High Speed Motor Test Rig Design Review I

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2-16-16

Presentation Overview

1. Background
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3. Project Description
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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

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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 prohibits bending forces to transfer 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.

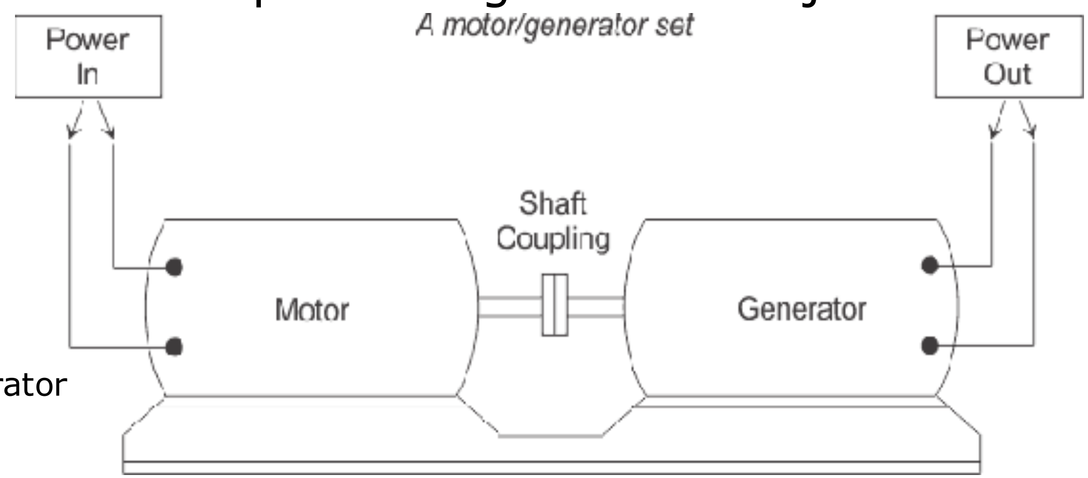

Figure 2. Motor-generator concept

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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.

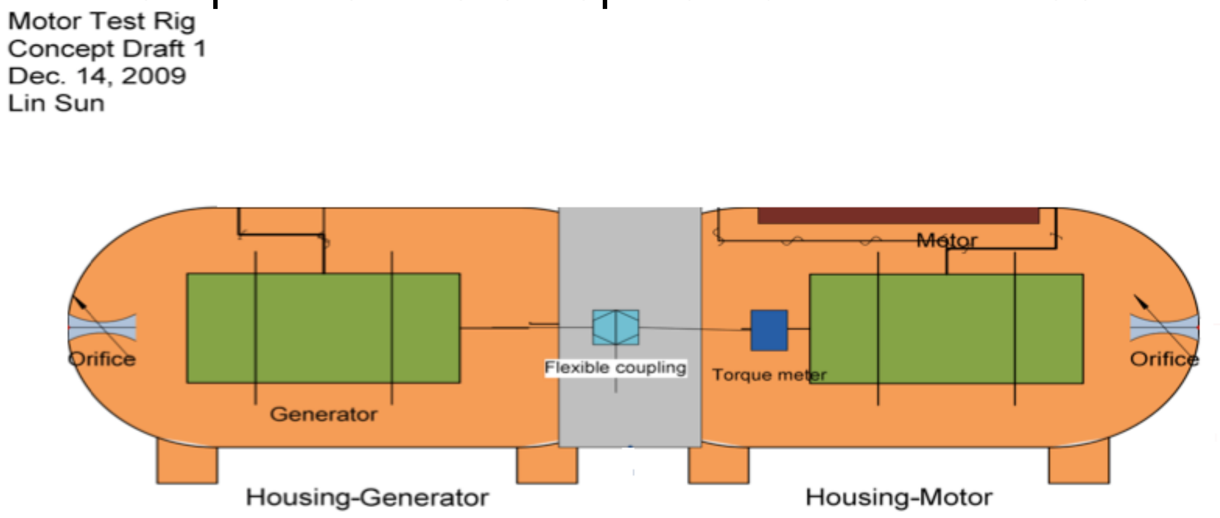

Figure 3. Motor-test rig concept draft

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.
- **Mechanical 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

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Ideal Design

- 2 rigid couplers, 20 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 design.

