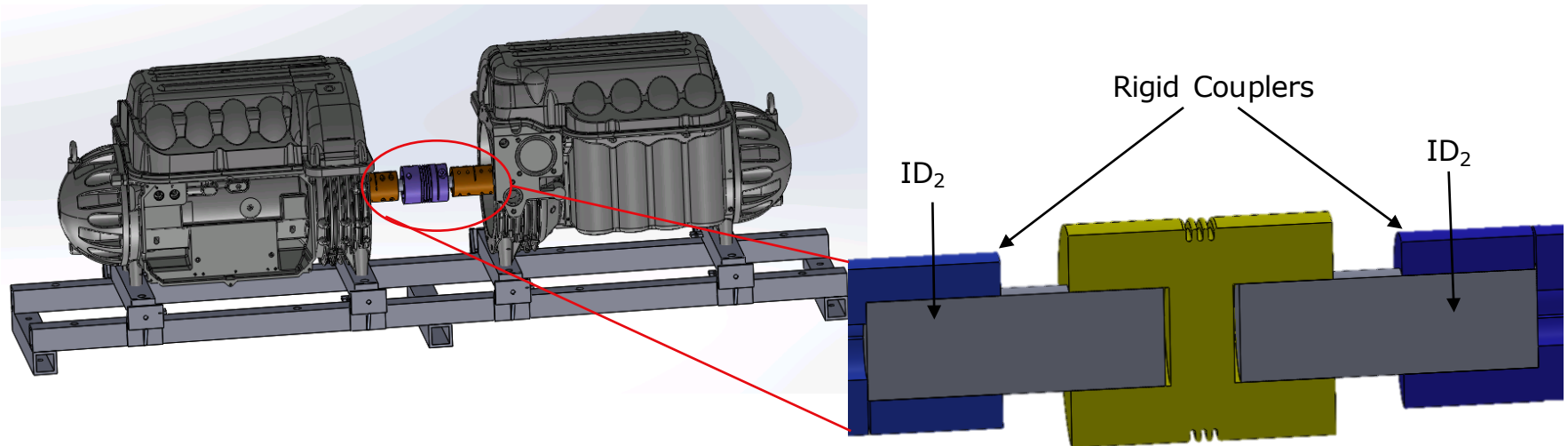
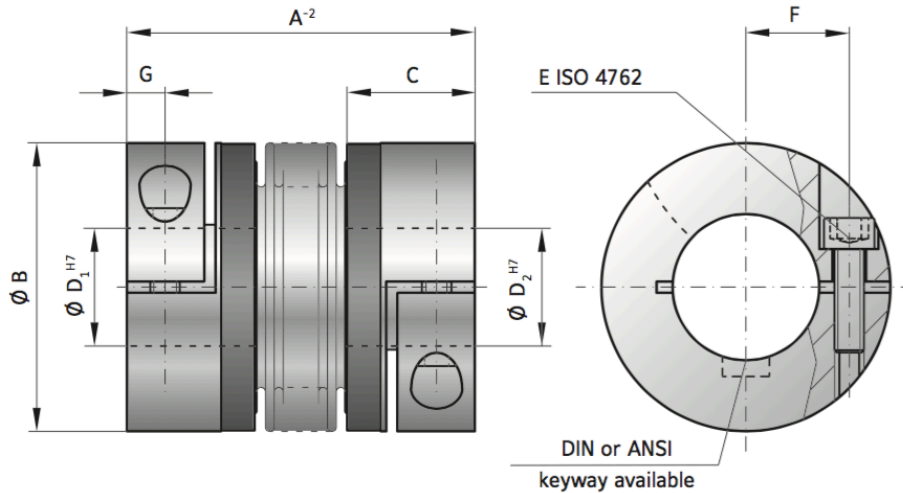


Figure 8. Section View of Rotating Assembly

# Components Selected

- **Flexible coupler: BK2 150 Bellows coupling**
  - 150 Nm rated torque
  - 50,000 RPM rating
  - Safety factor: 1.35
  - Misalignment tolerances: 0.2mm lateral, 1° angular, and 1 mm axial.
- **Current status:** Component has been ordered.



Overall length	(mm)	A <sup>-2</sup>	95	107	144
Outside diameter	(mm)	B	81		
Fit length	(mm)	C	36		
Inside diameter possible from $\emptyset$ to $\emptyset$ H7	(mm)	D <sub>1</sub> / D <sub>2</sub>	19-42		
Fastening screw ISO 4762		E	M10		
Tightening torque of the fastening screw	(Nm)		70		
Distance between centerlines	(mm)	F	27		
Distance	(mm)	G	11		

Figure 9. Bellow coupling BK2 150

# Components Selected

- **Laser alignment tool: TKSA 31**

- Measuring error less: <5%.
- Accuracy of 10  $\mu m$ .
- Reduces errors and system down time in alignment process.
- 6" clearance for rotation.
- Equipment will be rented to avoid purchasing costs.

- **Current Status:** Awaiting order approval from sponsor.



Figure 10. Laser alignment tool TKSA 31

# Components Selected

- **Shaft:**

- 1566 Hardened Steel.
- Connects rigid couplers to flexible coupler.

Diameter accuracy:  $50\mu m$

- **Current Status:** Component received, awaiting final machining.

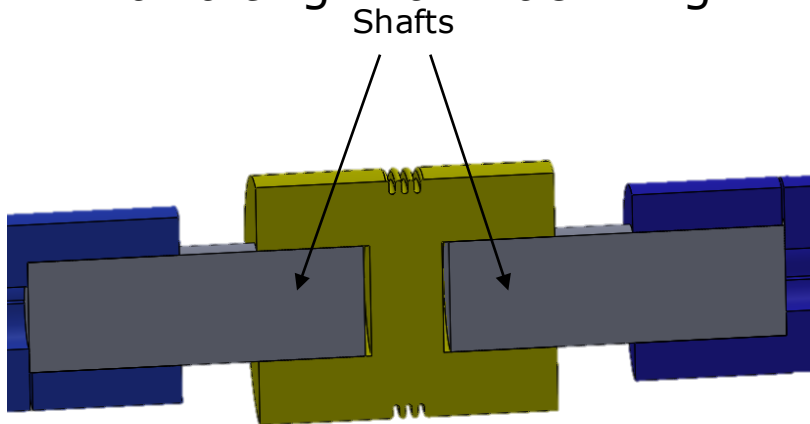


Figure 11: Section View of Rotating Assembly

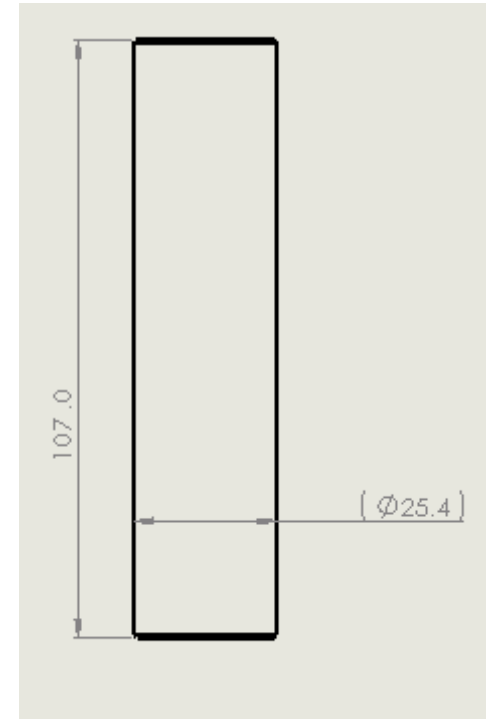
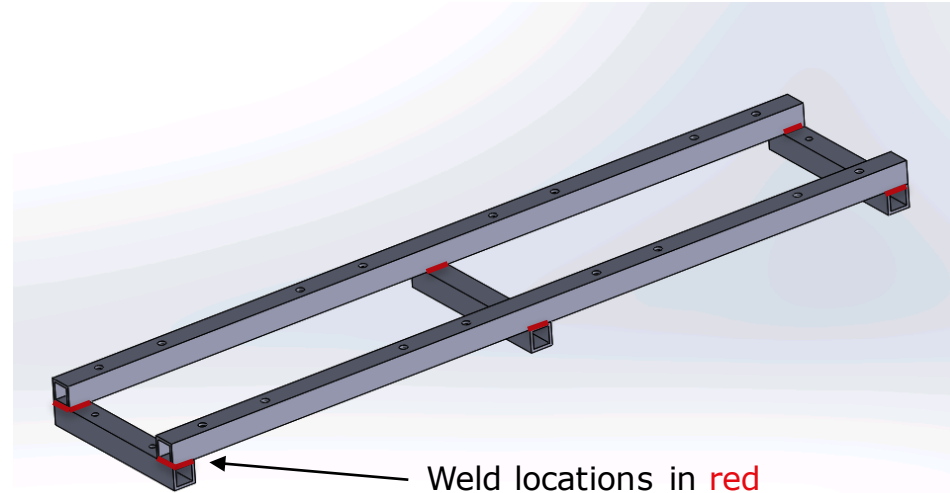


Figure 12. Shaft Dimensions (millimeters)

# Base Frame Design

- **Base frame:**
  - 2"x2"x1/4" mild steel
  - Supports the compressors
  - Rigidly fixed to floor
- **Current Status:** Materials received, awaiting fabrication at sponsor location.



