High Speed Motor Test Rig

Final Presentation

Spring 2016

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Liaison: William Sun
Faculty Advisor: Dr. Patrick Hollis

4-14-16

Presentation Overview

1. Background
2. Motivation
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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

Thyeasha Joseph

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

Thyeasha Joseph

Project Background

- **Motor-Generator system:** Couples two motors, one working as a driving 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 couplings minimize bending forces between shafts.
- Excessive radial loads can damage the motors and possibly fracture the couplings and shafts.
  - Motor-generator test rigs incorporate shaft alignment features.
  - Vertical and lateral positioning must be adjusted accurately.

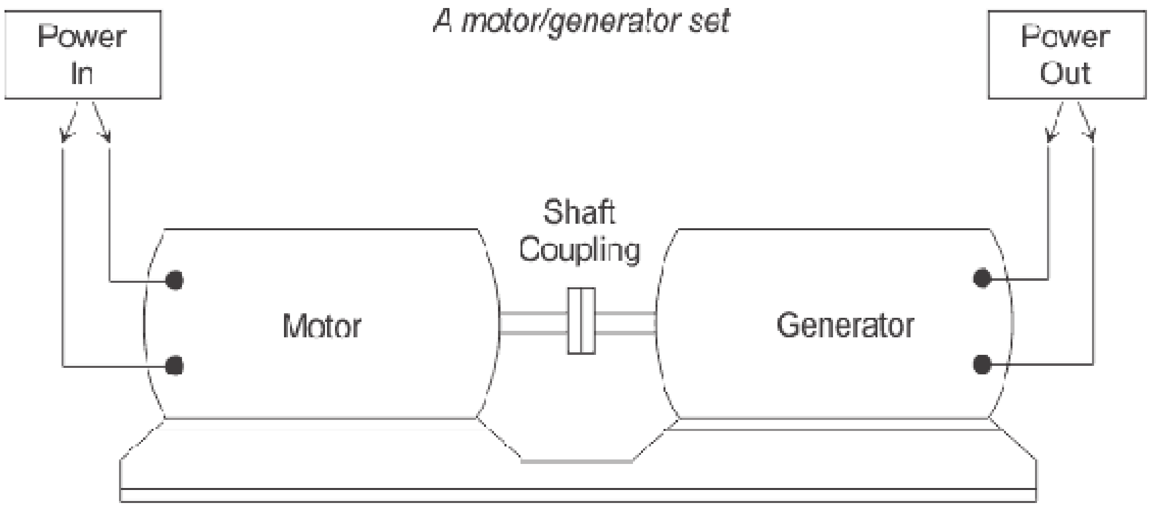


Figure 2. Motor-generator concept

Thyeasha Joseph

Motivation

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

- 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.

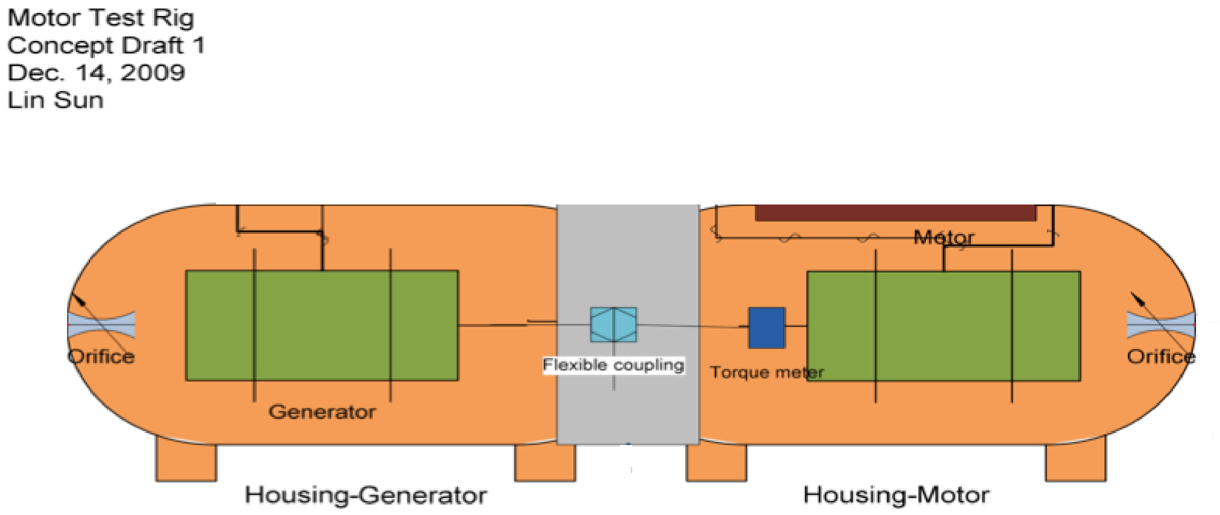


Figure 3. Motor Test Rig concept draft

Thyeasha Joseph

Project Description

- **Problem Statement:** Danfoss needs a motor-generator system to test compressor motor performances, primarily the shaft output torque. The solution needs to be simple while still allowing performance efficiency to be evaluated.
- **Goal aspects:**
  - Design of the base stand and design/selection of all components (couplers, tools, and torque transducer).
  - Alignment system design and process 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

Thyeasha Joseph

Ideal Design

A. Four Rigid Couplers
B. Two Compressors
C. Magtrol 308/311 Torque Transducers
D. Two R&W BK2 Flexible Couplers
E. 2"x2" Steel Tubing Frame (1/4" Thick)
F. Eight Set Screw Brackets (lateral alignment)

- Cost of each transducer: $8,000. Client has requested an alternative to reduce costs.

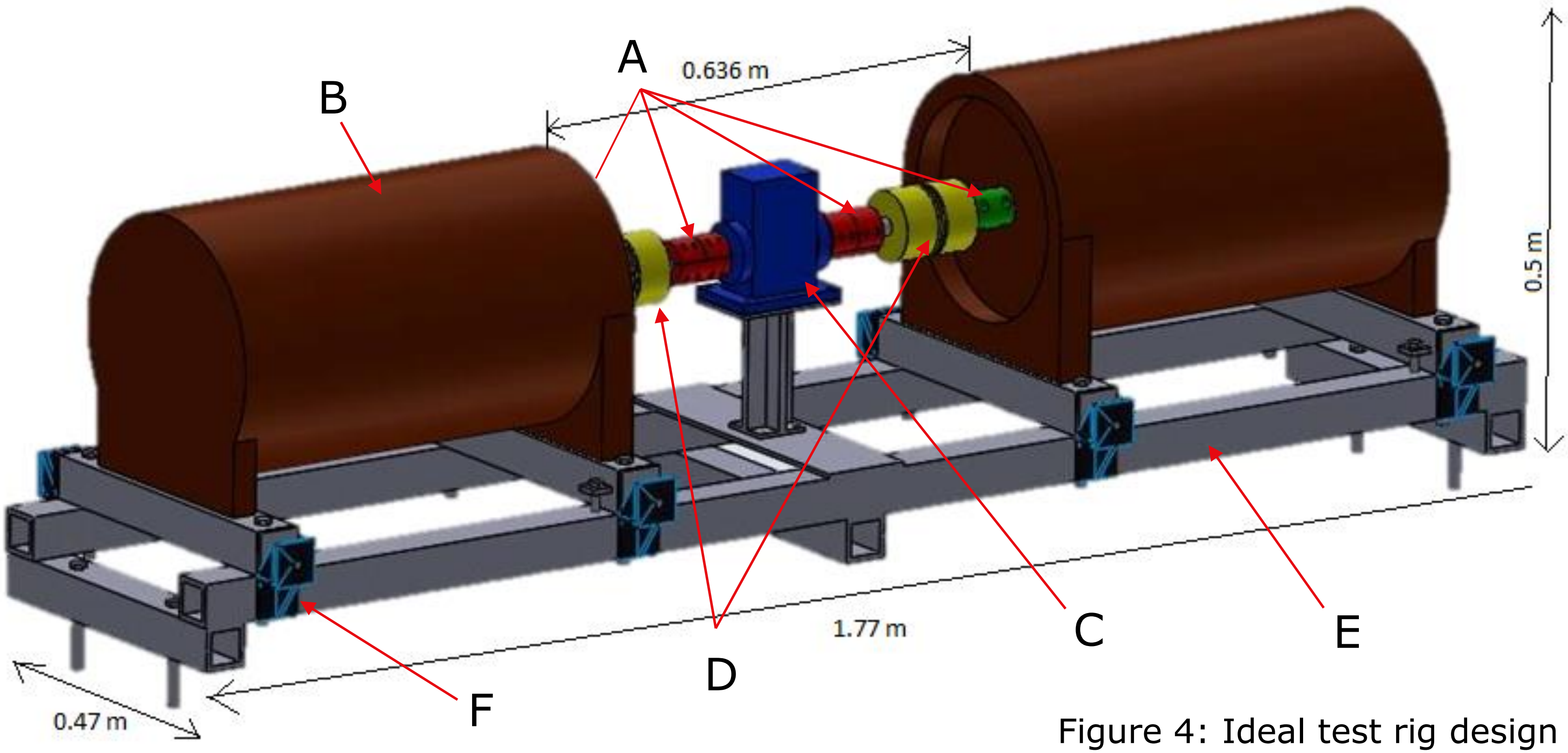
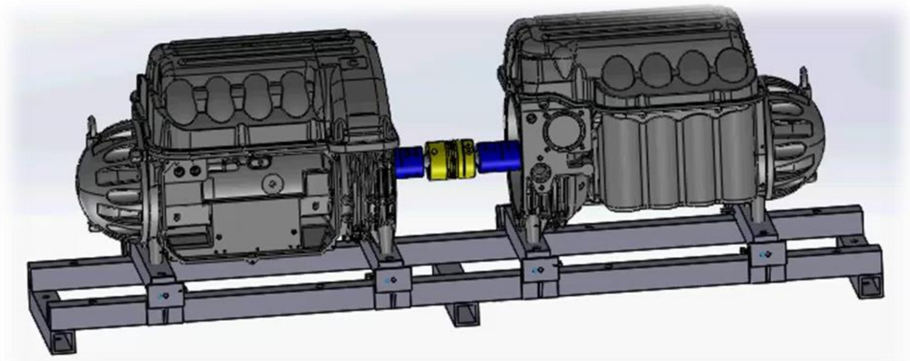


Figure 4: Ideal test rig design view

Final Design

A. One flexible coupler
B. Two rigid couplers
C. Two extension Shafts
D. Two compressors
E. Eight set screw brackets (lateral alignment)
F. Base frame