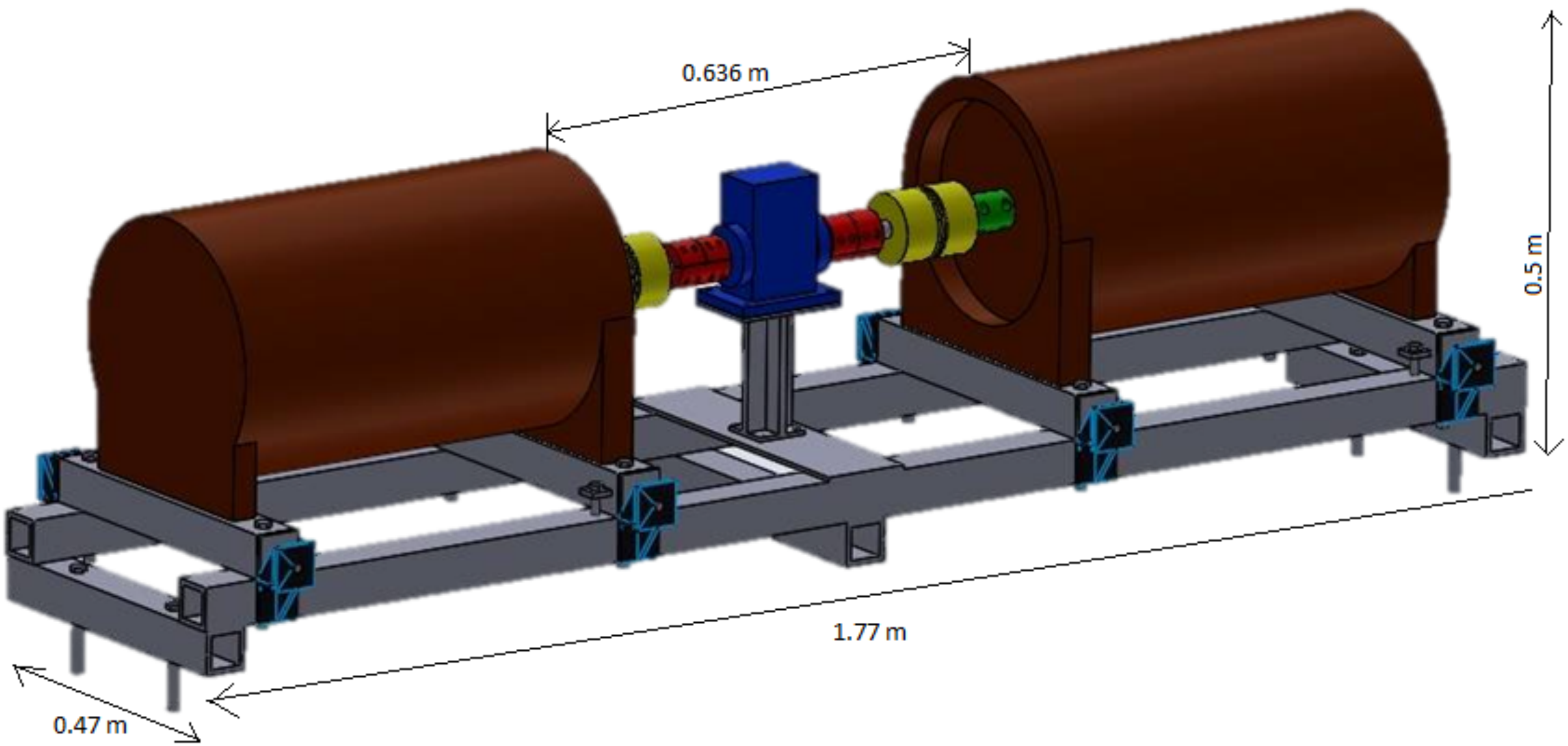

Figure 4: Ideal test rig design view

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Final Design

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

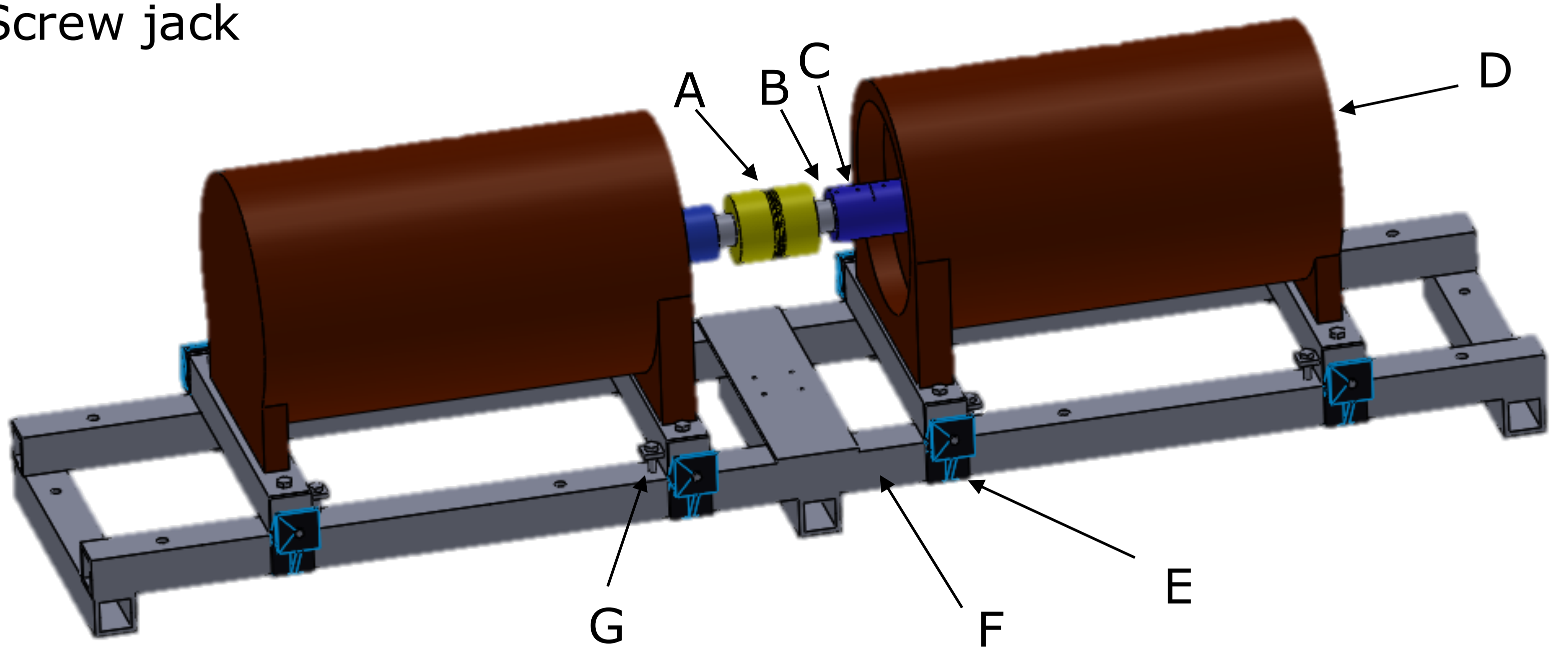

Figure 5: Final design assembly

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Components selected

- **Shaft extender: SUA 050**
  - Steel, ASTM A108
  - Length: 69.85mm
  - Inner bore: 22.225 mm
  - Shaft OD: 20.000 mm

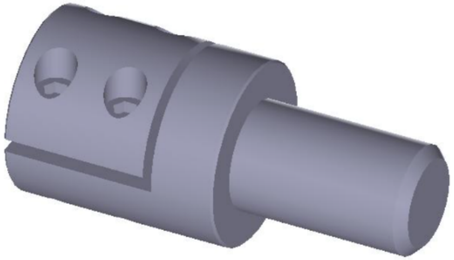

Figure 6. Shaft extender SUA 050

- **Rigid coupler: R2CC 075**
  - Re-machinable: Will be balanced and bored by Danfoss
  - Stainless Steel, ASTM A582
  - OD: 44.45 mm, Length: 66.67 mm
  - $ID_{transducer308/311}$:20 mm/10 mm
  - $ID_{shaft308/311}$: 20 mm/20 mm

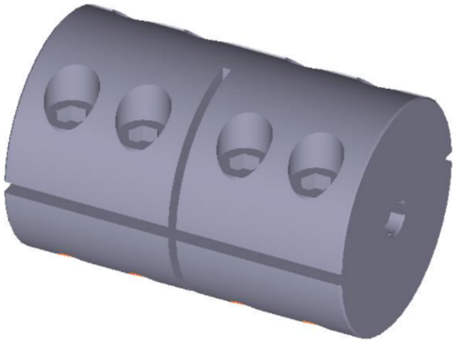

Figure 7. R2CC Rigid Coupler

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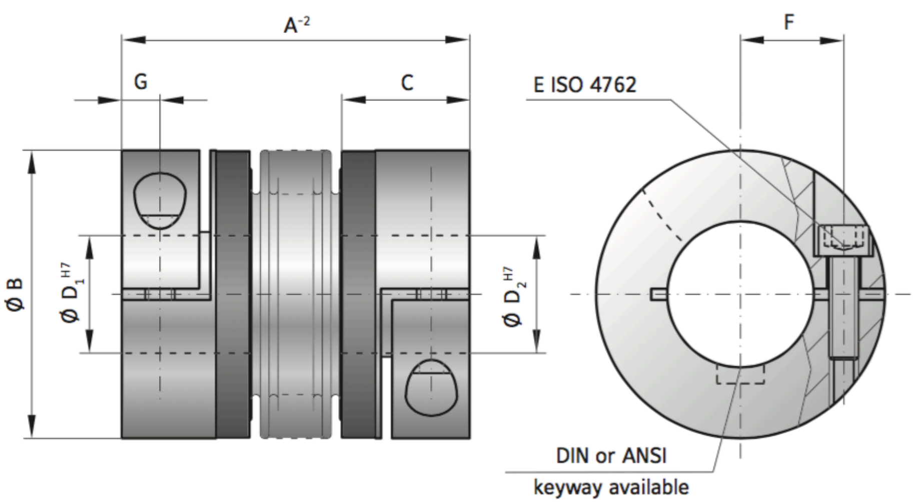
Components selected

- **Flexible coupler: BK2 150 Bellows coupling**
  - 150 Nm rated torque
  - 80,000 RPM rating
  - Safety factor: 2.11
  - Misalignment tolerances: 0.2mm lateral, 1°angular, and 1 mm axial.



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		

Figure 8. Bellow coupling BK2 150

Components selected

- **Torque transducer: Magtrol 308/311**
  - Torque measurement error: <0.1%.
  - High speed applications: 50,000/32,000 rpm.
  - Torque rating: 20 Nm/100 Nm.