Weld locations in red  
**Von Mises Stress**

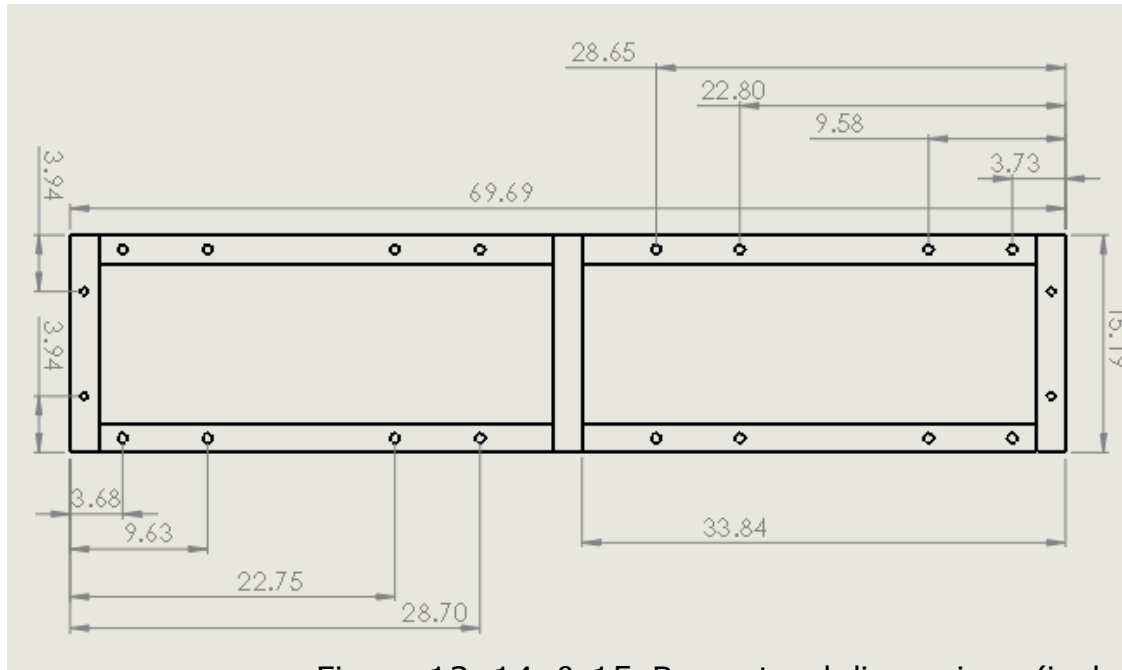
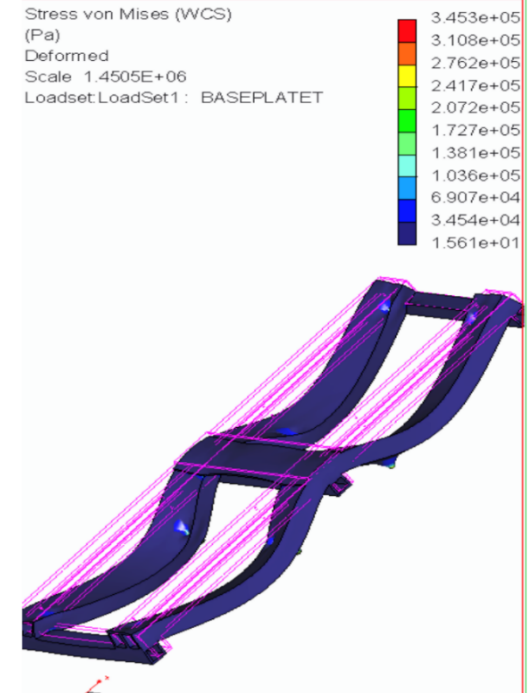
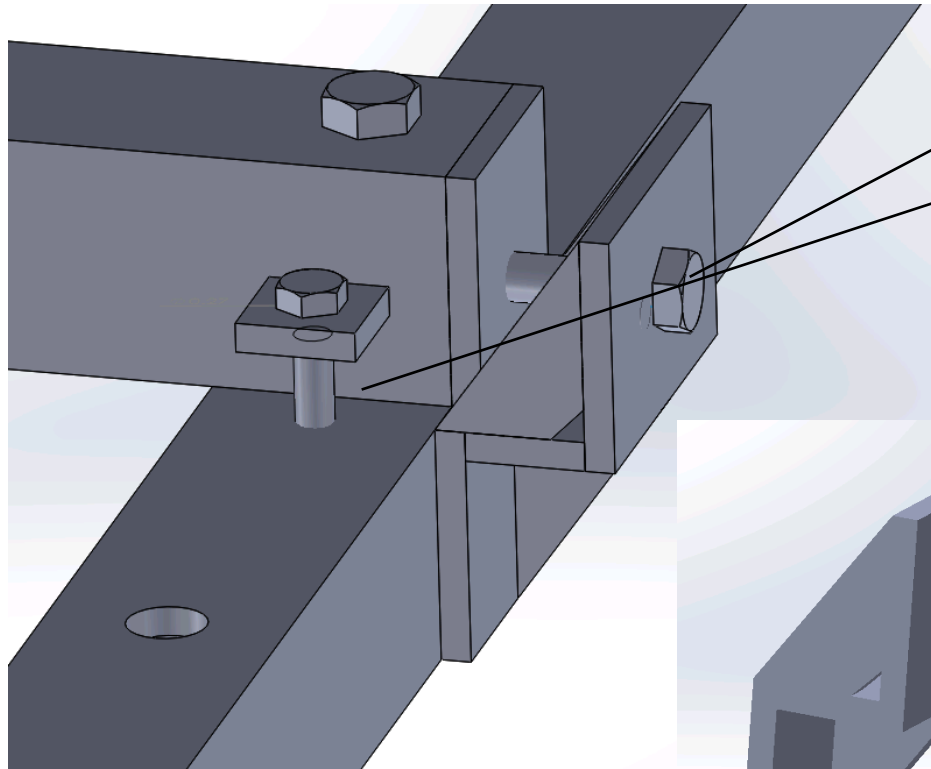


Figure 13, 14, & 15. Base stand dimensions (inches), 3D view, and FEA stress analysis.



# Base Frame Components



**Lateral alignment adjustment:**

3/8"-24

**Screw Jack**

Lifts member for shim insertion  
5/16"-18

**Current Status:** Awaiting fabrication at sponsor location.

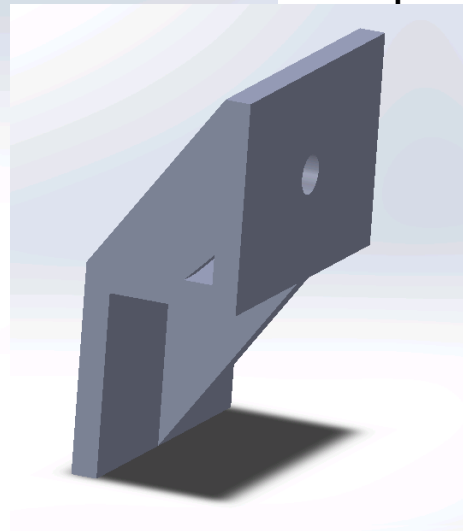


Figure 13: Set screws for horizontal alignment and screw jackets for shim insertion.