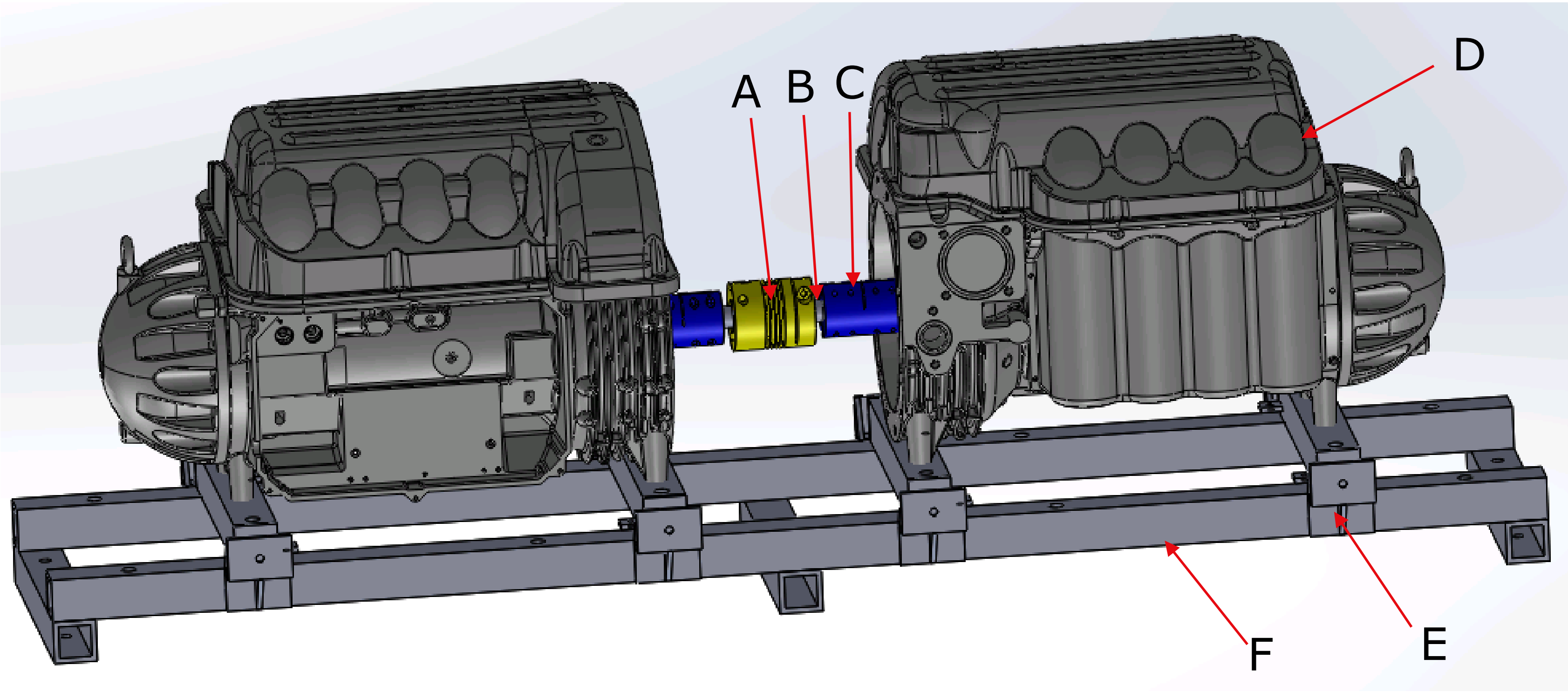


Figure 5: Final design assembly

Thyeasha Joseph

Components Selected

- **Re-Machinable Rigid Couplers (2)**
  - Re-machined to required inner diameter.
  - ID_1: 22mm (Compressor shaft)
  - ID_2: 25.4mm
- Shaft-coupling fit: "H7/h6", snug fit yet allows assembly/disassembly freely.

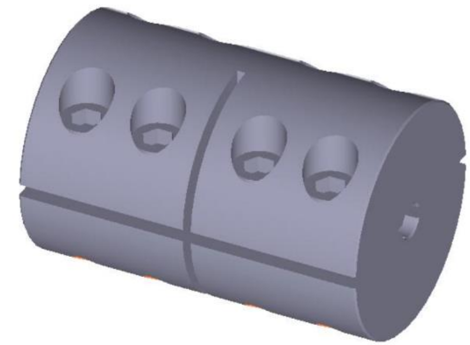


Figure 6. Rigid Coupler

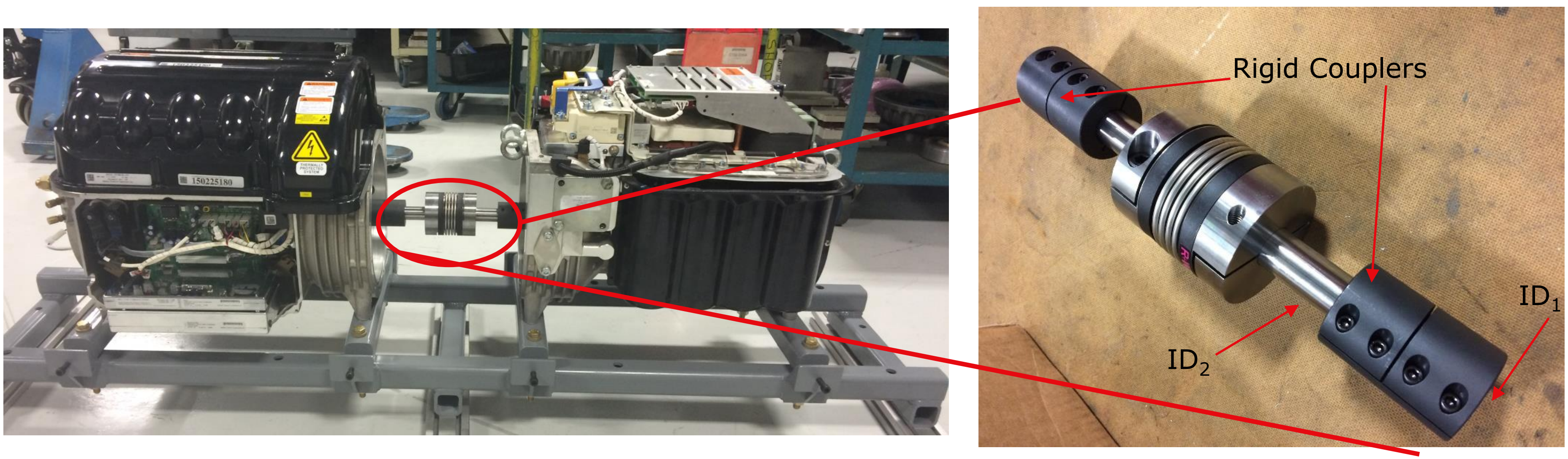


Figure 7. Assembled system with rotating assembly

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Components Selected

- **Flexible coupler: BK2 150 Bellows coupling**
  - 150 Nm rated torque
  - 10,000 RPM rating
  - Misalignment tolerances: 0.2mm lateral, 1°angular, and 1 mm axial.
  - ID: 25.4mm

Figure 8. Bellow coupling BK2 150

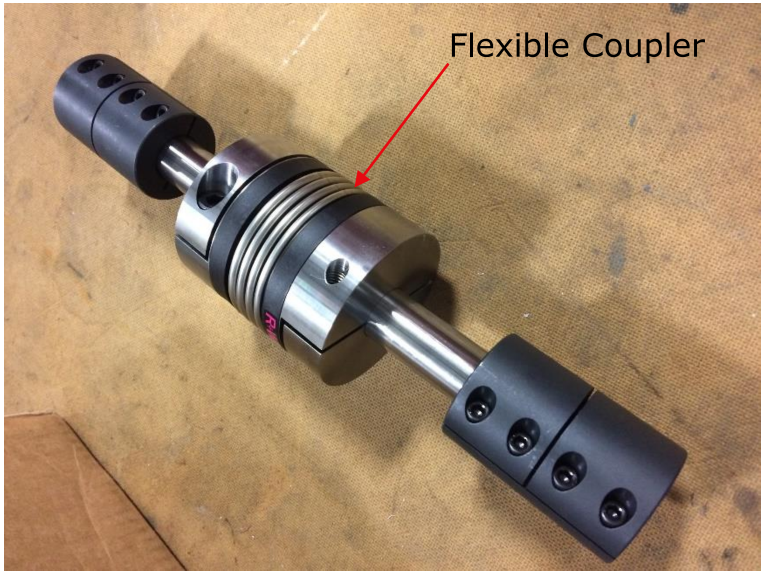


Figure 9. Rotating Assembly

Overall length (mm)	A^{-2}	95	107	144
Outside diameter (mm)	B	81		
Fit length (mm)	C	36		
Inside diameter possible from Ø to Ø H7 (mm)	D_1/ D_2	19-42		
Fastening screw ISO 4762	E	M10		
Tightening torque of the fastening screw (Nm)	E	70		
Distance between centerlines (mm)	F	27		
Distance (mm)	G	11		

Table 2. Flexible coupler specifications

Francisco Barreto

Components Selected

Shaft Alignment Measuring Tool: Dial Indicator

As the plunger rod is pushed in, the dial rotates clockwise.

- Two identical indicators rigidly mount to rotating assembly.
- Accuracy of 0.001 inches.
- Magnetic base allows rigid connection.
- Cost effective and readily available.