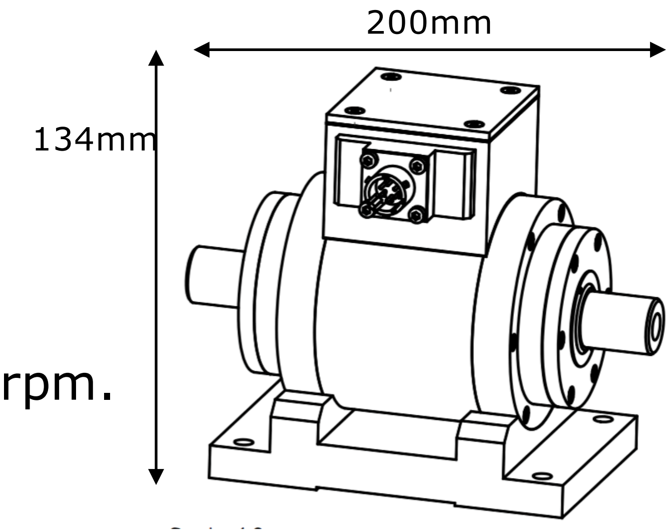


Figure 7. R2CC Rigid Coupler

- **Laser alignment tool: TKSA 31**
  - Measuring error less: <5%.
  - Accuracy of 10 μm.
  - Reduces errors and system down time in alignment process.
  - 6in clearance for rotation.

Figure 8. Laser alignment tool TSKA 31

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Components selected

- **Shaft:**
  - Steel, ASTM A108
  - Connects rigid coupler to flexible coupler.

  Diameter accuracy: $25\mu m$

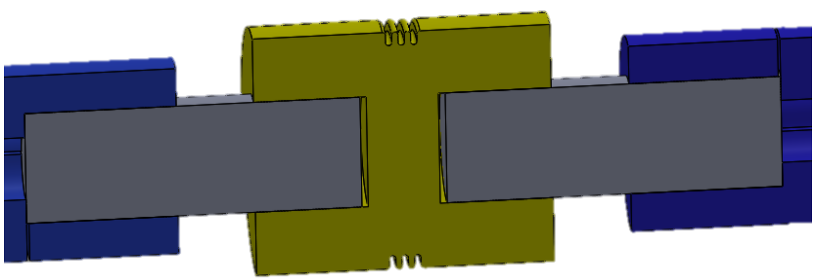

Figure 9: Shaft in the assembly

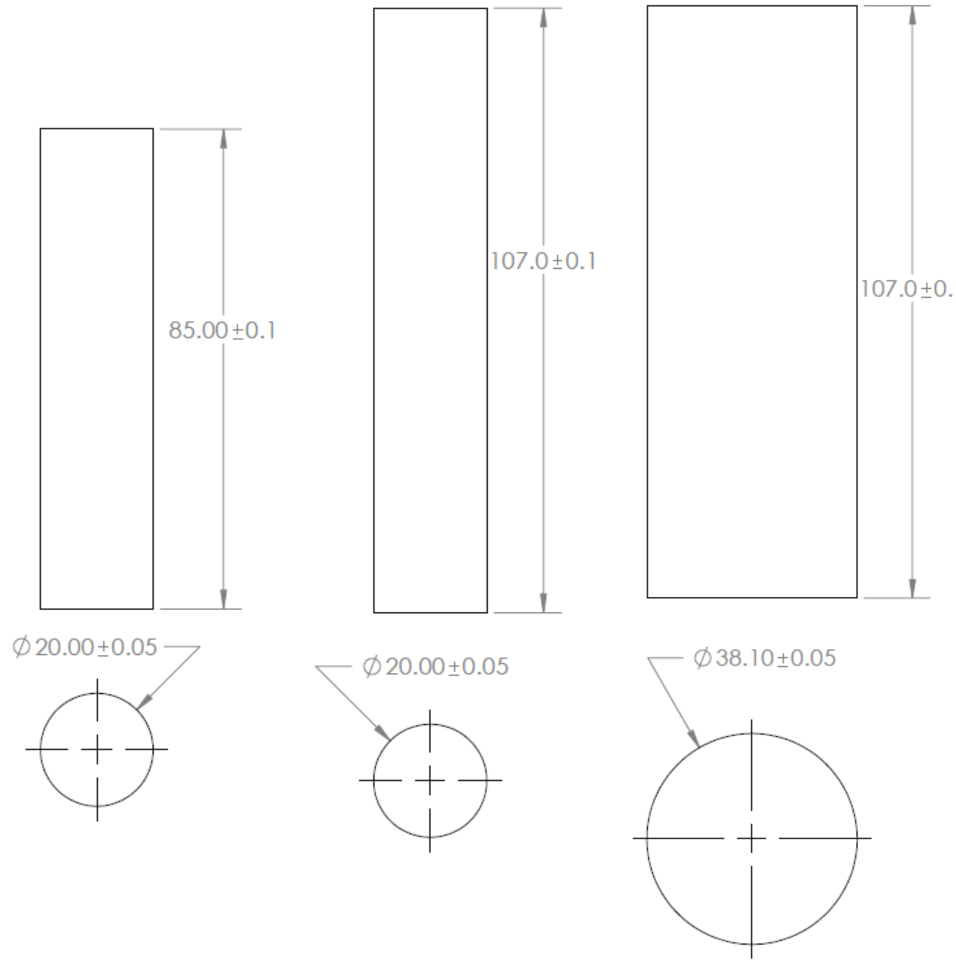

Figure 9. Shaft dimensions for scenario with torque transducer Magtrol 308/311 and without the torque transducer

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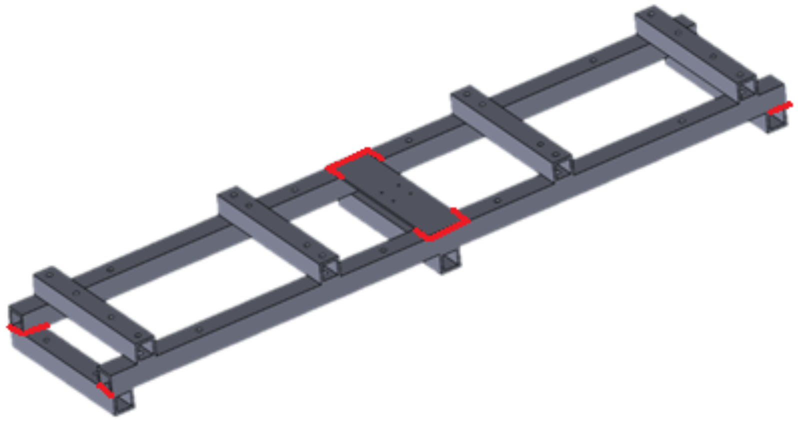
Base frame design

- **Base frame:**
  - 2x2x1/4”
  - Support the compressor, torque transducer and fix to the ground.