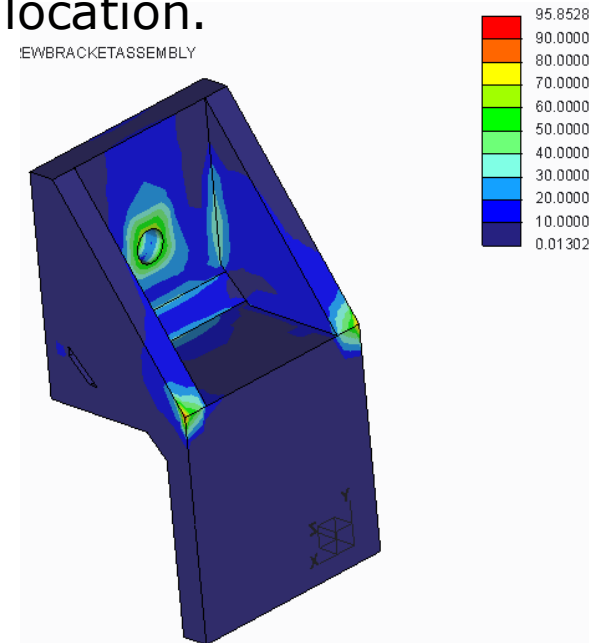


Figure 14: Von Mises stress analysis.  
Max stress: 80MPa

# Base Frame Components

## Vertical alignment adjustment:

### Shim Stock:

- Brass and Stainless steel
- Thicknesses of 0.001, 0.003, 0.006, 0.009, 0.012, 0.02, and 0.031 inches.
- A=57mm, C=11mm, B=51mm

**Current Status:** Material received.

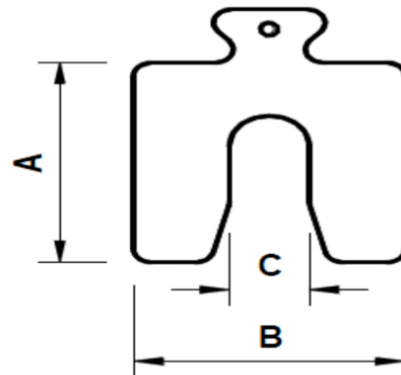
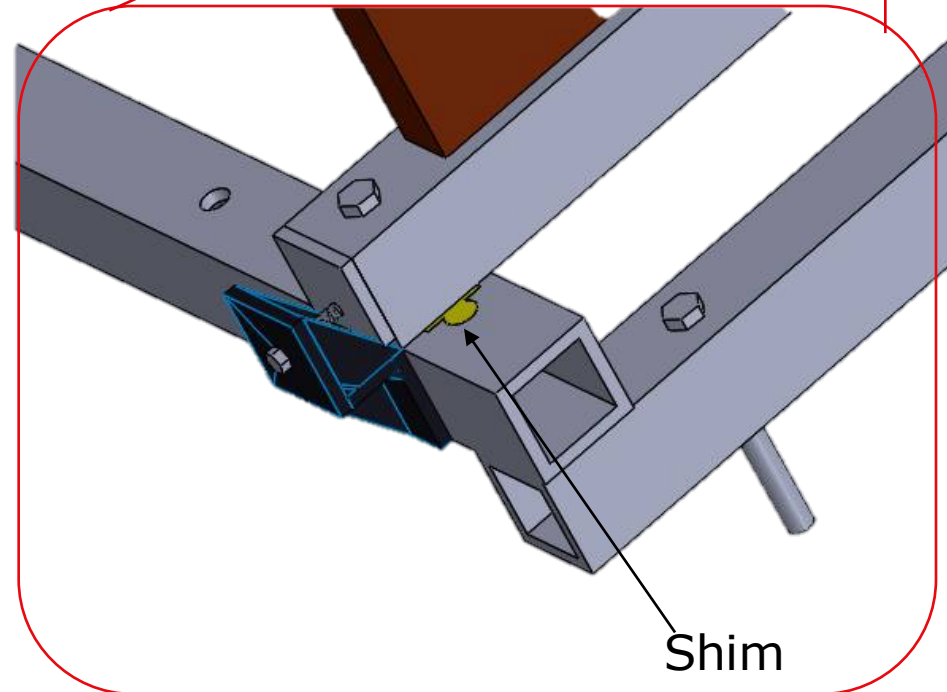
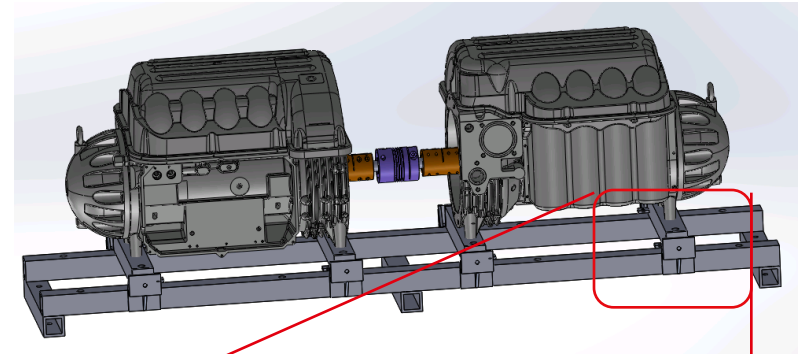


Figure 20, 21 & 22. Shim stock(left), shim dimensioning (center), shim location (right).

# Base Frame Anchoring Method

## Frame Anchoring Method

- Harmonic resonance is susceptible if the system is mounted to a table top surface.
- Solution: system will be designed for concrete fastening.
- Will be bolted to factory concrete floor to ensure safety.
- Concrete anchors will be used.
  - M12 bolt, minimum of 4 inch length to ensure fitting.



Figure 23. Concrete Anchor Bolt



# Natural Frequency Analysis

- Maximum rotation speed: 40,000 RPM = 667 Hz
- Based on the deflection, the frequency is stipulated at 708 Hz.
  - Safety Factor: 1.12

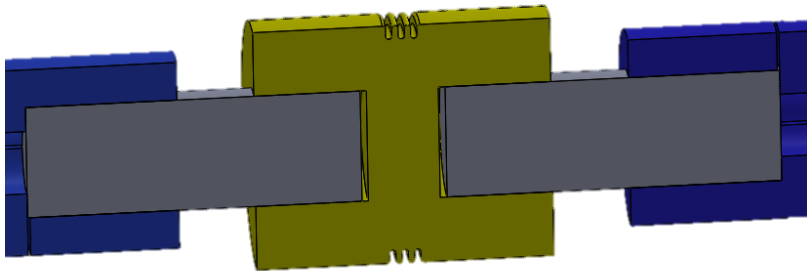


Figure 24. Rotating assembly section view

$$\omega = \left\{ \frac{g(m_1 w_1 + m_2 w_2 + \dots)}{(m_1 w_1^2 + m_2 w_2^2 + \dots)} \right\}^{\frac{1}{2}}$$

Figure 25. Natural frequency as a function of mass and deflection

# Final Design

- 1 Flexible Coupler
  - BK2 150/25.4/25.4
  - 25.4 mm bore
- 2 Rigid Couplers
  - McMaster-Carr Re-Machinable
    - ID<sub>1</sub>: 22 mm
    - ID<sub>2</sub>: 25.4 mm
- 2 Shafts
  - Diameter: 25.4 mm
  - Length: 107 mm
- 2 TT Series Compressor