Adjustable connecting rods

Magnetic base

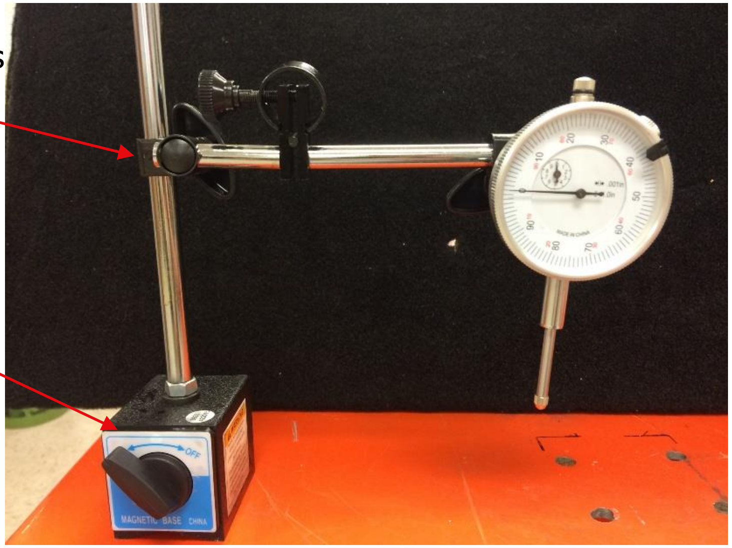


Figure 10. Magnetic base with indicator

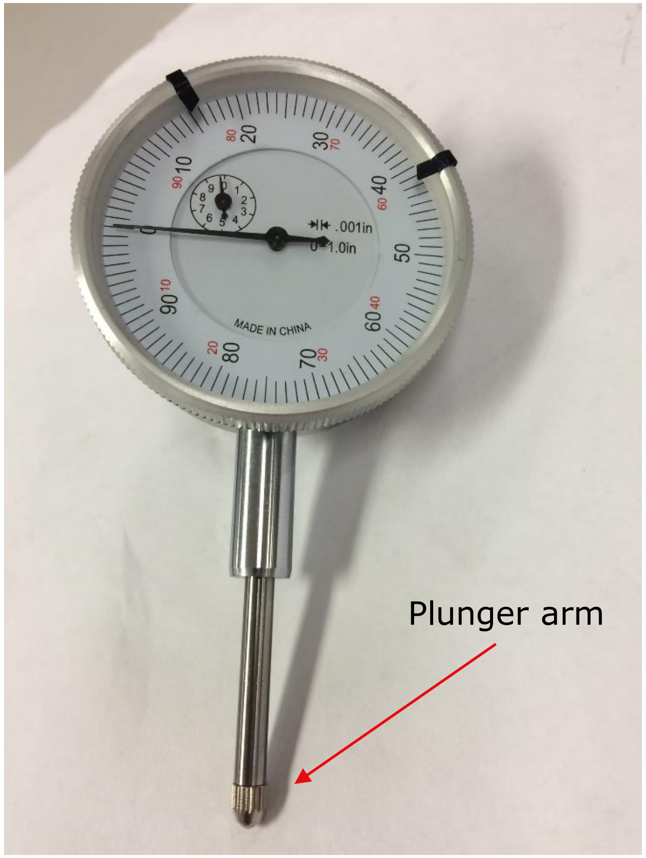


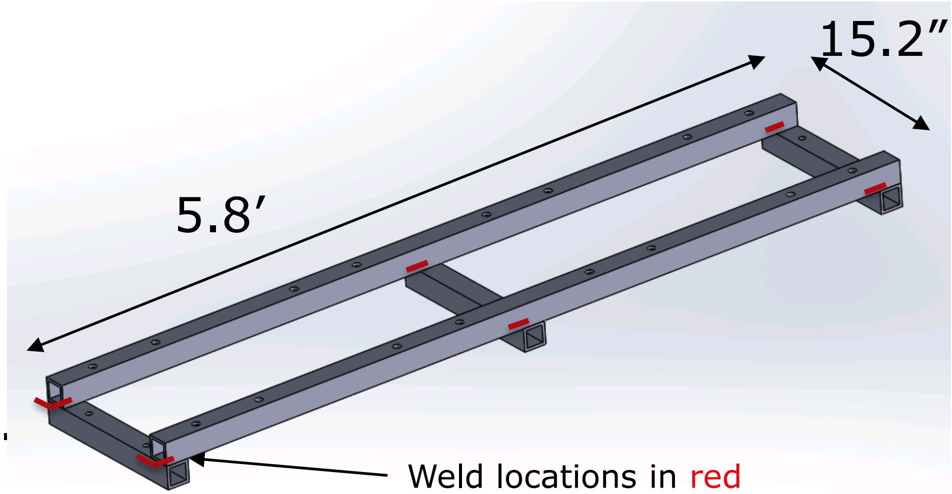
Figure 11. Dial indicator

Francisco Barreto

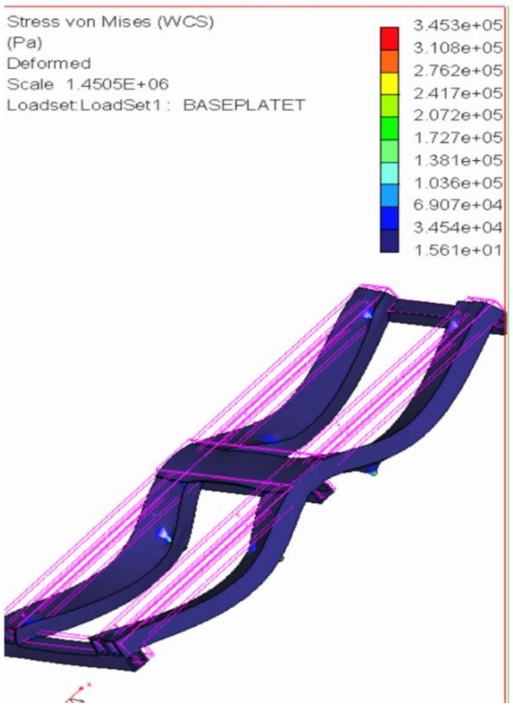
Base Frame Design

- **Base frame:**
  - 2″x2″ mild steel tubing (1/4″ thick)
    - Chosen for its ability to resist warping during welding and availability.

FEA showed a maximum of 0.34 MPa.
Steel yield strength: 250 MPa



Von Mises Stress



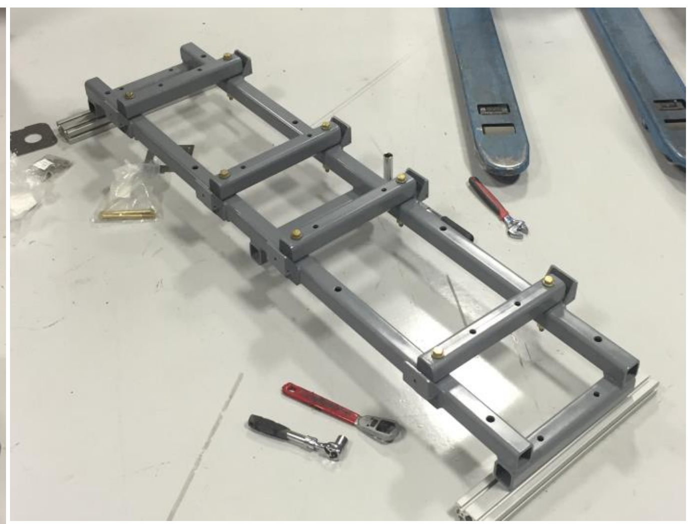
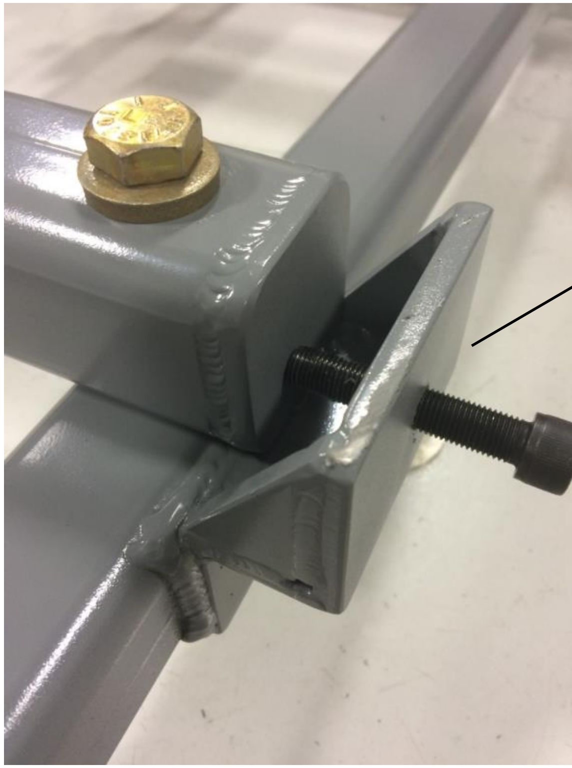


Figure 12, 13, & 14. Base stand dimensions (inches), base frame, and FEA stress analysis.

Francisco Barreto

Base Frame Components



Lateral alignment adjustment:

3/8”-24 Cap screw:
One rotation displaces the screw 0.042 inches.

Yield Stress: 250MPa

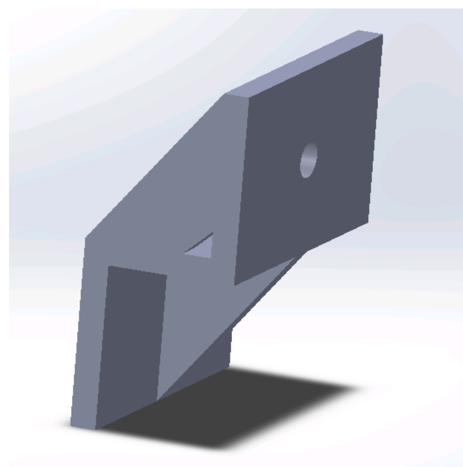


Figure 15: Set screws for horizontal alignment and screw jackets for shim insertion.

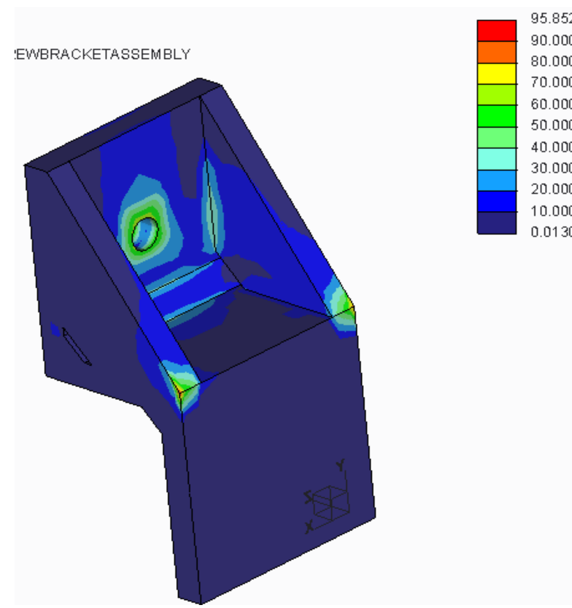


Figure 16: Von Mises stress analysis.
Max stress: 95 MPa

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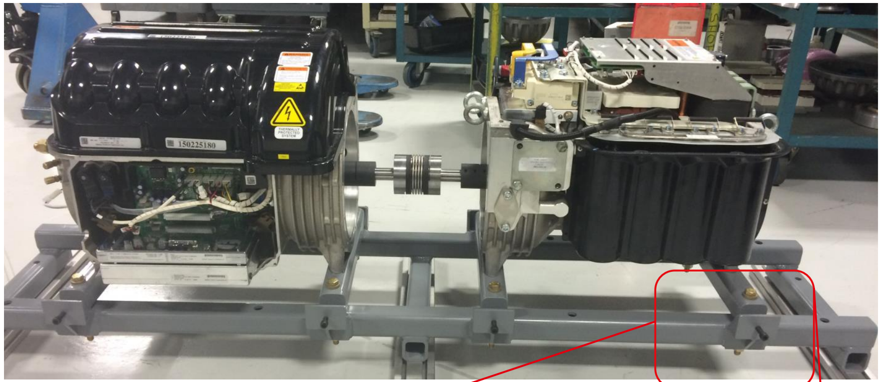
Base Frame Components

Vertical alignment adjustment:



Shim Stock:

- Brass and Stainless steel
- Thicknesses of 0.001, 0.003, 0.006, 0.009, 0.012, 0.020, and 0.031 inches.
- Shims were cut manually with shears.

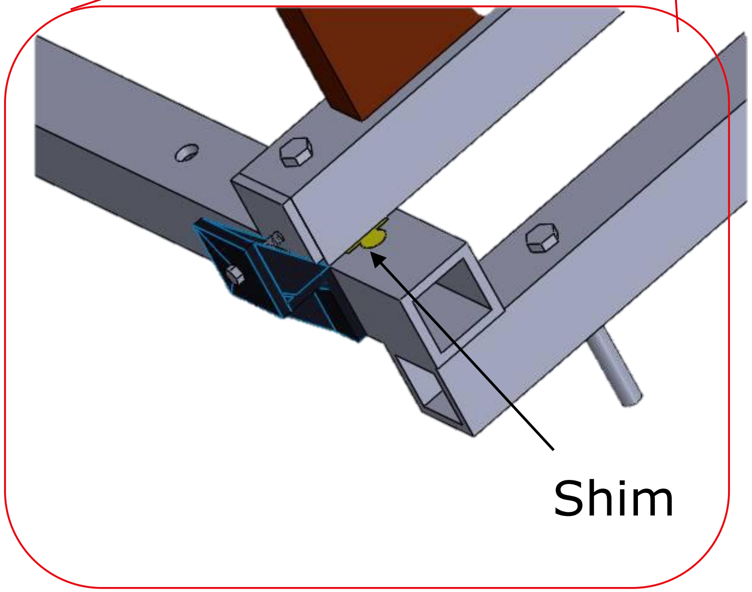


Figure 17, 18 & 19. Shim stock(left), cut shims (middle), shim location (right).

Base Frame Anchoring Method

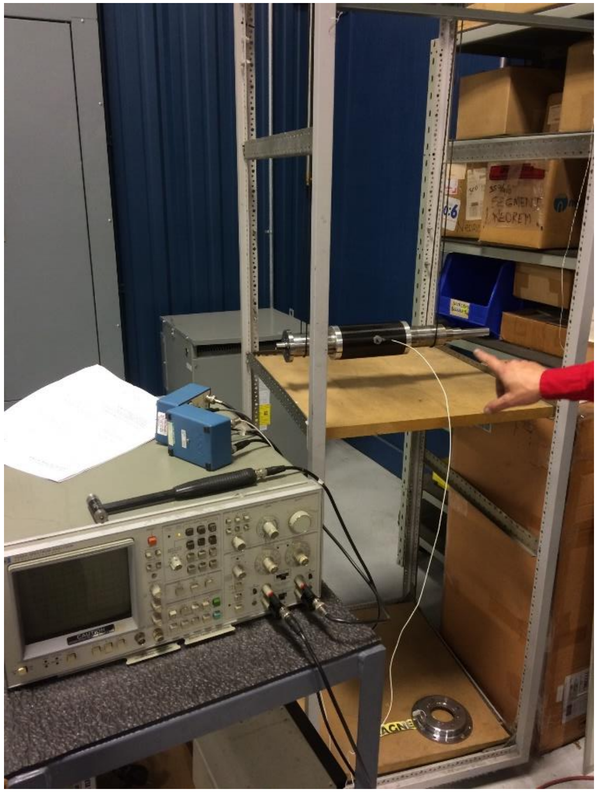
Harmonic resonance is susceptible if the system is mounted to a table top surface.