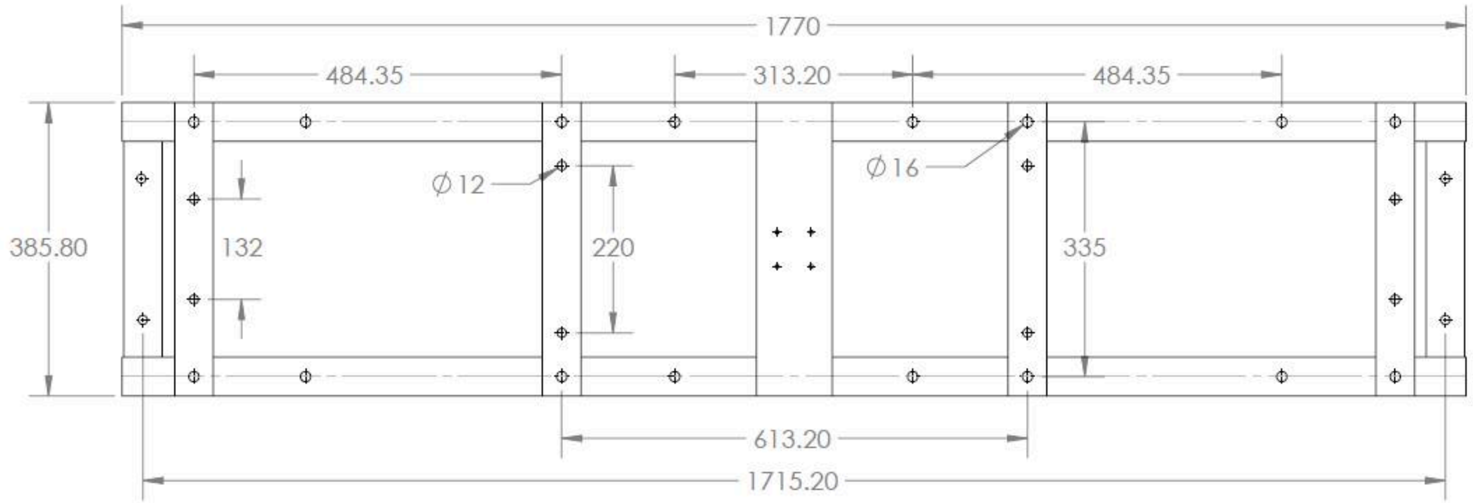


Figure 10 & 11. Base stand dimensions and 3D view

Base frame design

- Maximum Displacement: 0.1 μm
- Maximum Stress: 3.4 MPa

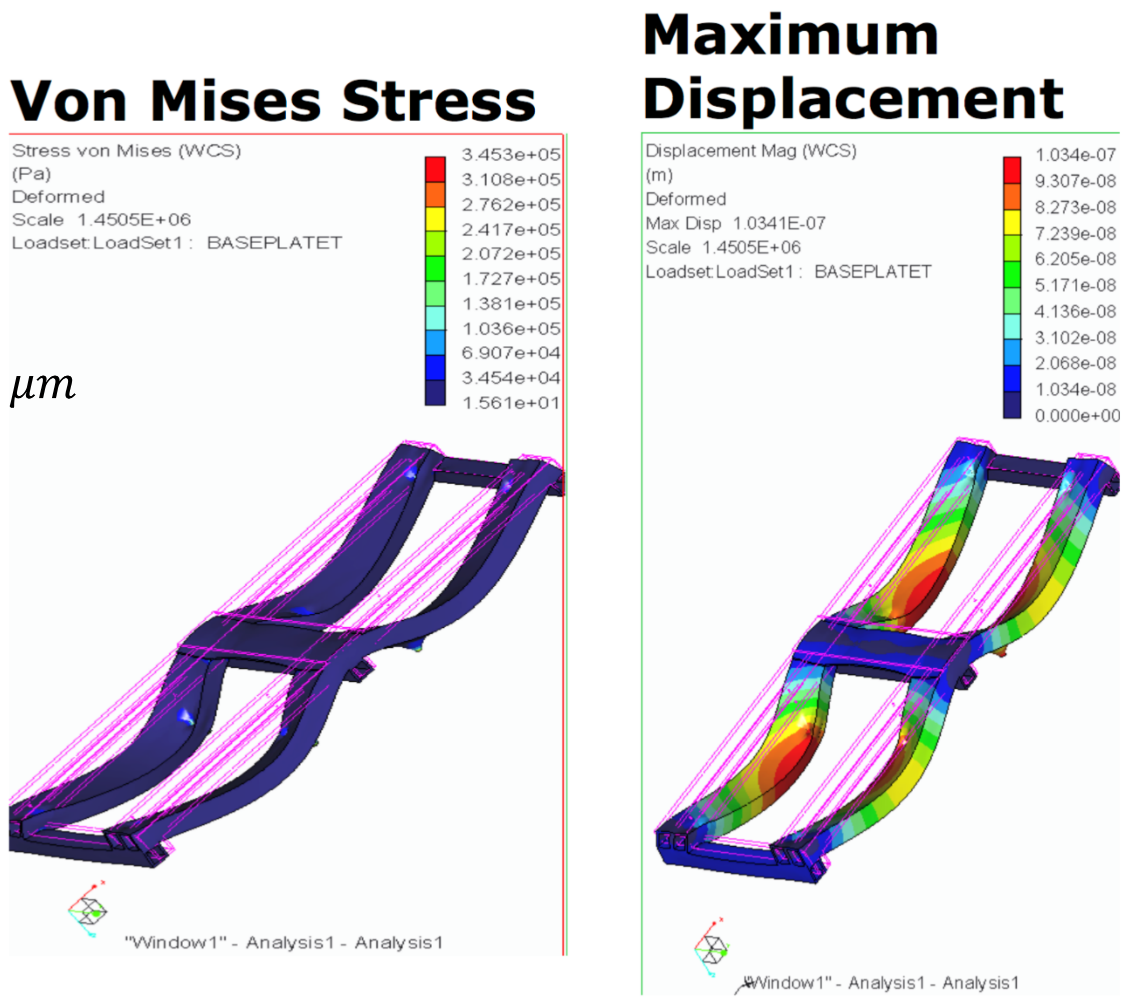


Figure 12. FEA Analysis

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Base frame components

Lateral alignment adjustment:

M8, pitch 1.25 mm
M10, pitch 0.75 mm

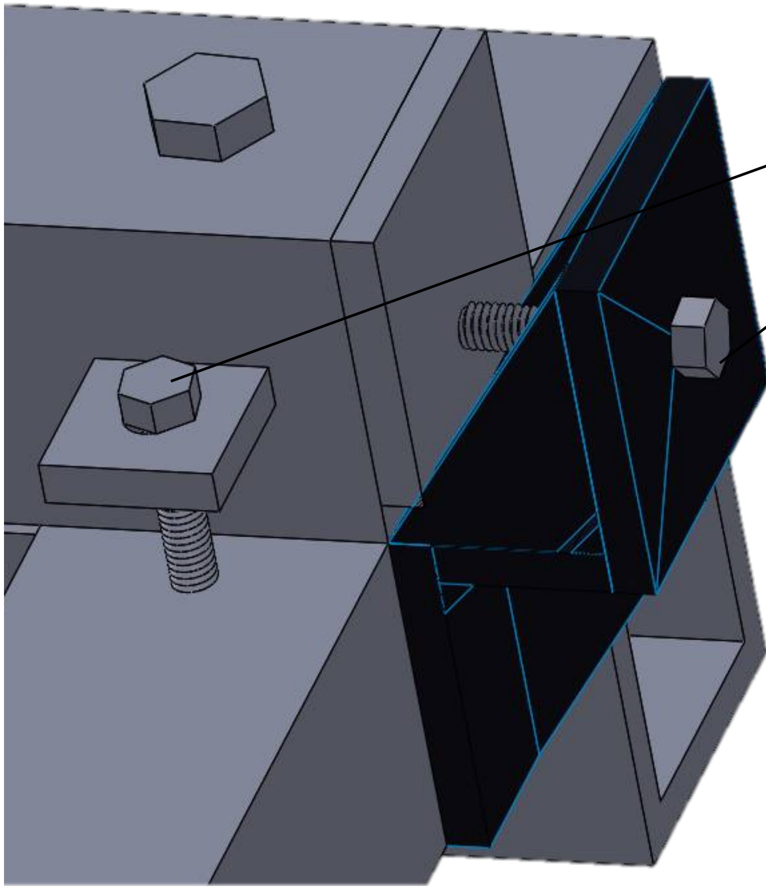

Figure 13: Set screws for horizontal alignment and screw jackets for vertical alignment