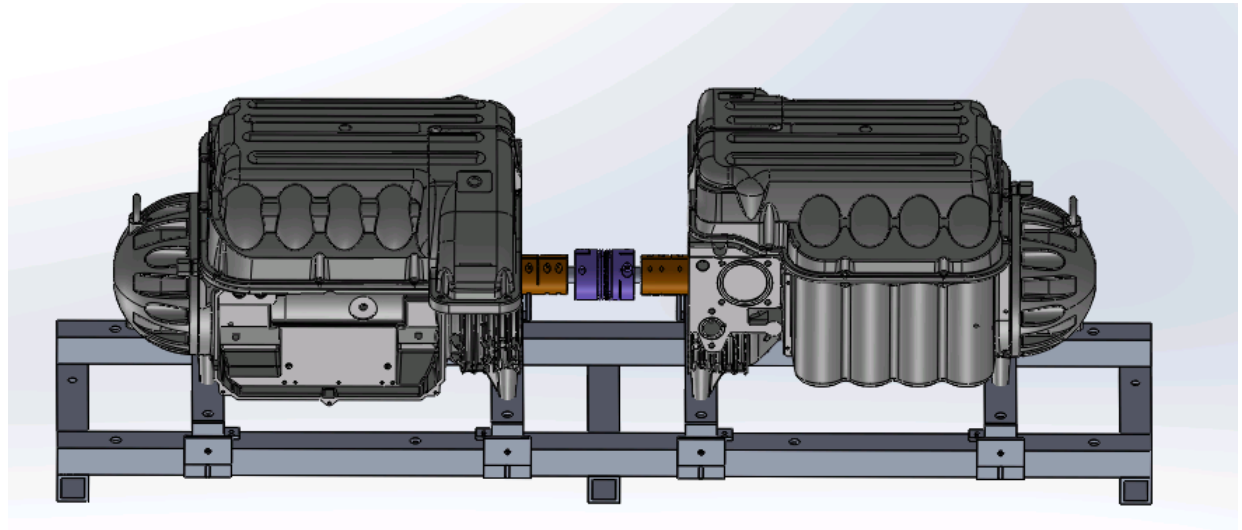


Figure 26: Cut view of final design

- Vertical and horizontal positioning adjustment with shims and set screw.
- Alignment is assisted by a laser aligning tool.

# Assembly Process

- 1. Base frame: Welded components first.
  - Cross members bolted.
- 2. First compressor is mounted (assistance with crane required) to cross members.

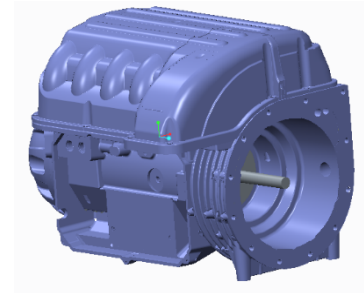
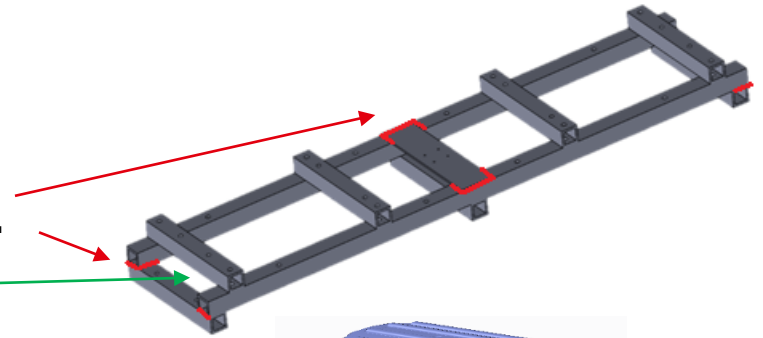


Figure 27: Stand alone compressor and base frame

- 3. Rigid couplers, steel dowels, and flexible couplers are secured together to first compressor.

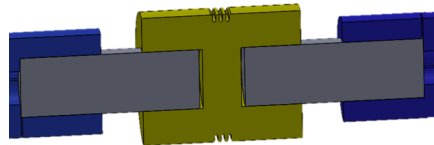
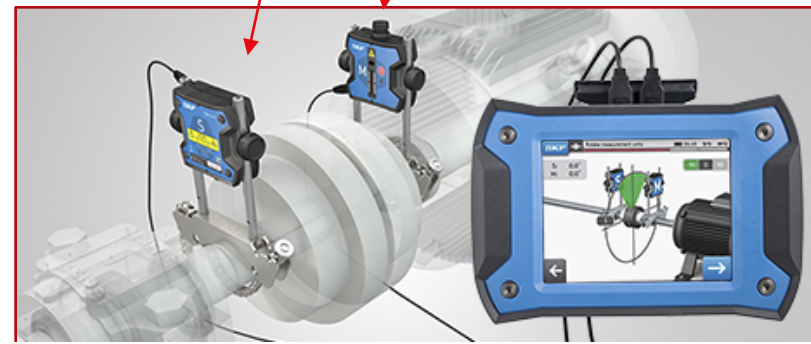
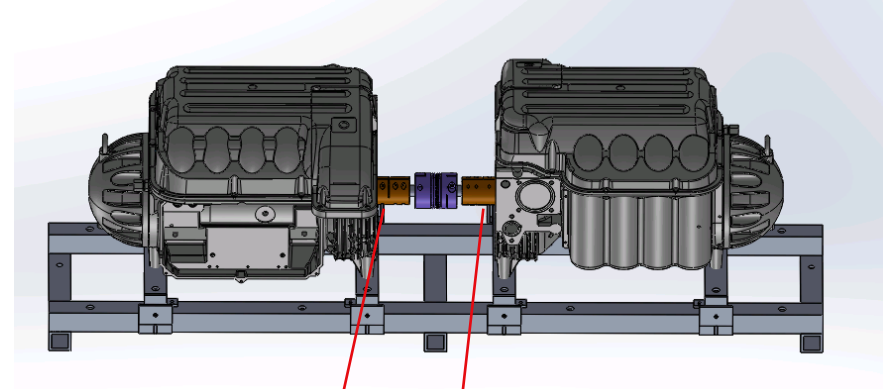


Figure 28: Rotating assembly

- 4. Second compressor is mounted to cross members, and shaft is coupled to rotating assembly.

# Alignment Process

- Tool mounts to both rigid couplers after assembly. Secured by using clamps.
- Shafts are rotated together, as this happens the laser guides process data.
- Live readings are displayed directing the user which direction to align system.



Vertical correction – Side view – Shimming

Horizontal correction – Top view

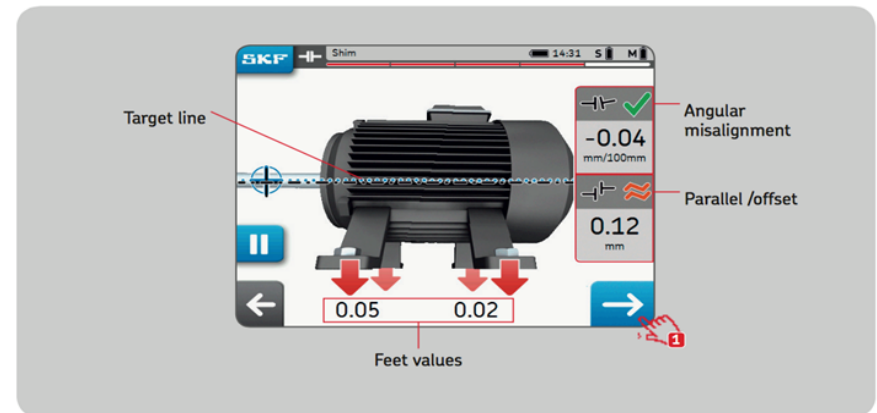
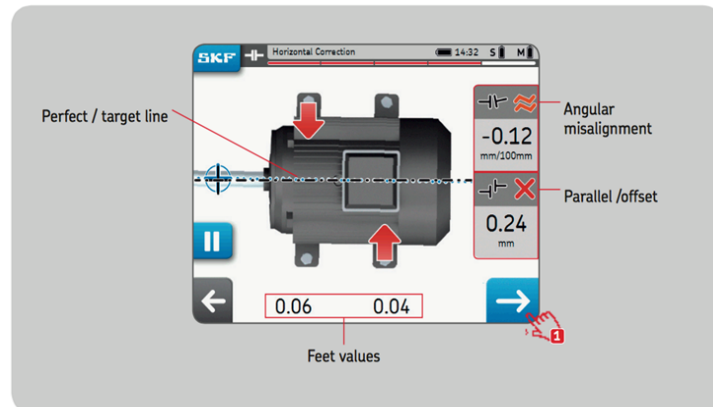


Figure 28: Final design cut view and alignment process

# Risk Analysis: Projectiles

- Due to the high speeds, there is a concern of the possibility of harmful projectiles.