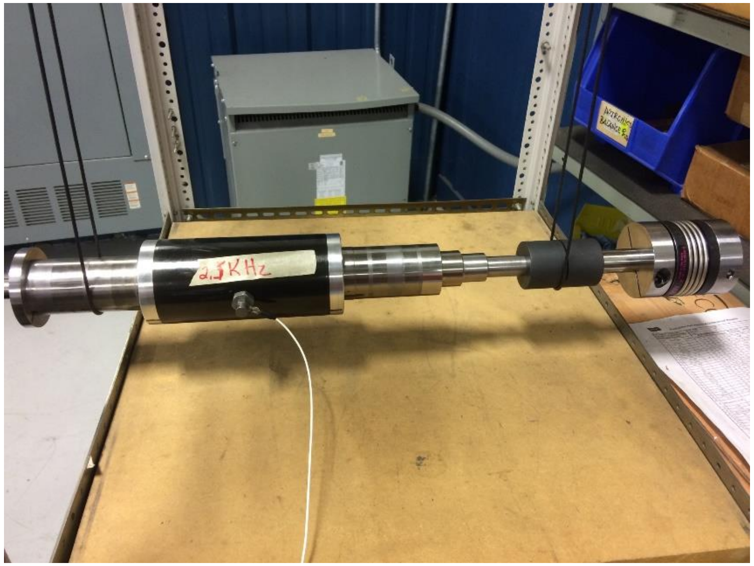
- To keep a fixed position, the test rig is fastened to the ground.
- It is recommended that it be bolted to facility concrete floor to ensure safety.
- Concrete anchors will be used.
- M12 bolt, minimum of 4 inch length to ensure fitting.

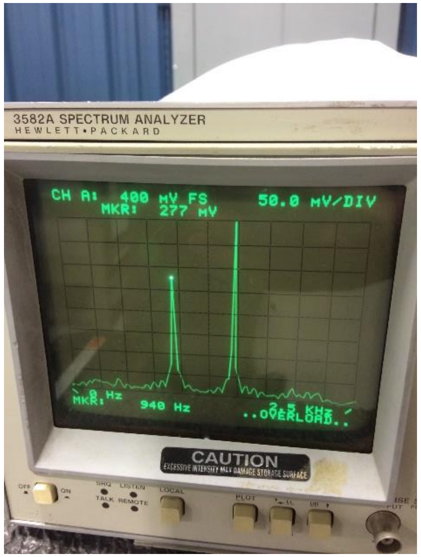
Figure 20. Concrete Anchor Bolt

Natural Frequency: Modal Testing

- Resonance frequency of rotating assembly must be higher than 667 Hz.
- Half of the rotating assembly was mounted to a TT compressor shaft for analysis.
- A frequency of 940 Hz was found for the assembled couplers.







Figures 21,22,23. Test setup, assembled shaft, results screen

Francisco Barreto

Final Design

- 1 Flexible Coupler
  - BK2 150 Bellows Coupling
  - ID: 25.4 mm
- 2 Rigid Couplers
  - Re-Machined
  - ID_1: 22 mm
  - ID_2: 25.4 mm
- Base Frame
  - 2″ x 2″ mid steel tube, ¼″ thick
- 2 TT Series Compressor
- Alignment adjustments with shims and set screws.

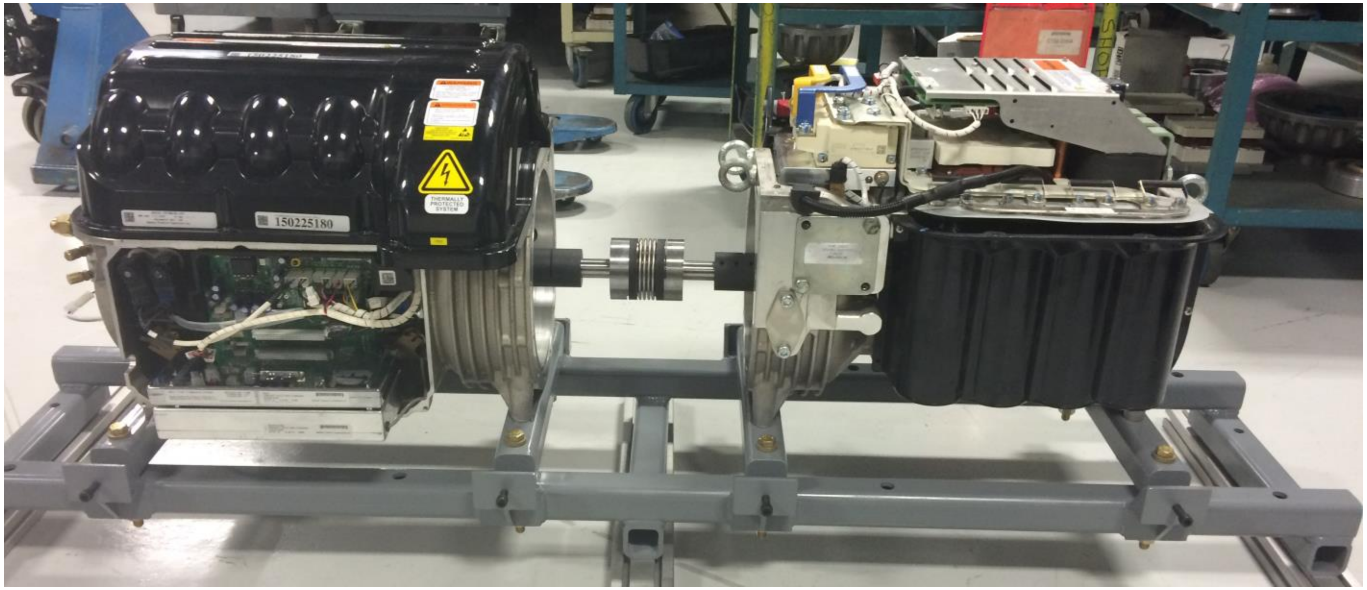


Figure 24: Completed assembly

Assembly Process

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

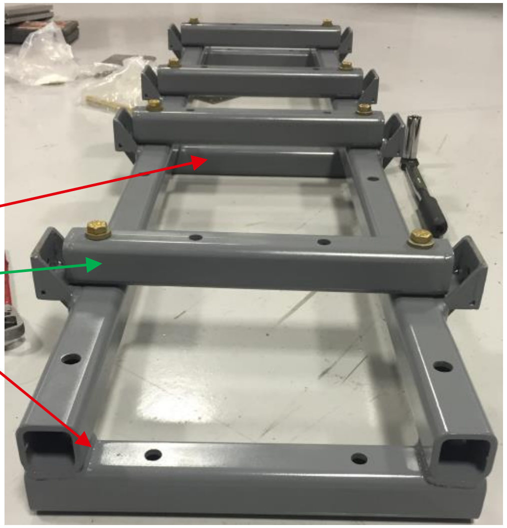


Figure 25: Base frame

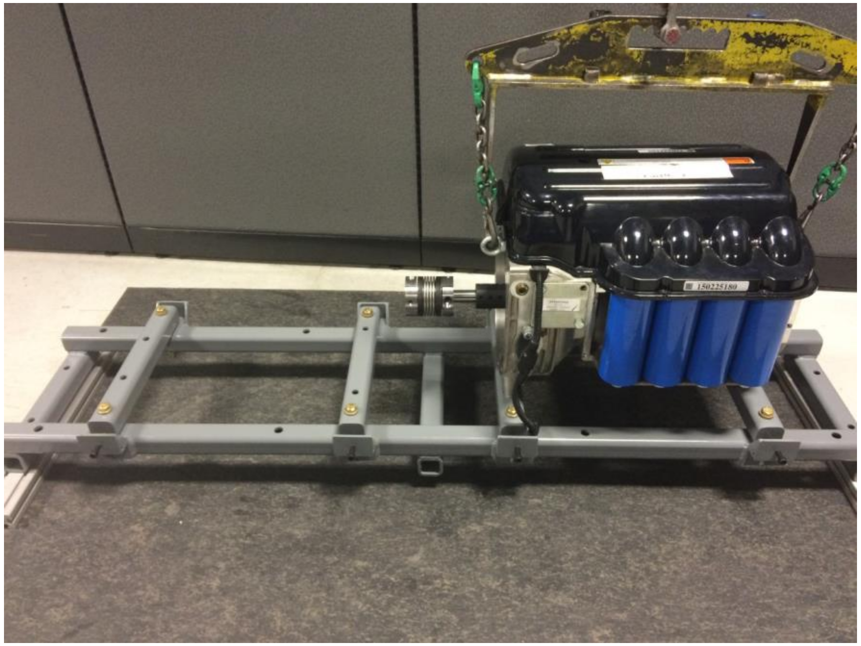


Figure 26. Assembly with one compressor on hoist.

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Assembly Process Continued

3. Rigid couplers, steel dowels, and flexible couplers are secured together to first compressor.
4. Second compressor is mounted to cross members, and shaft is coupled to rotating assembly.

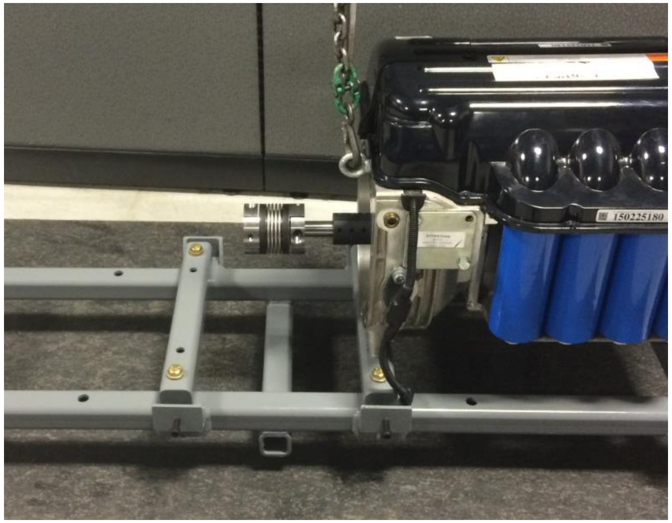
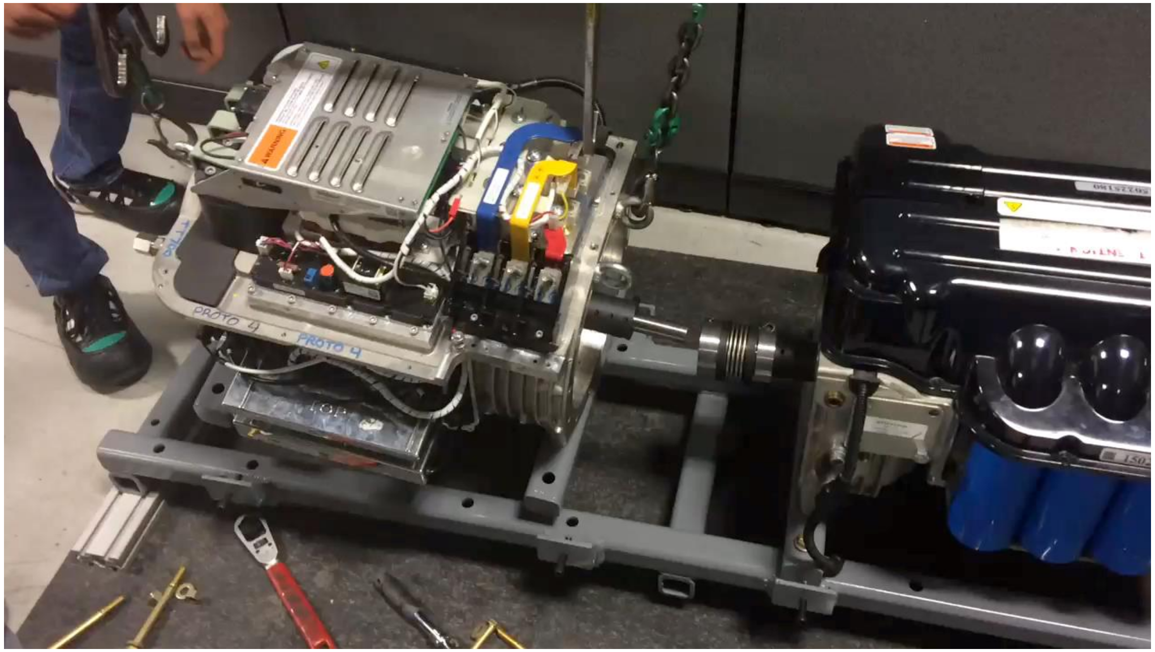


Figure 28. Rotating assembly on first compressor



Video 1. Lowering second compressor onto base frame.