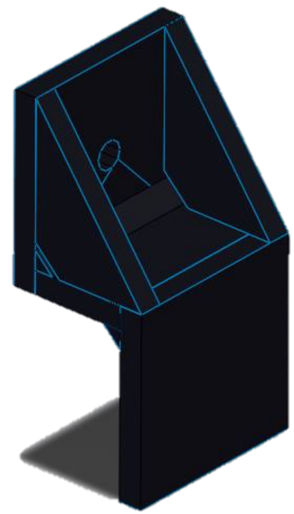

Figure 14: 3D view of brackets for horizontal alignment

Base frame components

- Maximum stress:
  - Tab: 94 MPa
  - Bracket: 80 Mpa
  - Yield strength of A36 steel: 250MPa

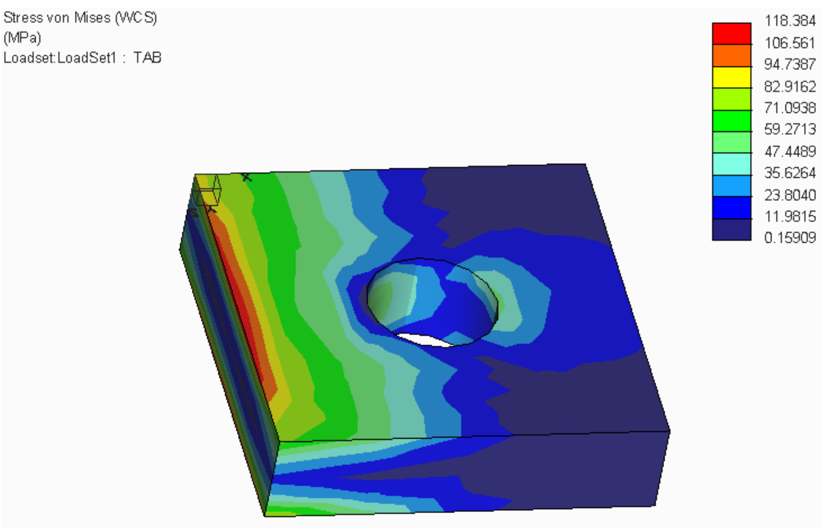

Figure 15: Stress on the tabs

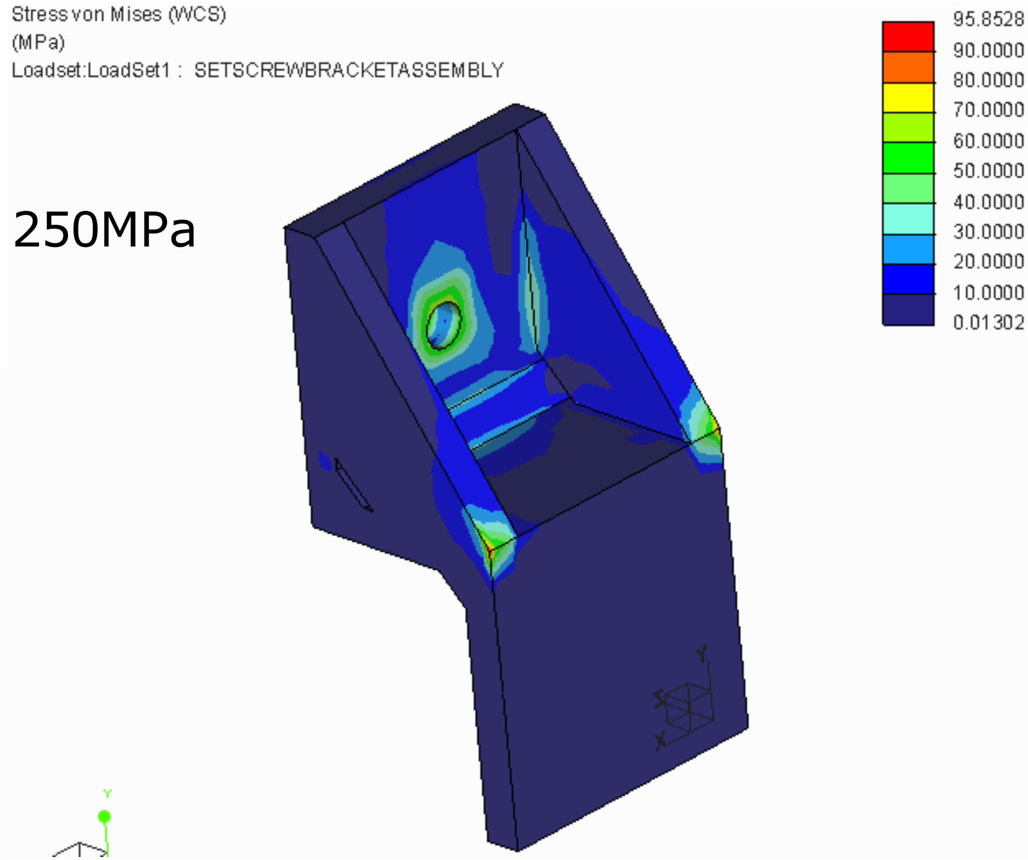

Figure 16: Stress on the brackets

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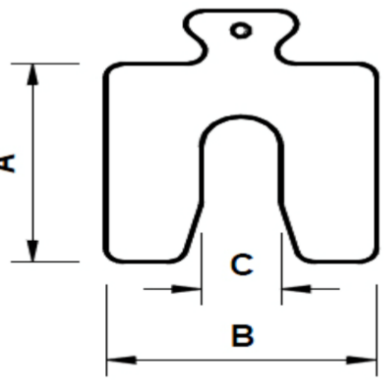
Base frame components

Vertical alignment adjustment:

Shim Stock:

- Stainless steel
- Thicknesses of 13, 127 and 254 μm.
- Tolerance: 0.8, 8, and 13 μm.
- A=57mm, C=11mm, B=51mm