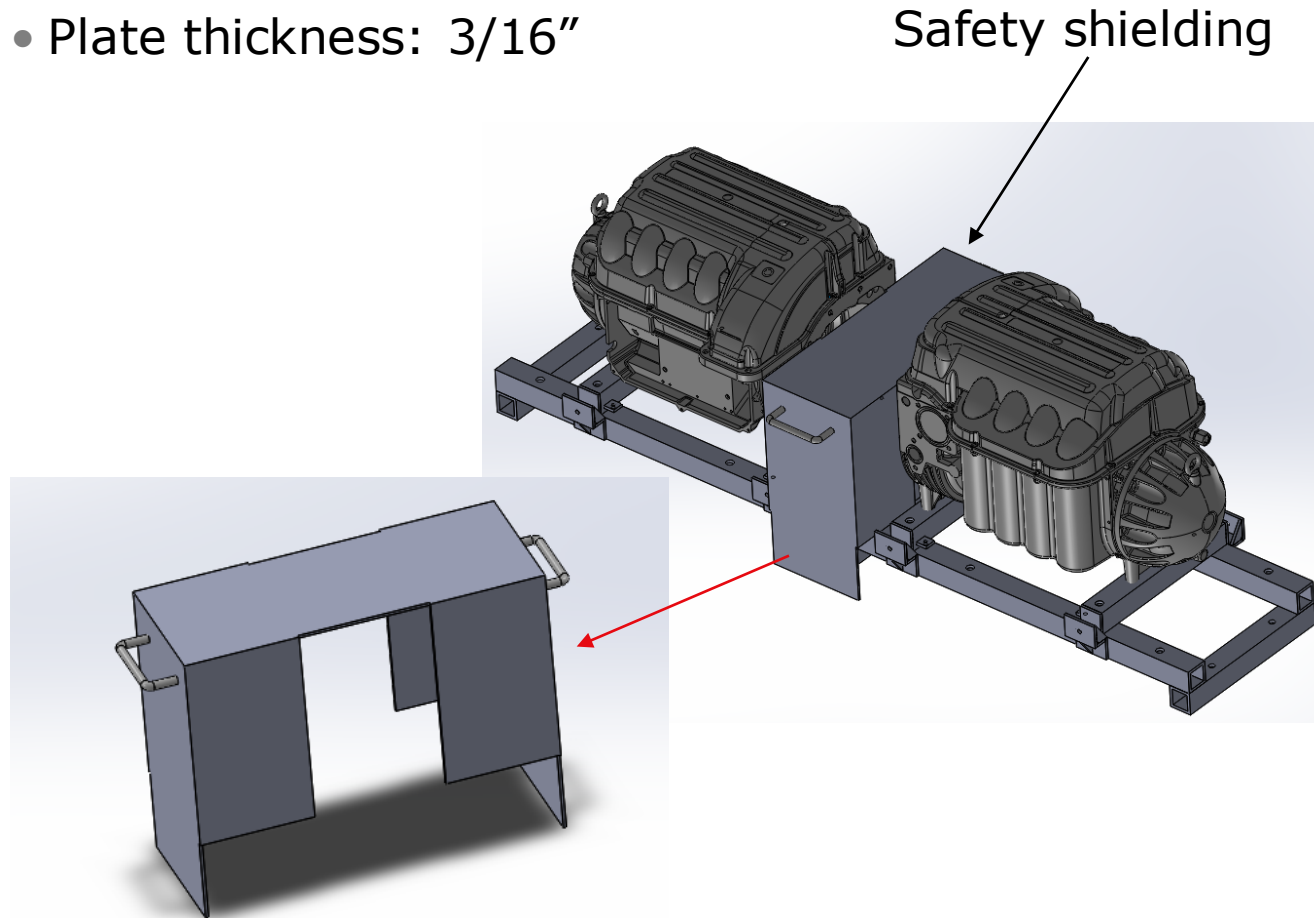
Component	Mass (kg)	Momentum (m*kg)/s	Impact Force (N)	Stress (psi)
Flexible Coupler	0.72	35.8	70,086	2,249
Flexible Coupler Screw	0.012	.577	7,897	532.7

Table 2. Safety shield impact analysis

- Material Selected: A36 Steel
  - Yield Strength: 36,000 psi
  - Brinell hardness : 149

# Safety Shielding Design

- Sponsor advised using steel shielding instead of plexiglass.
- Plate thickness: 3/16"



# Gantt Chart

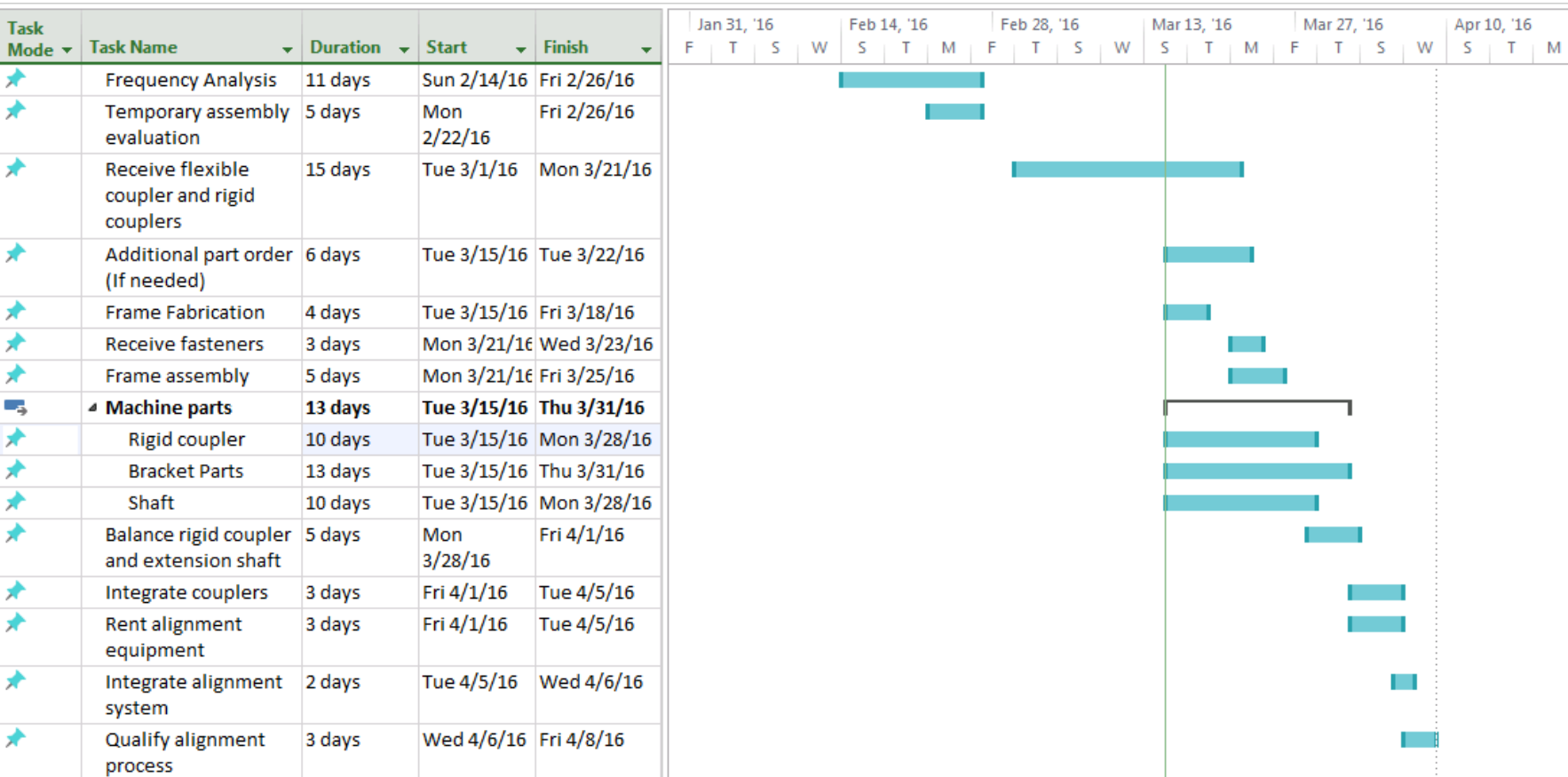


Figure 26. Gantt Chart, Spring Semester.