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Alignment Process

- Dial indicators are attached to each shaft.
  - Secured by magnetic base.
- Readings taken at 12, 3, 6, and 9 o'clock
- Excel data sheet used to process values for incremental compressor movement.

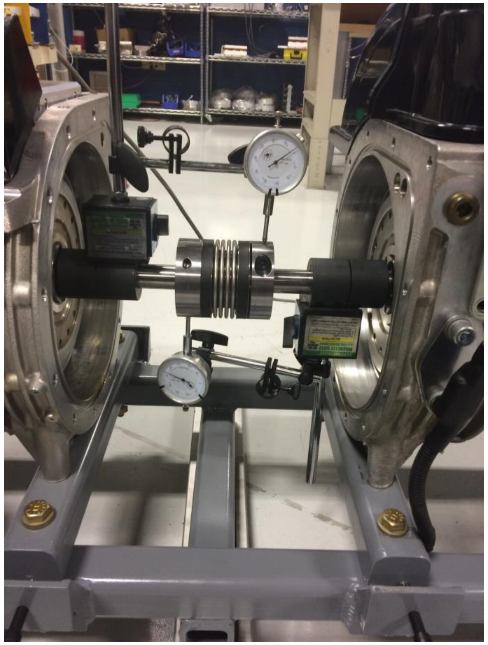

Figure 29. Cross Dial Setup

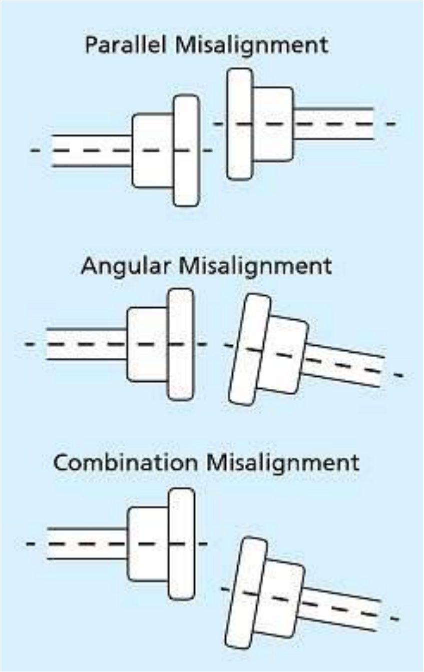

Figure 30. Types of misalignment

Video 2. Dial indicator rotation

Matthew Ketchum

Alignment Process Continued

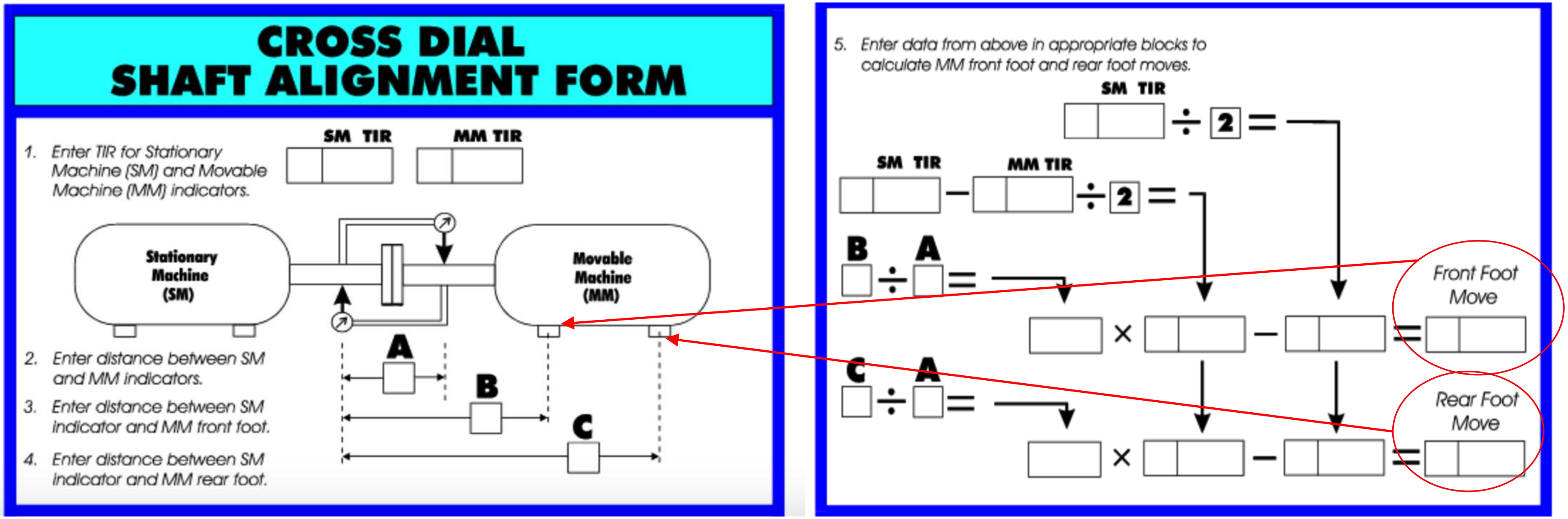

Figure 31. Alignment form

TIR: True Indicated Reading

- The dial displays double the misalignment value. Half of this value is the true displacement.

The alignment form applies to both vertical and horizontal positioning.

Alignment Results

To achieve successful alignment, the final misalignment of the shafts was to be within the tolerances of the flexible coupler.

- **Maximum allowable misalignment:** 0.008” lateral and 1° angular.
- **Final misalignment results:** 0.0025” lateral (horizontal direction) and 0.013° angular.

Vertical:

Front Shim (inches)	Rear Shim (inches)	TIR sm (inches)	TIR mm (inches)
0.000	0.000	-0.005	-0.013
0.013	0.040	0.000	0.0005
-0.0006	-0.002		

Table 3. Vertical alignment adjustment values

Horizontal:

Front Adjustment (inches)	Rear Adjustment (inches)	TIR sm (inches)	TIR mm (inches)
0.000	0.000	0.016	0.008
0.004	0.036	0.015	0.005
-0.0022	0.004	0.009	0.007
0.0015	0.018	0.008	0.006
-0.002	0.0025		

Table 4. Horizontal alignment adjustment values

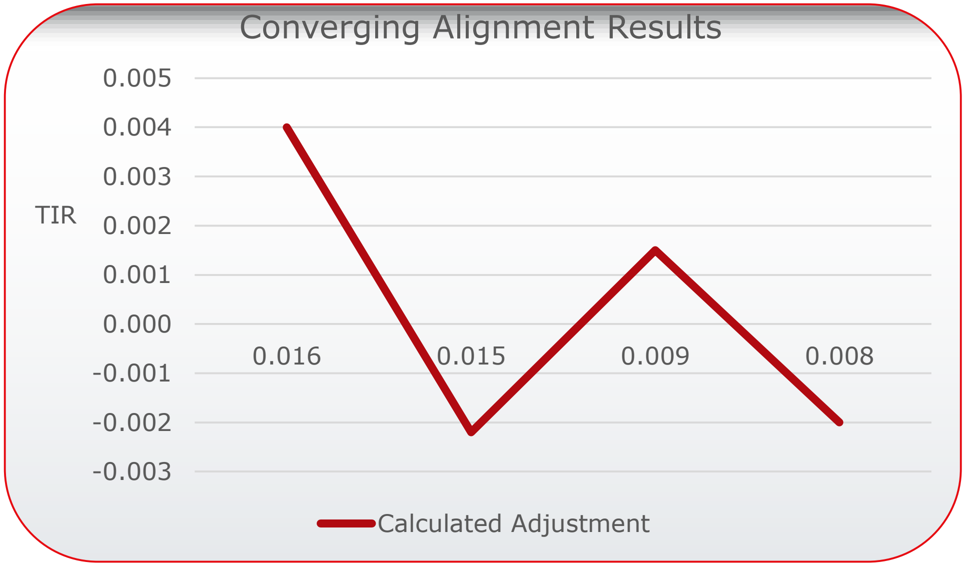

Figure 32. Converging alignment results

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Alignment Results, Sources of Error

- Run-out for rotating assembly:
  - Rigid couplers: 0.019"/0.021", Flexible coupler: 0.015", Extension shafts: 0.012"/0.015".
- Average dial indicator bar sag: 0.014"
- Human errors: Dial zeroing is inconsistent, dials are not at exactly 180 degrees from each other, or dial arms are not perpendicular to the measured surface.

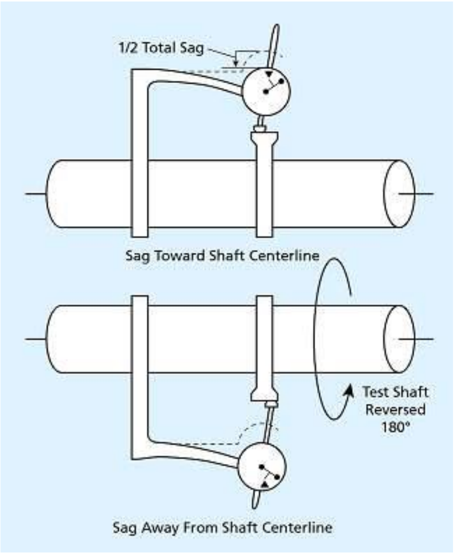

Figure 32. Bar sag.