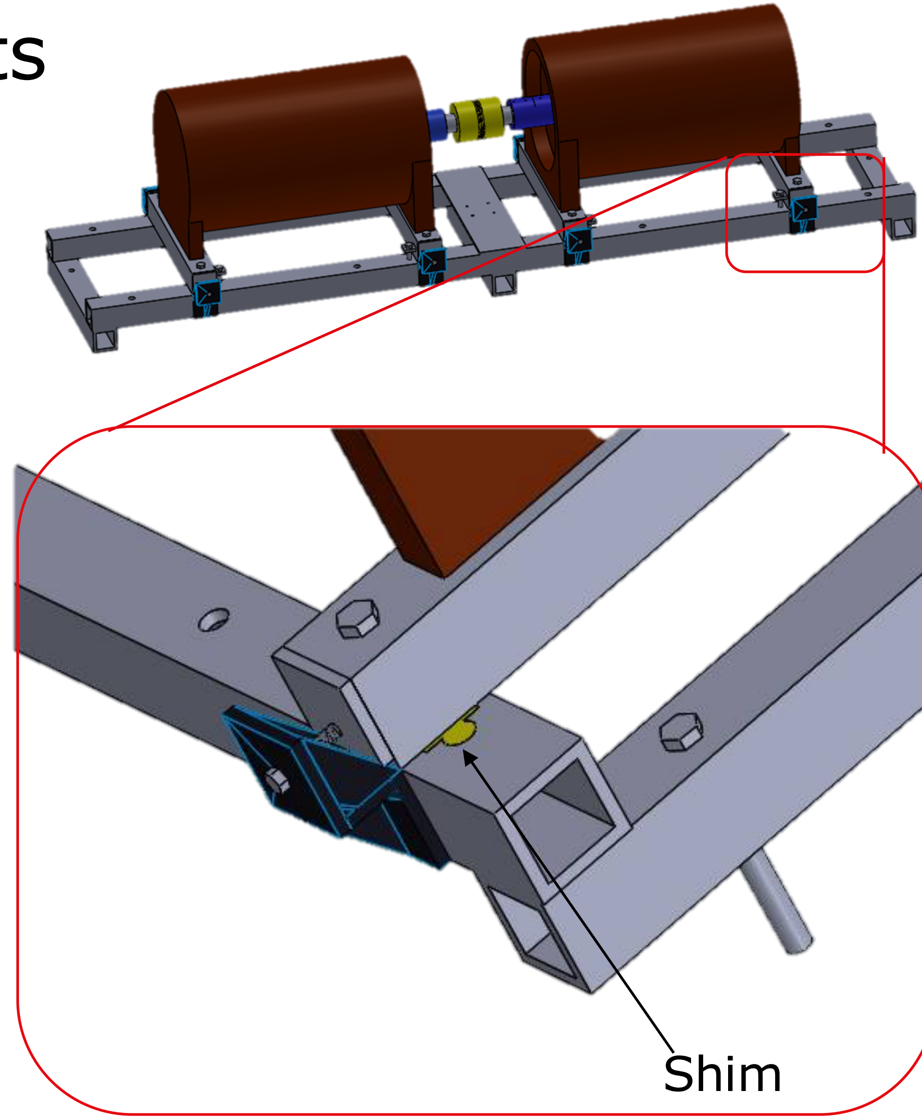


Figure 17, 18 & 19. Shim stock(left), shim dimensioning (center), shim location (right).

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 of 4 inch length to ensure fitting.

Figure 20. Concrete Anchor Bolt

Durval Marques

Final design: Natural Frequency

- Maximum rotation speed: 40,000 RPM = 667 Hz
- For safety reasons the sponsor recommended 800 Hz.
- Based on the deflection we estipulate the frequency.
- For the system is 830 Hz, SF=1.24, the real frequency is smaller due the flexible coupler, which decreases the stiffness.

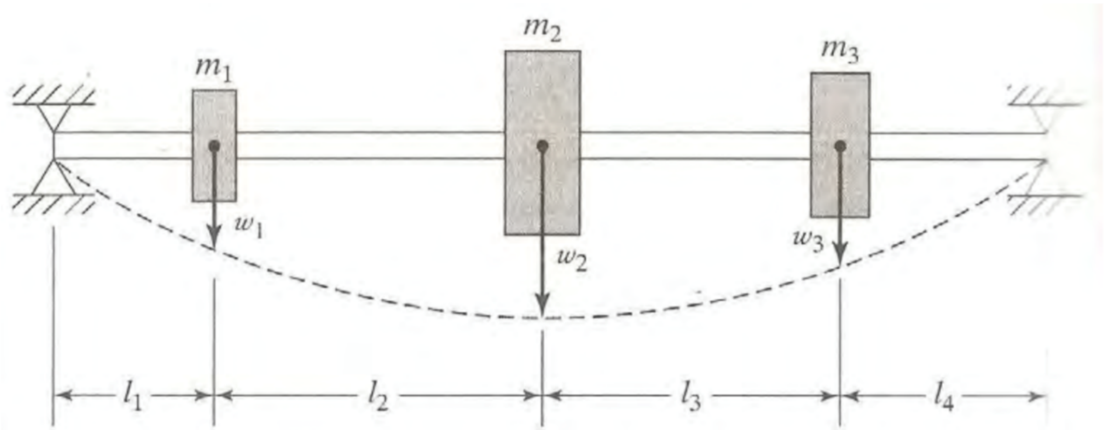


Figure 21. Deflection analysis for natural frequency calculation

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

Figure 17. Natural frequency as a function of mass and deflection

Final design

- 1 Flexible Coupler
  - BK2 150/38/38/A
  - 38.1 mm bore
- 2 Rigid Couplers
  - R2CC-150-150-S
  - Inner bore: 22.225 mm
  - Outer bore: 38.1 mm
- 2 Shafts
  - Diameter:38.1 mm
  - Length: 107 mm

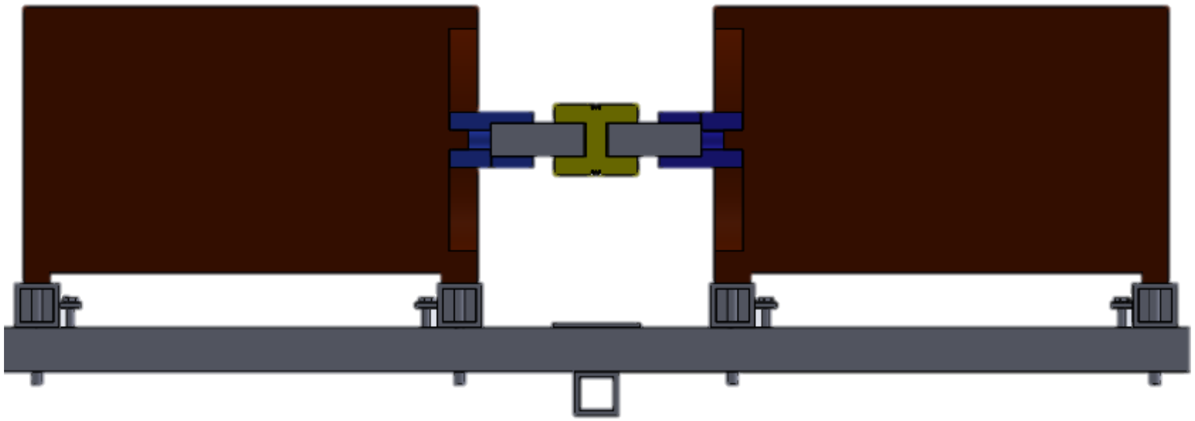


Figure 22: Cut view of final design

- Increased natural frequency
  - Small and thick shaft
- Adjustable for the torque transducer
- Easy manufacturing

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Safety Shielding

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

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Gantt Chart

	Task Mode	Task Name	Duration
1		Frequency Analysis	4 days
2		Frame Drawing Completion	6 days
3		Bracket Drawings	6 days
4		Shaft Drawing	6 days
5		Shim Analysis	4 days
6		Safety shield frame	11 days
7		Danfoss drawing review	1 day
8		Bolt Selection	4 days
9		Order raw materials	2 days
10		Order fasteners	2 days
11		Seek machine shop for large mill	6 days
12		Frame fabrication	6 days
13		Compressor install	2 days
14		TKSA 31 training	6 days
15		Alignment practice	3 days
16		Low speed testing	5 days
17		**Test rig assesment**	**3 days**
18		Evaluate couplers	3 days
19		Evaluate shafts	3 days
20		Evaluate compressors	3 days
21		Further testing at higher speeds	11 days