## Recent Milestones:

- Received steel order for frame. Fabrication has started.
- Have received all raw materials and fasteners.
- Flexible coupler purchase approved and ordered.

# Conclusion & Future work

- Materials/Components recently received (3-8-16):
  - Tube steel for frame
  - Shim stock
  - Set screw bracket steel.
- Materials/Components recently received (3-15-16):
  - Fasteners, rigid couplers, hardened shafts.
- Flexible coupler ordered (3-11-16), awaiting arrival.
- Awaiting completed frame fabrication at Danfoss for team's inspection.
- Awaiting alignment tool rental confirmation.
- Assemble compressors and rotating assembly with frame.
- Begin alignment testing process.



# References:

1. <http://www.magtrol.com/datasheets/tm301-308.pdf>
2. <http://www.magtrol.com/datasheets/tm309-313.pdf>
3. <http://catalog.climaxmetal.com/item/re-machinable-couplings/re-machinable-couplings-r2cc-series/r2cc-075-075>
4. <http://catalog.climaxmetal.com/item/shaft-adapters/step-up-clamp-on-adapter-sua-series/sua-050>
5. <http://www.skf.com/group/products/maintenance-products/alignment-tools/shaft-alignment-tools/shaft-alignment-tool-tksa31/index.html>
6. [http://www.rw-america.com/products/bellows\\_couplings/bk/bk2/](http://www.rw-america.com/products/bellows_couplings/bk/bk2/)
7. [http://repositorio.unesp.br/bitstream/handle/11449/121247/silva\\_msp\\_tcc\\_guara.pdf?sequence=1](http://repositorio.unesp.br/bitstream/handle/11449/121247/silva_msp_tcc_guara.pdf?sequence=1)



# PURCHASE ORDER REQUISITION

Vendor: McMaster Carr

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Contact: [www.mcmaster.com](http://www.mcmaster.com)

DATE: 10-Mar-16

DATE REQUIRED: \_\_\_\_\_

CAPITAL EXPENDITURE (please tick):

CURRENCY: USD

**NOTE: THIS IS NOT A PURCHASE ORDER AND CANNOT BE ISSUED TO SUPPLIER**

TURBOCOR P/N	DESCRIPTION	VENDOR P/N	QTY	UNIT PRICE	TOTAL PRICE	PROJECT NUMBER	ACCOUNT NUMBER
	Alloy Steel Socket Head Cap Screw, Thread size: 3/8"-24, Length: 2". Package Qty: 5	90044A158	2	\$8.87	\$ 17.74		
	Machinable-Bore One-Piece Clamp-On Rigid Shaft Coupling	3084K34	2	\$42.46	\$ 84.92		
	Hardened Shaft, Steel, Diameter:1", Length: 10",	6061K608	1	\$15.05	\$ 15.05		
	General Purpose Low Carbon Steel, 1/4" Thick, 2" Width, 3ft Length.	8910K557	1	\$ 20.82	\$ 20.82		
	High Strength Steel Cap Screw, Zinc Yelloww Chromate, 1/2"-13, Length: 5 1/2", Partially Threaded (Pack Qty: 5)	91257A374	2	\$ 12.58	\$ 25.16		
	Extra-Wide Hex Nut, Zinc Yellow Chromate, 1/2"-13 (Pack Qty: 25)	96460A370	1	\$ 10.11	10.11		
	Over Sized Flat Washer, Zinc Yellow-Chromate Plated, 1/2" Screw Size, 0.531" ID, 1.062" OD. (Pack Qty: 25)	98025A133	1	\$ 11.44	\$ 11.44		
	High Strength Steel Cap Screw, Zinc Yellow Chromate, M12 x 1.75, Length: 70mm, Partially Threaded. (Pack Qty: 5)	95327A695	2	\$ 9.20	\$ 18.40		

**FREIGHT:** A) PREPAID (included)   
 B) PREPAID & CHARGE   
 C) COLLECT   
 D) FIXED AMOUNT

amount

**TOTAL** \$ 203.64

Special instructions: \_\_\_\_\_

\_\_\_\_\_

Prepared by: \_\_\_\_\_ ( Print name )

Approved by: \_\_\_\_\_ ( Manager )

Approved by: \_\_\_\_\_ ( Director )

PUR-00007F01





# PURCHASE ORDER REQUISITION

Vendor: McMaster-Carr

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

DATE: 22-Feb-16

DATE REQUIRED: ASAP

CAPITAL EXPENDITURE (please tick):

CURRENCY: USD

Contact: [www.mcmaster.com](http://www.mcmaster.com) Phone: 404-346-7000

**NOTE: THIS IS NOT A PURCHASE ORDER AND CANNOT BE ISSUED TO SUPPLIER**

TURBOCOR P/N	DESCRIPTION	VENDOR P/N	QTY	UNIT PRICE	TOTAL PRICE	PROJECT NUMBER	ACCOUNT NUMBER
	2"x2"x1/4" Low Carbon Steel tube, Length: 6ft	6527K614	4	\$69.82	\$ 279.28		
	2"x1/4" Low Carbon Steel strip, Length: 6ft	8910K557	1	\$35.89	\$ 35.89		
	2"x1/4" Low Carbon Steel strip, Length: 2ft	8910K557	1	\$16.15	\$ 16.15		
	Brass Shim Stock, 6"x60" , Thickness: 0.001"	9504K41	1	\$ 11.53	\$ 11.53		
	Brass Shim Stock, 6"x60" , Thickness: 0.003"	9504K45	1	\$ 11.42	\$ 11.42		
	Brass Shim Stock, 6"x60", Thickness: 0.006"	9504K49	1	\$ 16.97	\$ 16.97		
	Brass Shim Stock, 6"x60", Thickness: 0.009"	9504K53	1	\$ 22.65	\$ 22.65		
	Brass Shim Stock, 6"x60", Thickness: 0.012"	9504K55	1	\$ 24.30	\$ 24.30		
	Brass Shim Stock, 6"x60", Thickness: 0.02"	9504K58	1	\$ 35.60	\$ 35.60		
	Brass Shim Stock, 6"x60", Thickness: 0.031"	9504K6	1	\$ 53.47	\$ 53.47		

**FREIGHT:** A) PREPAID (included)

B) PREPAID & CHARGE

C) COLLECT

D) FIXED AMOUNT  amount

**TOTAL** \$ 507.26

Special instructions:

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Prepared by: \_\_\_\_\_ ( Print name )

Approved by: \_\_\_\_\_ ( Manager )

Approved by: \_\_\_\_\_ ( Director )

PUR-00007F01



# PURCHASE ORDER REQUISITION

Vendor: Mitchell Instrument Company Inc

DATE: 24-Feb-16

1570 Cherokee St. San Marcos CA 92078

Fax: 800-648-2411

DATE REQUIRED: ASAP

CAPITAL EXPENDITURE (please tick):

CURRENCY: USD

Contact: Phone: 888-270-2690 www.mitchellinstrument.com

**NOTE: THIS IS NOT A PURCHASE ORDER AND CANNOT BE ISSUED TO SUPPLIER**

TURBOCOR P/N	DESCRIPTION	VENDOR P/N	QTY	UNIT PRICE	TOTAL PRICE	PROJECT NUMBER	ACCOUNT NUMBER
	SKF TKSA 31 Laser Shaft Aleignment System	SKF-TKSA31	1	\$3,595	\$3,595		

**FREIGHT:** A) PREPAID (included)   
 B) PREPAID & CHARGE   
 C) COLLECT   
 D) FIXED AMOUNT  amount

TOTAL	\$3,595.00
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Special instructions: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Prepared by: \_\_\_\_\_ ( Print name )

Approved by: \_\_\_\_\_ ( Manager )



R+W America  
 1120 Tower Lane  
 Bensenville, IL 60106  
 Phone: 630-521-9911  
 Fax: 630-521-0366  
 Email: [info@rw-america.com](mailto:info@rw-america.com)  
 Web: [www.rw-america.com](http://www.rw-america.com)

Danfoss  
 Mr. Kevin Lohman  
 1769 E. Paul Dirac Drive  
 Tallahassee, FL 32310

[Fax: kevin.lohman@danfoss.com](mailto:kevin.lohman@danfoss.com)

SALES QUOTE # 65010		
Date	03-10-2016	Page 1/1
Ref.# /	65010 / 209644 (40)	
Cust.# R+W	Leon Voskov	
contact		

Dear Kevin:

Thanks for the opportunity to quote this project. We are pleased to offer the following:

Line	Qty.	Description	Unit Price	Total
(1)	1	<b>Bellows Coupling</b> BK2 / 150 / 95 / 25.4 / 25.4 Bore D1: 25.4 H7 Bore D2: 25.4 H7	329.56	329.56 USD
<b>Total</b>				<b>329.56 USD</b>

Payment Terms      Net 30

Lead time: 2-3 weeks

Feel free to contact us with any questions or changes.