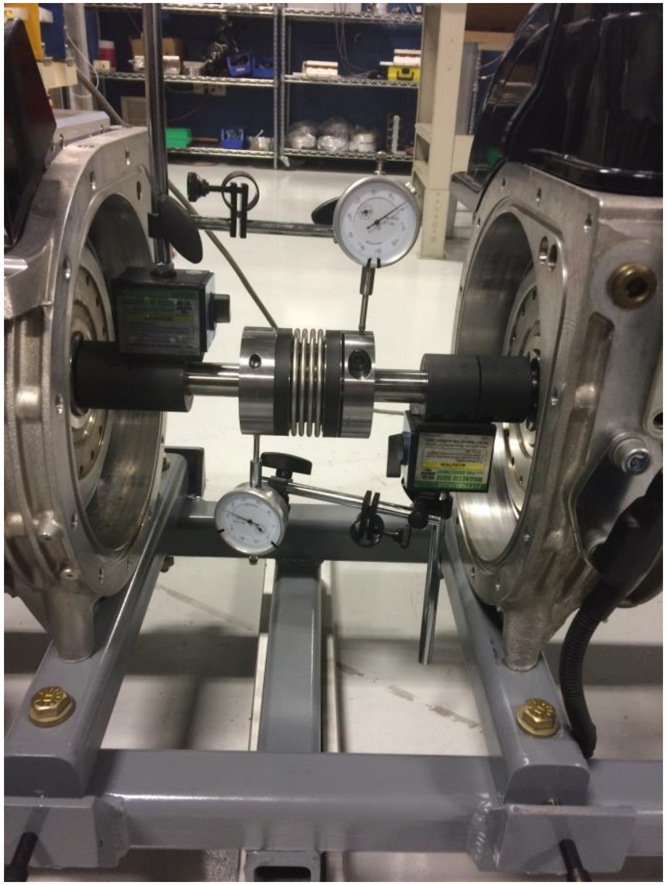
Figure 33. Dial indicators on rotating assembly

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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 5. Safety shield impact analysis

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

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Safety Shielding Design

- Sponsor advised using steel instead of Plexiglass for the shielding.
- Plate thickness: 3/16”

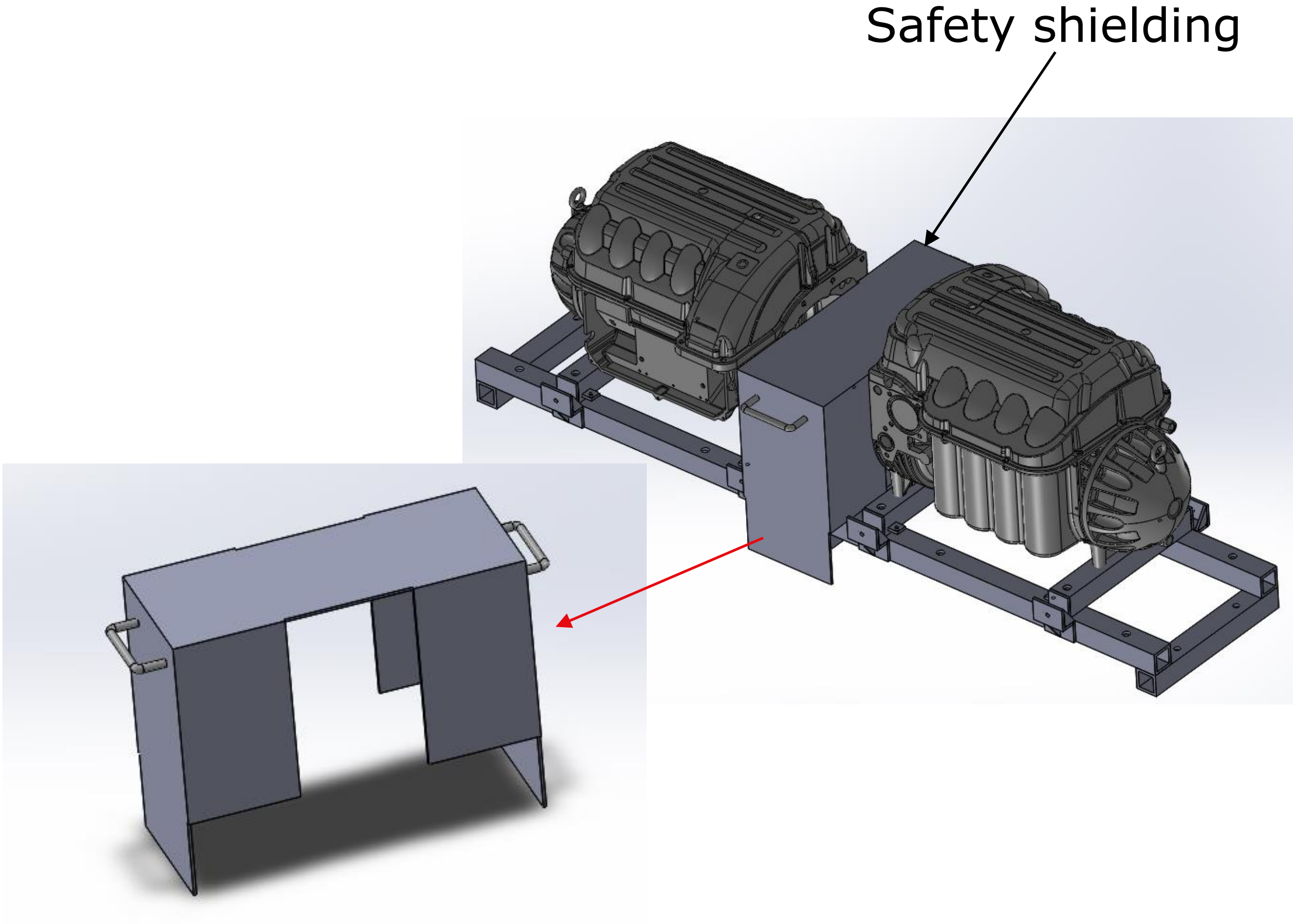

Figure 34. Safety shielding. Figure 35. Assembly with safety shielding.

Matthew Ketchum

Gantt Chart

Task Mode	Task Name	Duration	Start	Finish
	Frequency Analysis	11 days	Sun 2/14/16	Fri 2/26/16
	Temporary assembly evaluation	5 days	Mon 2/22/16	Fri 2/26/16
	Receive flexible coupler and rigid couplers	15 days	Tue 3/1/16	Mon 3/21/16
	Additional part order (If needed)	6 days	Tue 3/15/16	Tue 3/22/16
	Frame Fabrication	4 days	Tue 3/15/16	Fri 3/18/16
	Receive fasteners	3 days	Mon 3/21/16	Wed 3/23/16
	Frame assembly	5 days	Mon 3/21/16	Fri 3/25/16
	Machine parts	**13 days**	**Tue 3/15/16**	**Thu 3/31/16**
	Rigid coupler	10 days	Tue 3/15/16	Mon 3/28/16
	Bracket Parts	13 days	Tue 3/15/16	Thu 3/31/16
	Shaft	10 days	Tue 3/15/16	Mon 3/28/16
	Balance rigid coupler and extension shaft	5 days	Mon 3/28/16	Fri 4/1/16
	Integrate couplers	3 days	Fri 4/1/16	Tue 4/5/16
	Rent alignment equipment	3 days	Fri 4/1/16	Tue 4/5/16
	Integrate alignment system	2 days	Tue 4/5/16	Wed 4/6/16
	Qualify alignment process	3 days	Wed 4/6/16	Fri 4/8/16

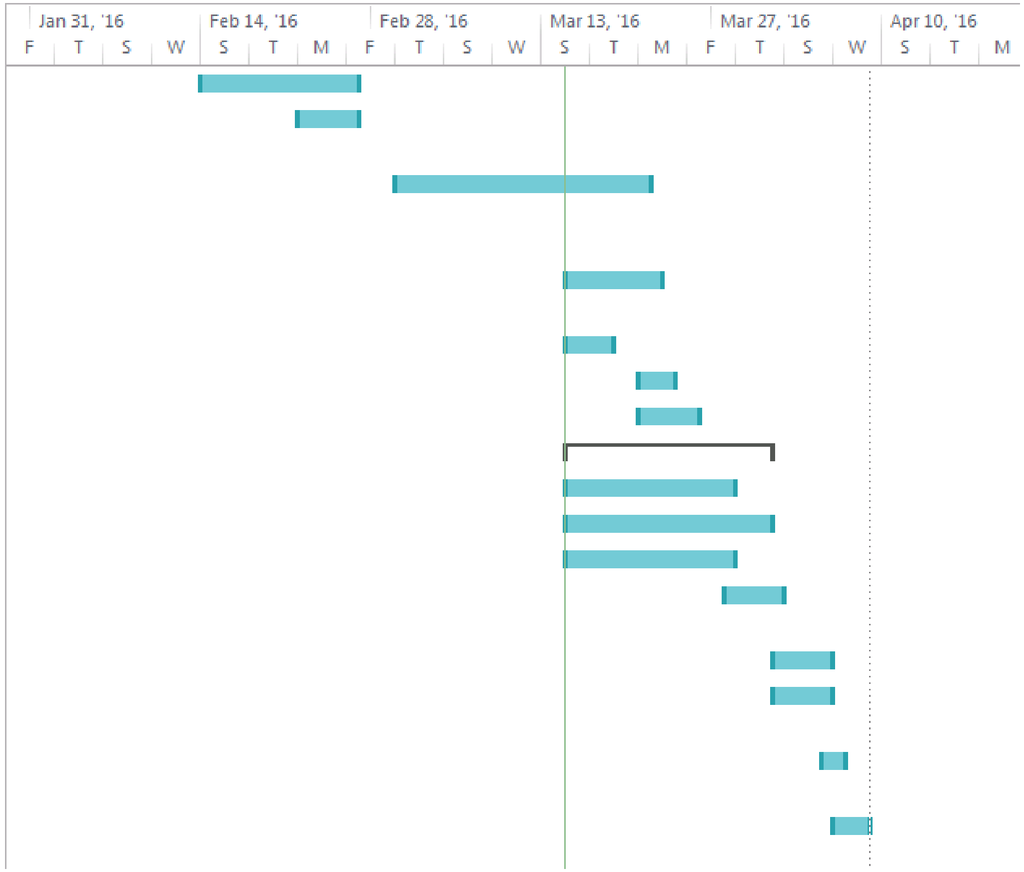

Figure 35. Gantt Chart, Spring Semester.

Recent Milestones:

- Assembly completed in one day.
- Testing took one day, final results showed a successful proof for the alignment process.

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Cost Breakdown

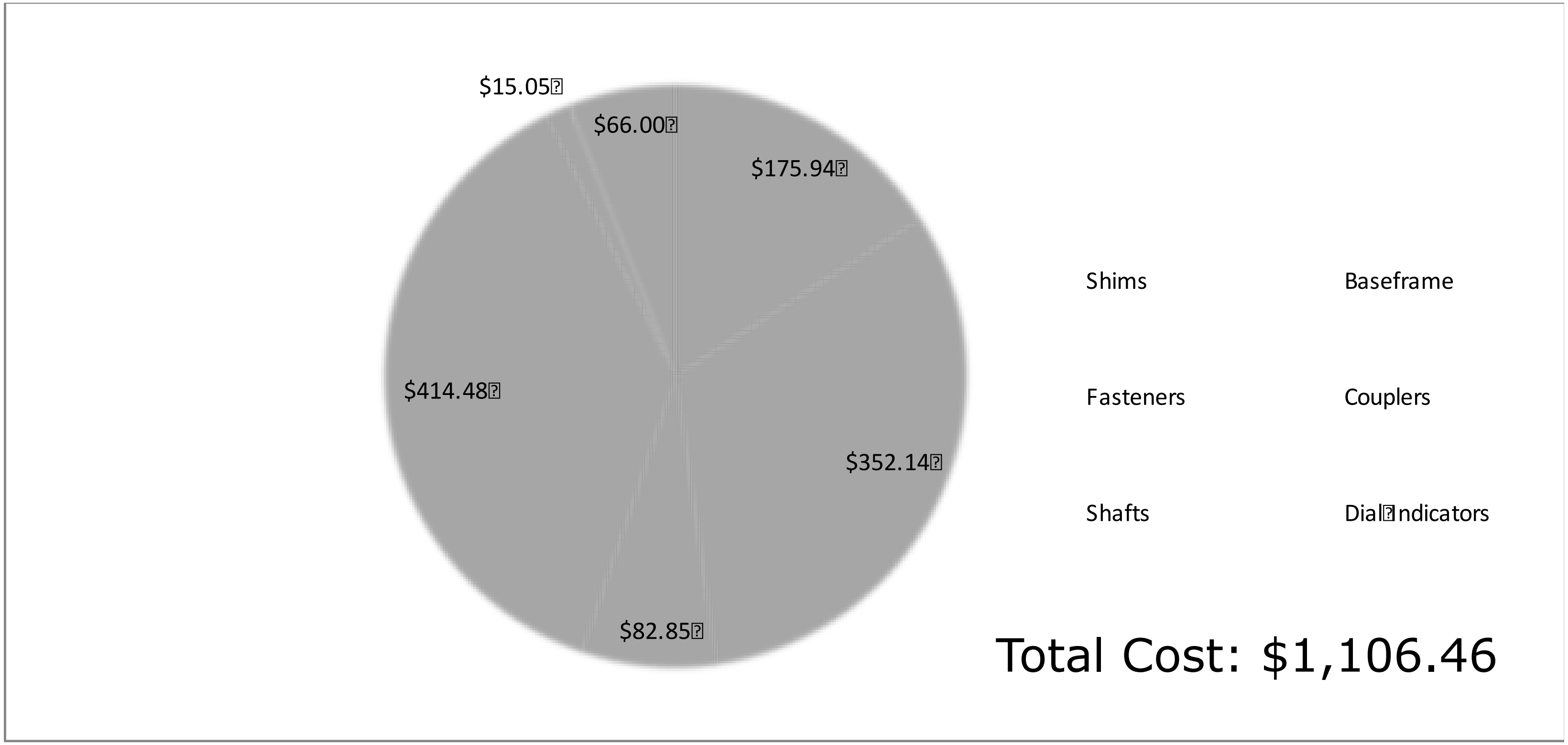

Figure 36. Cost breakdown

Conclusion & Future work

- The rotating assembly was found to have a natural frequency of 940 Hz. This is satisfactory for lower speed rotations and alignment process qualification.
- Dial indicator alignment process is sufficient for the test rig operation.
  - **Final misalignment results:** 0.0025" lateral (horizontal direction) and 0.013° angular.
  - Developed process was proved to align shafts.
- Next steps are to work towards high speed rotation, this requires:
  - Re-balancing the rotating assembly components.
- If high speed rotation can be achieved, the system will be ready for torque transducer integration.
  - Estimated cost to achieve this next phase: $17,436-$19,936.