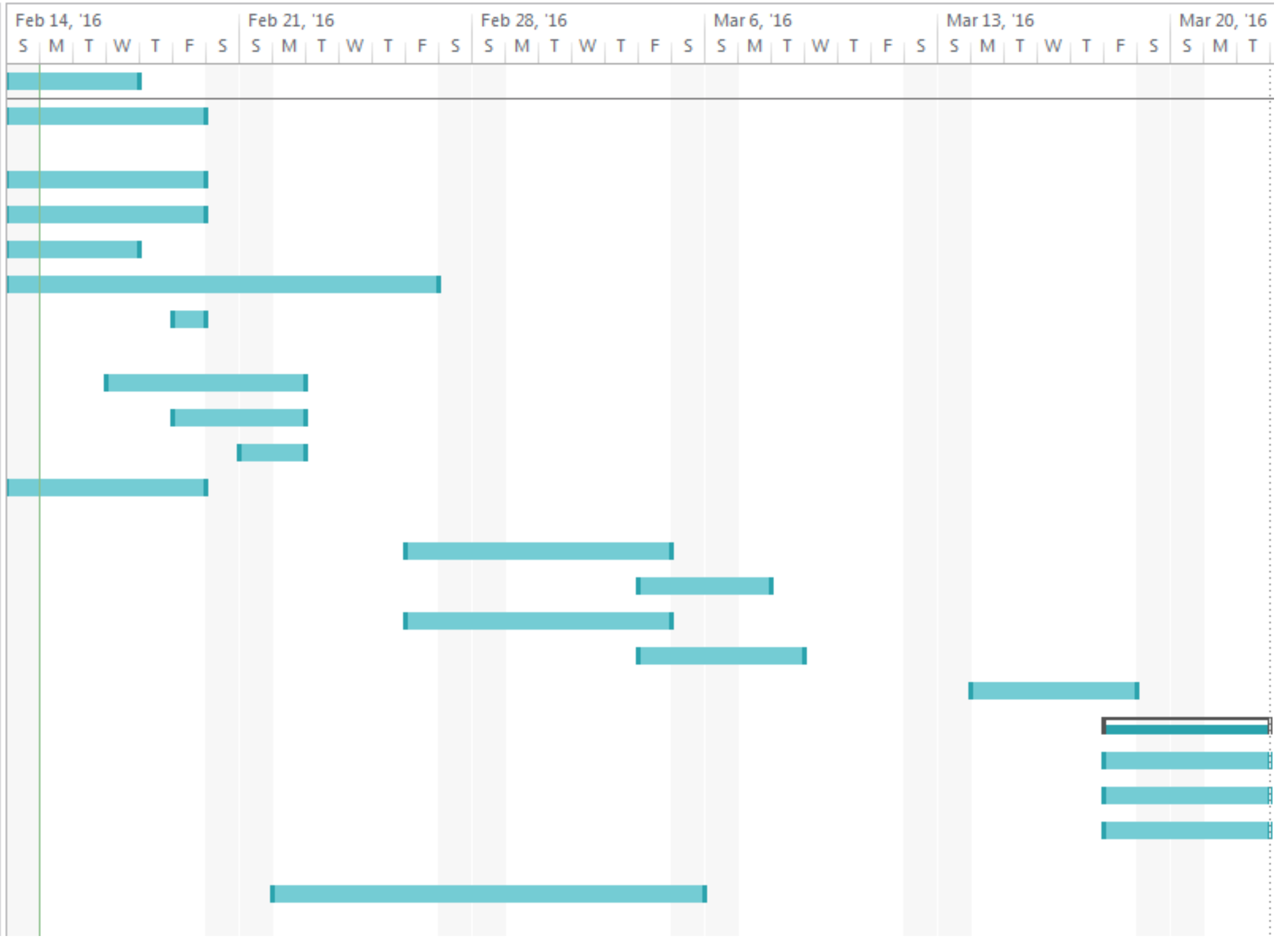

Figure 23. Gantt Chart, Spring Semester.

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Conclusion & Future work

- Frame material, couplers, and alignment equipment order will be placed through Danfoss.
- Assembly and manufacturing will be done at Danfoss.
- The system will not be on resonance.
- Validate the natural frequency through a test.
- Validate the alignment system with assembled system.

References:

1. http://www.magtrol.com/datasheets/tm301-308.pdf

2. http://www.magtrol.com/datasheets/tm309-313.pdf

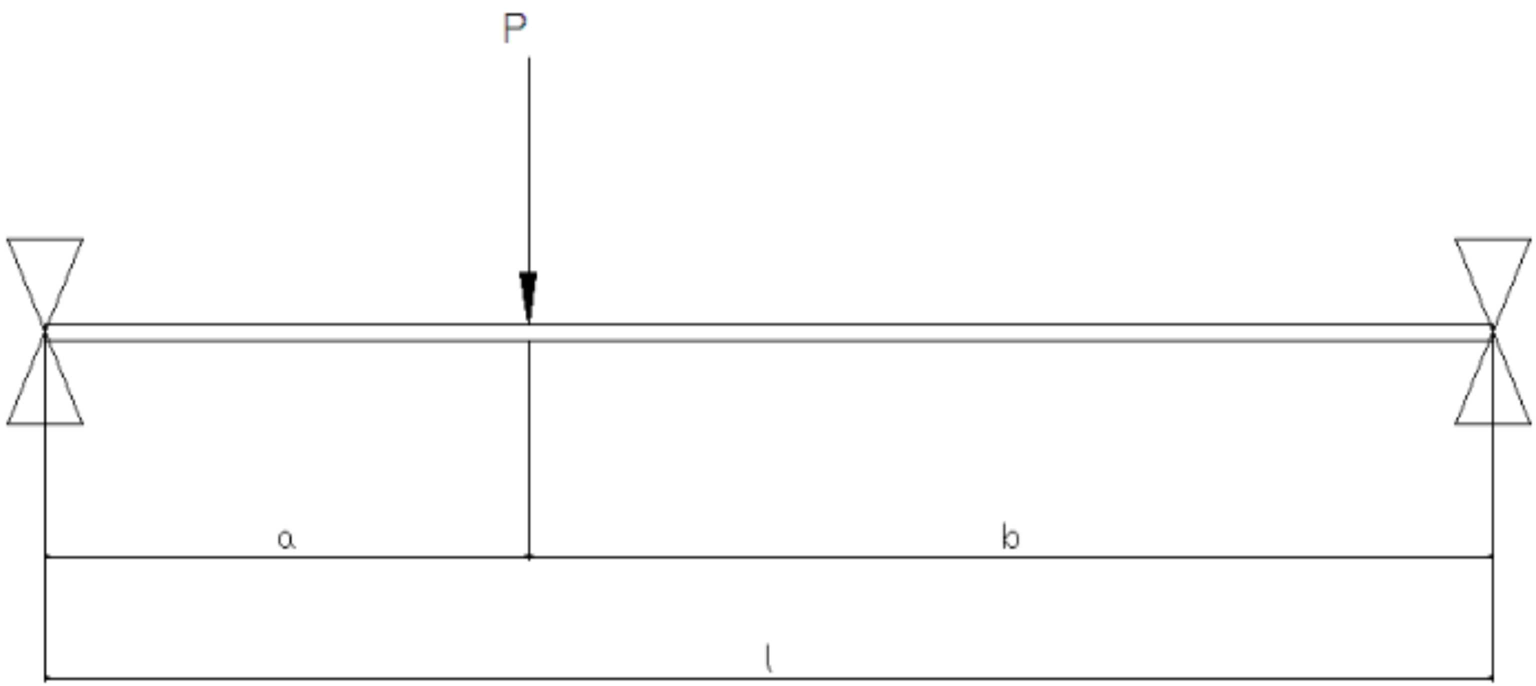
3. http://catalog.climaxmetal.com/item/re-machinable-couplings/re-machinable-couplings-r2cc-series/r2cc-075-075

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/

7.http://repositorio.unesp.br/bitstream/handle/11449/121247/silva_msp_tcc_guara.pdf?sequence=1