This quote is valid for 3 months and subject to our general terms and conditions. Terms and conditions can be found at: [info.rw-america.com/organization](http://info.rw-america.com/organization)

Best regards,

R+W America  
 Leon Voskov

# Natural Frequency Analysis

1<sup>st</sup> simulation step by step  
Frequency: 337 Hz

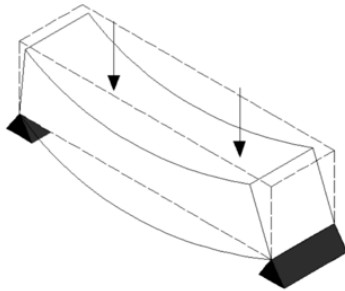
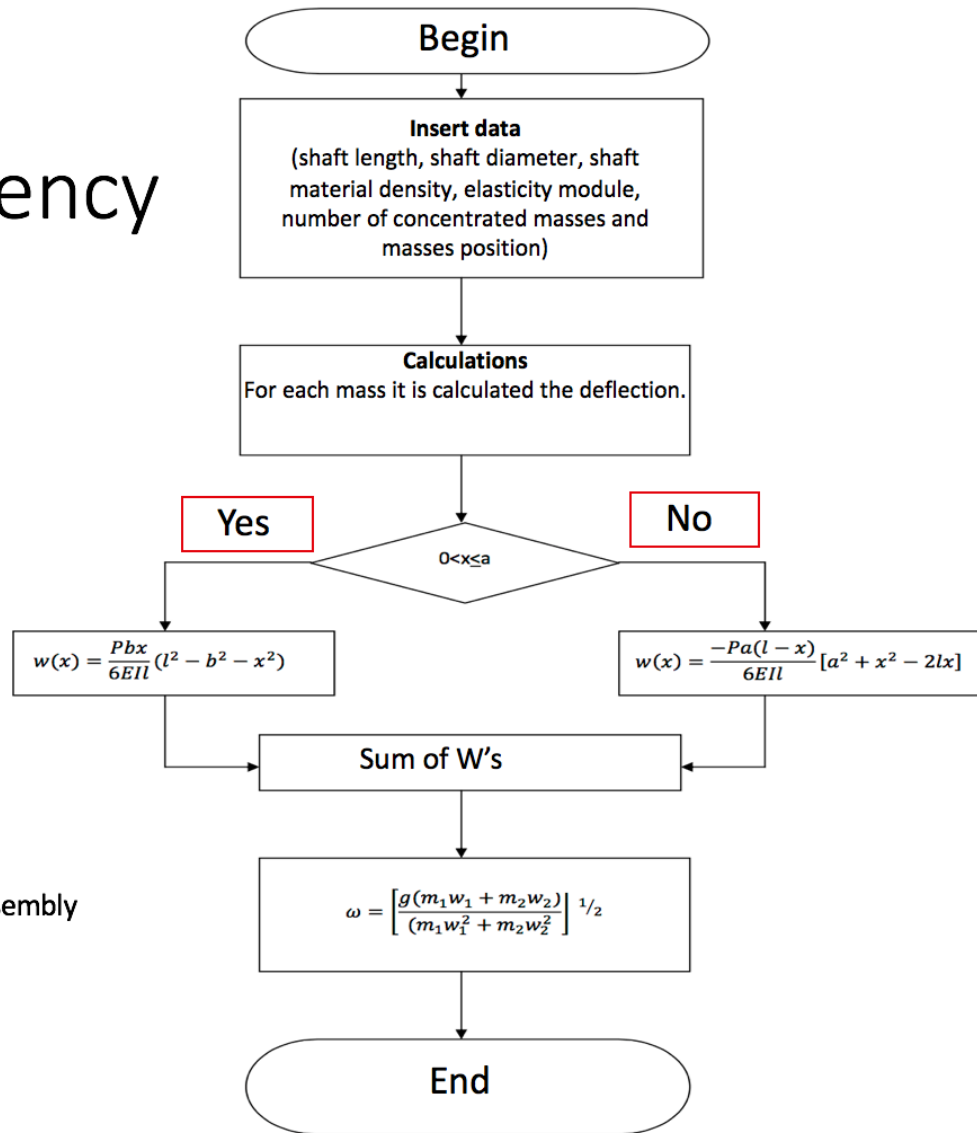


Figure #: Scenario analyzed: rotating assembly as an entire shaft



# Natural Frequency Analysis

2<sup>nd</sup> simulation step by step

Frequency: 708 Hz

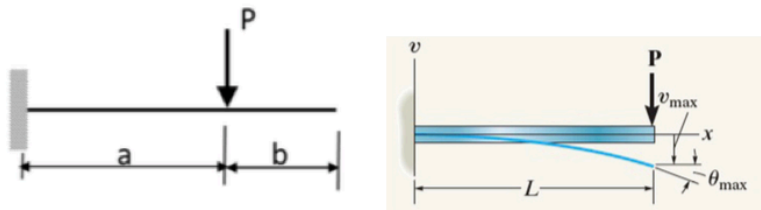
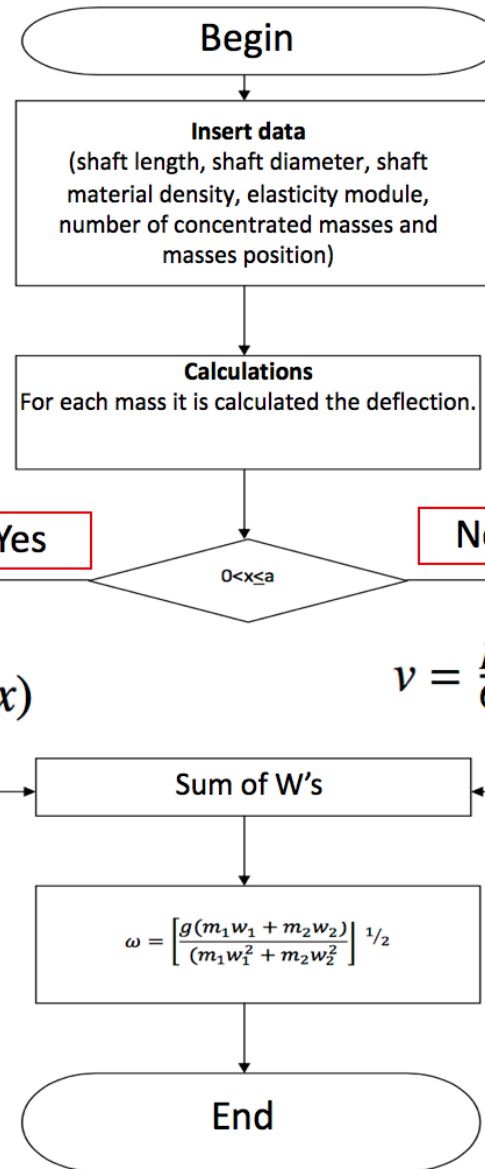
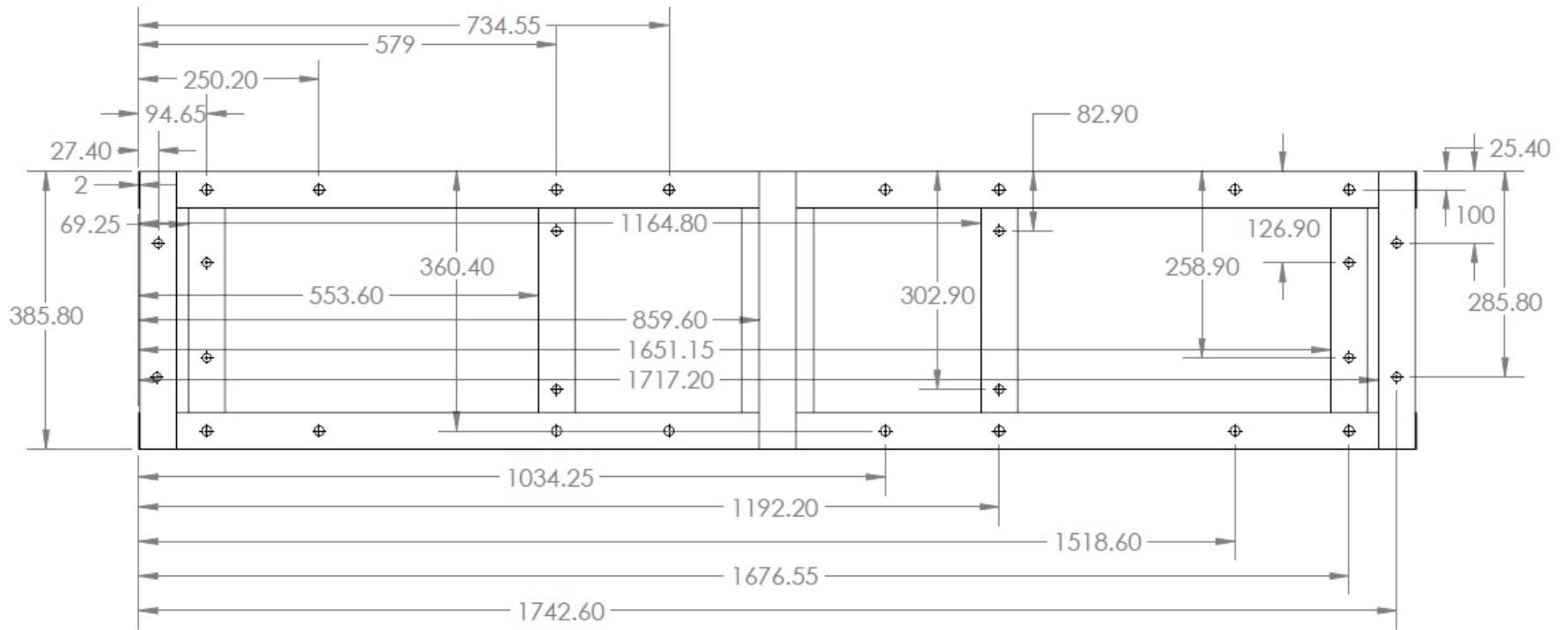