Future Work Recommendation:

- Evaluate if the benefits of the next phase design is worth the cost.
- Purchase a laser shaft aligner or specially designed dial indicator alignment kit for higher accuracy shaft alignment.

Matthew Ketchum

Acknowledgements

Team 4 thanks Danfoss Turbocor for the opportunity to work on a new and unique system design. Gratitude to William Sun, Kevin Lohman, and Julio Lopez, who provided imperative help for project progress.

Dr. Patrick Hollis and Dr. Nikil Gupta gave continuous feedback that developed individuals to improve their understanding of real world engineering.

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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/

7.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

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 Stength 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 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
1570 Cherokee St. San Marcos CA 92078
Fax: 800-648-2411

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

DATE: 24-Feb-16

DATE REQUIRED: **ASAP**

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
	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

Special instructions:

Prepared by: ______________________ (Print name)

Approved by: ______________________ (Manager)

R+W COUPLING TECHNOLOGY

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

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

Fax: kevin.lohman@danfoss.com

SALES QUOTE # 65010

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

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	**Bellows Coupling** BK2 / 150 / 95 / 25.4 / 25.4 Bore D1: 25.4 H7 Bore D2: 25.4 H7	329.56	329.56 USD
		Total		329.56 USD

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

Best regards,

R+W America

Leon Voskov

ENGINEERING TOMORROW

Danfoss

Natural Frequency Analysis

1st simulation step by step

Frequency: 337 Hz

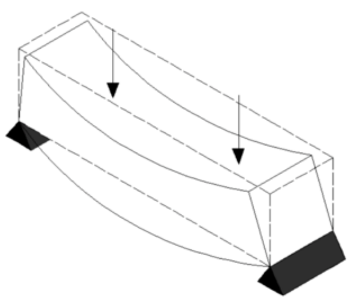
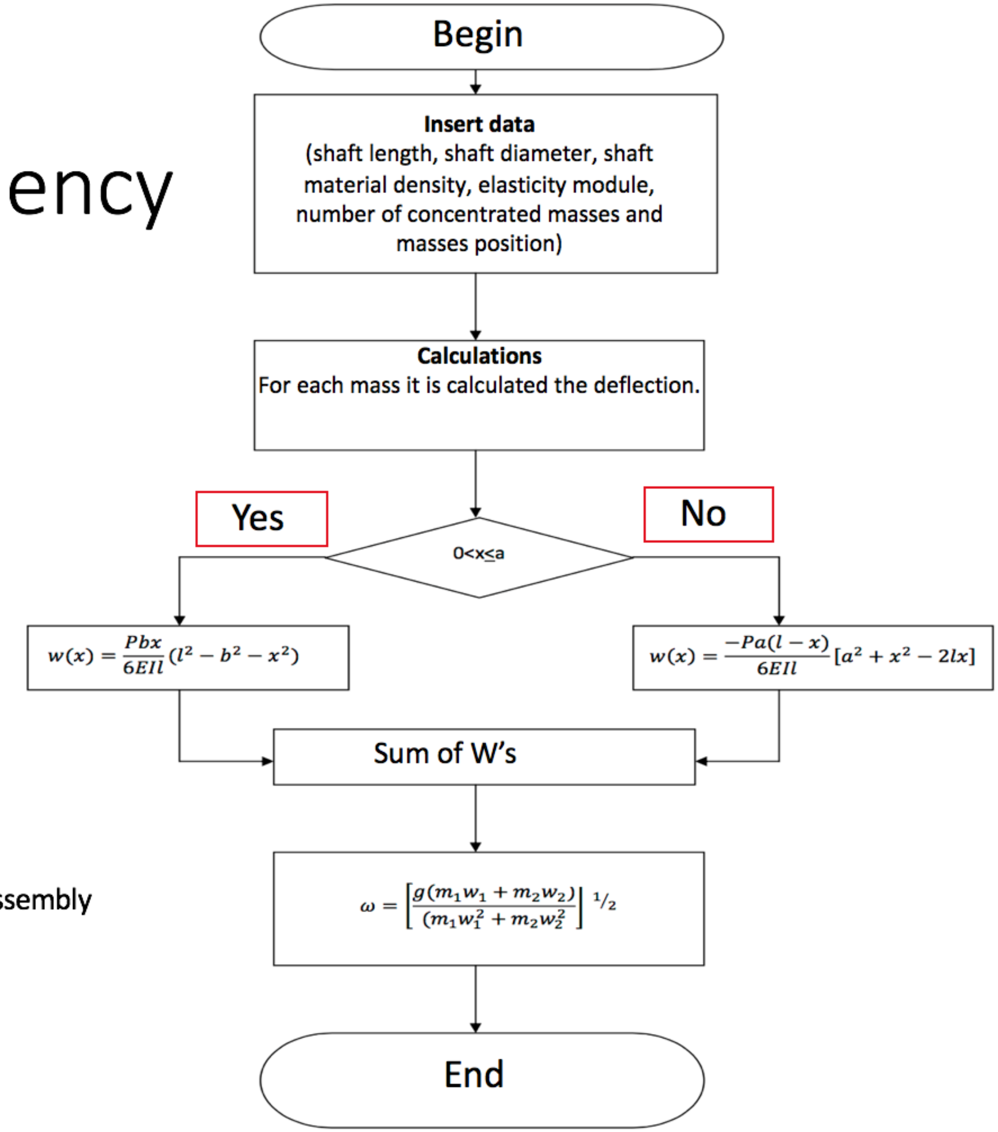


Figure #: Scenario analyzed: rotating assembly as an entire shaft



Natural Frequency Analysis

2nd simulation step by step

Frequency: 708 Hz

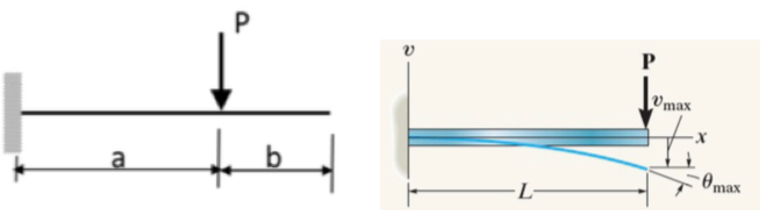


Figure #: Scenario analyzed: rotating assembly as half shaft

Begin

Insert data
(shaft length, shaft diameter, shaft material density, elasticity module, number of concentrated masses and masses position)

Calculations
For each mass it is calculated the deflection.

$0<x\leq a$

Yes:

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

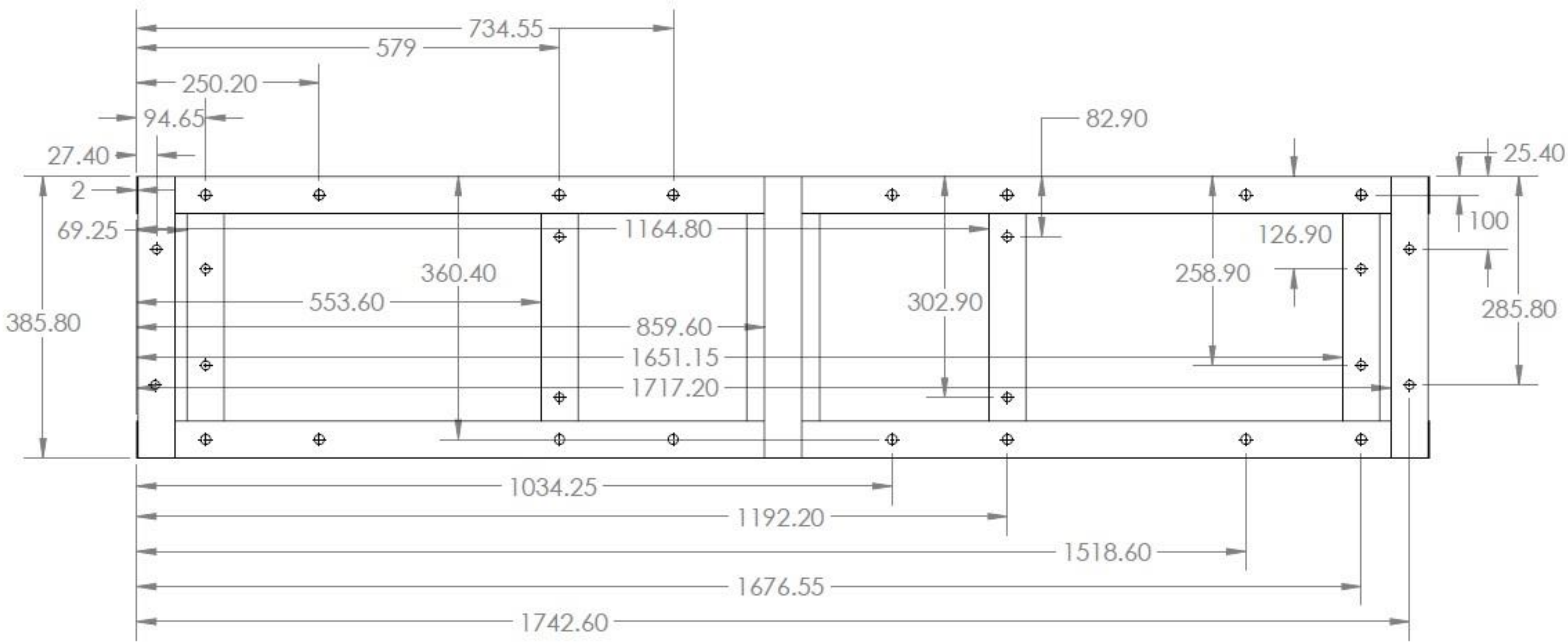
No:

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

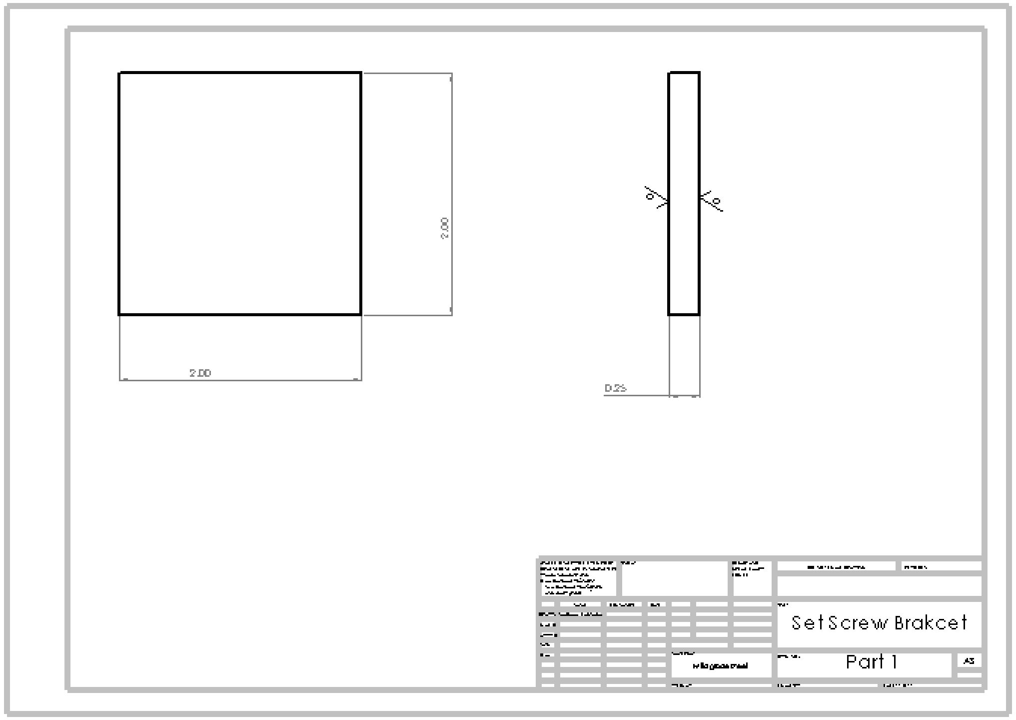
Sum of W's

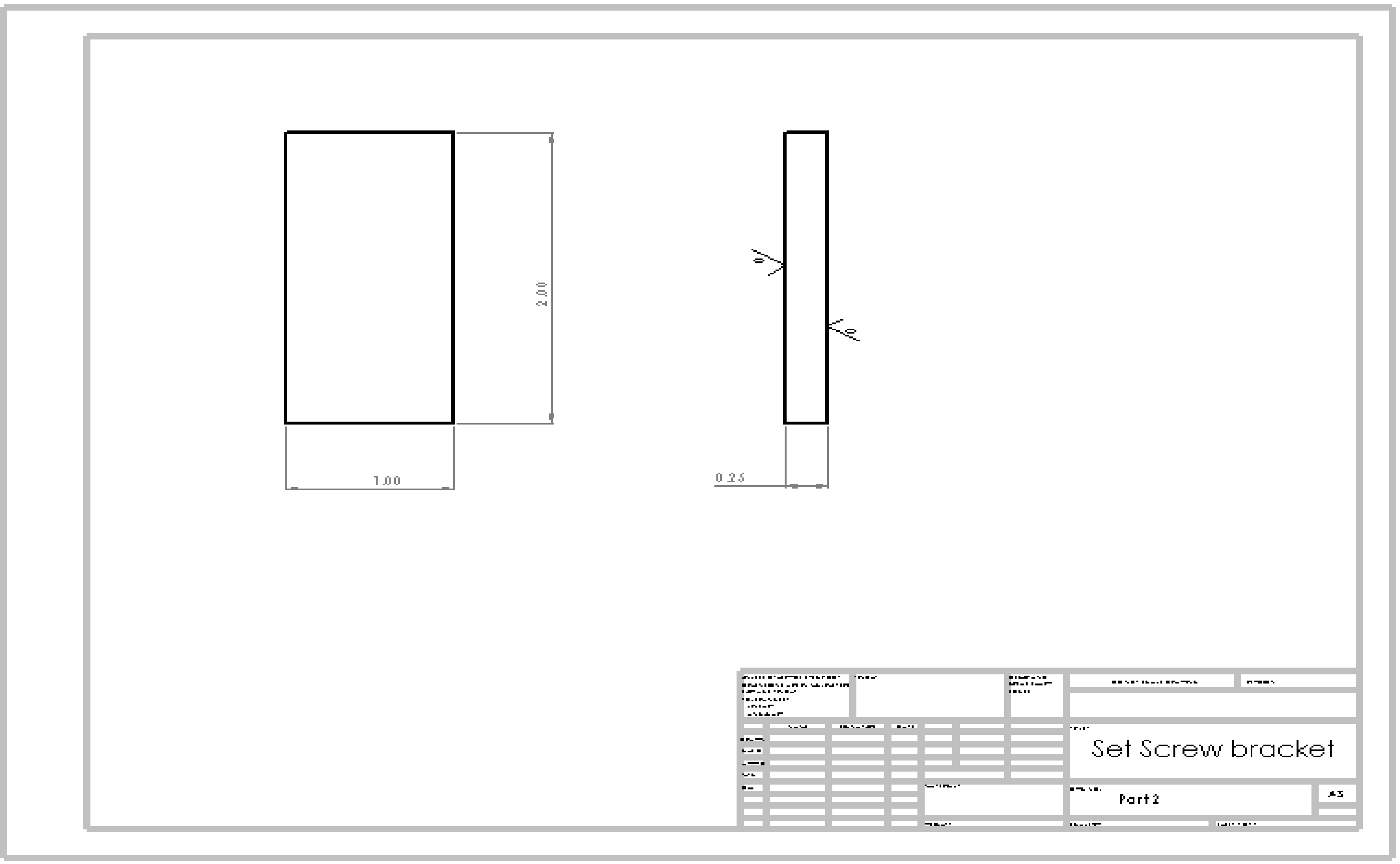
$$\omega = \left[\frac{g(m_1w_1 + m_2w_2)}{(m_1w_1^2 + m_2w_2^2}\right]^{1/2}$$

End

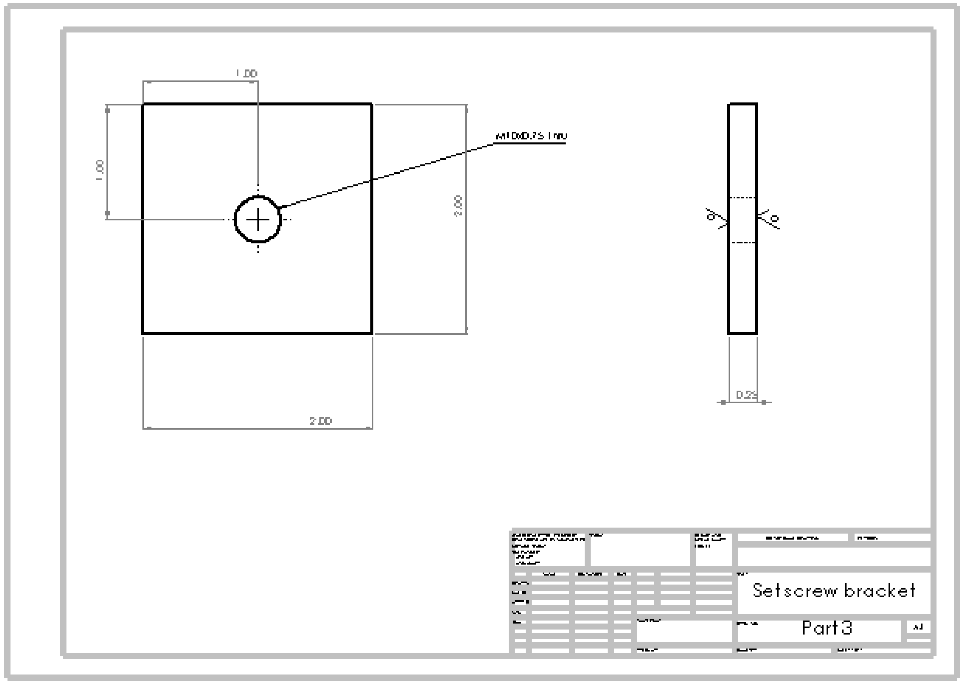


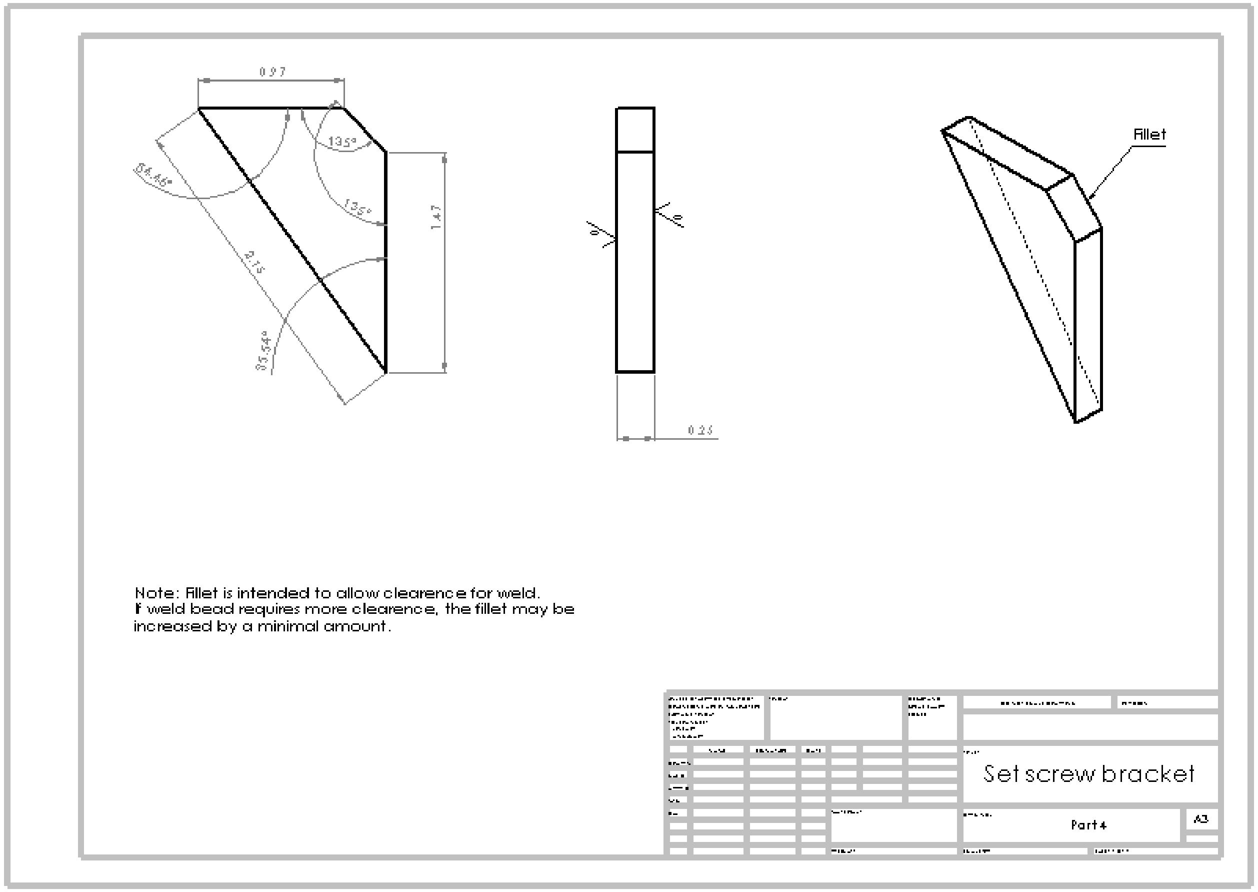
734.55
579
250.20
94.65
27.40
2
69.25
385.80
82.90
25.40
100
1164.80
126.90
360.40
258.90
553.60
302.90
285.80
859.60
1651.15
1717.20
1034.25
1192.20
1518.60
1676.55
1742.60


2.00
2.00
0.25
Set Screw Brakcet
Part 1
A5



2.00
1.00
0.25
Set Screw bracket
Part 2


1.00
1.00
M10X0.75 Thru
2.00
2.00
0.25
Setscrew bracket
Part3


0.97
135°
54.46°
135°
1.47
2.15
35.54°
0.25
Fillet
Note: Fillet is intended to allow clearence for weld.
If weld bead requires more clearence, the fillet may be increased by a minimal amount.
Set screw bracket
Part4
A3