Figure #: Scenario analyzed: rotating assembly as half shaft

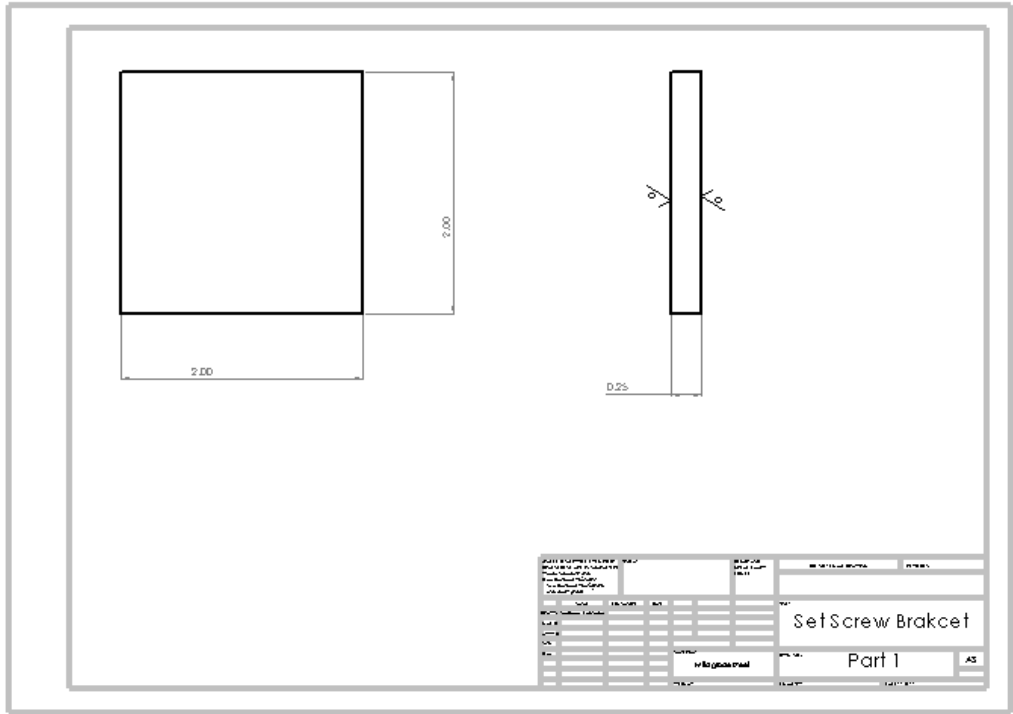
$$v = \frac{Px^2}{6EI} (3a - x)$$

$$v = \frac{Pa^2}{6EI} (3x - a)$$

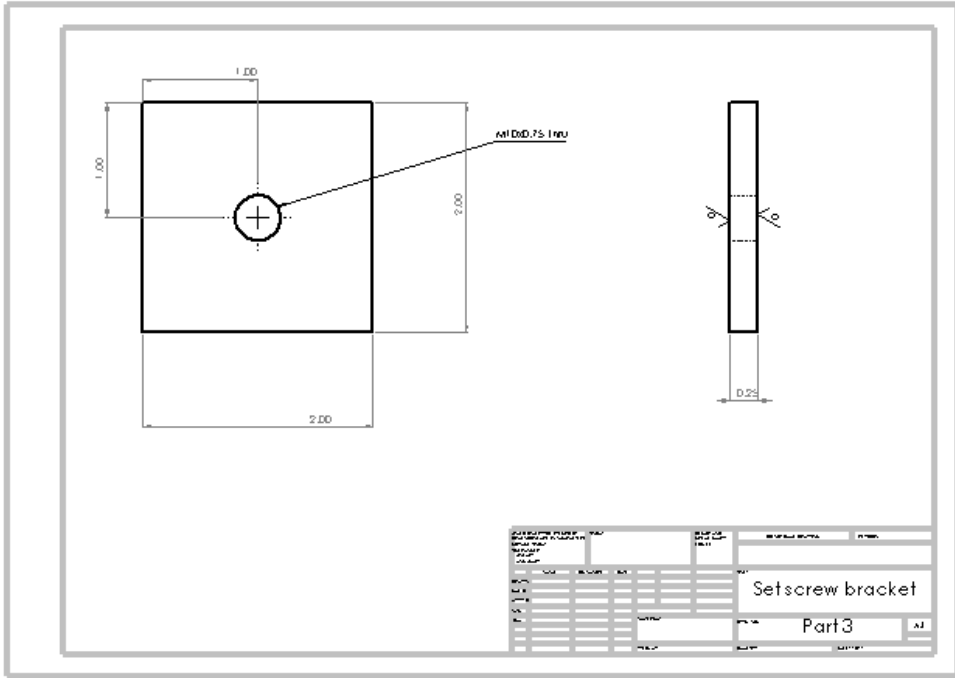


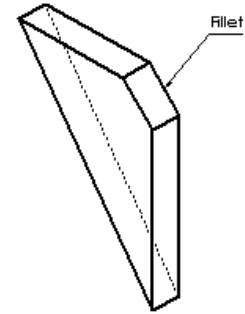
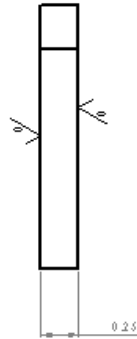
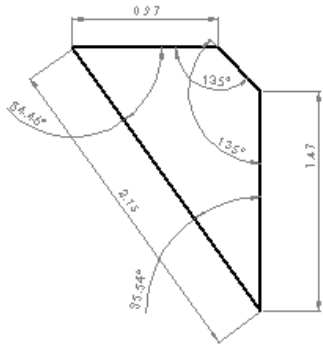












Note: Fillet is intended to allow clearance for weld.  
 If weld bead requires more clearance, the fillet may be increased by a minimal amount.

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Set screw bracket

Part 4

A3