P
a
b
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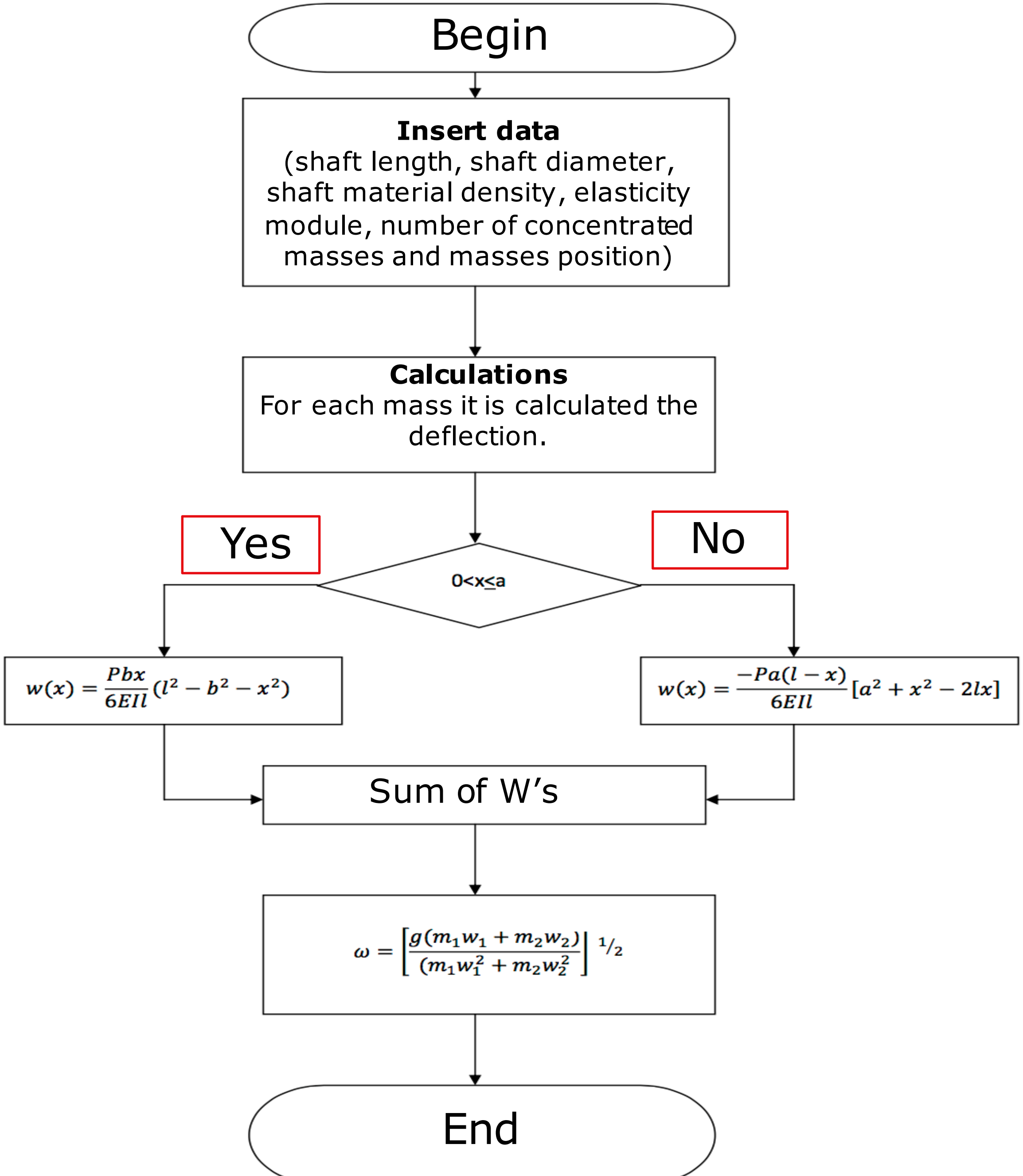
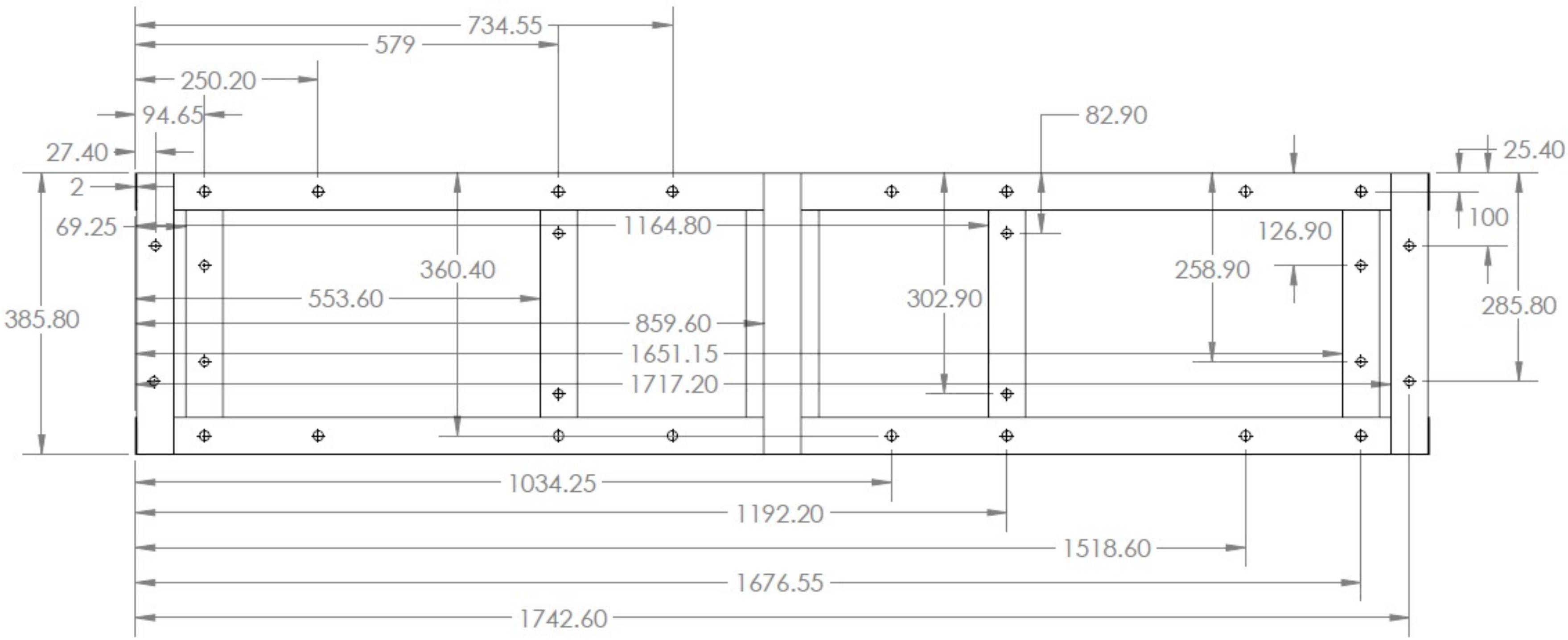

Begin
Insert data
(shaft length, shaft diameter, shaft material density, elasticity module, number of concentrated masses and masses position)
Calculations
For each mass it is calculated the deflection.
Yes
No
0<x≤a
$w(x) = \frac{Pbx}{6EIl}(l^2 - b^2 - x^2)$
$w(x) = \frac{-Pa(l-x)}{6EIl}[a^2 + x^2 - 2lx]$
Sum of W's
$\omega = \left[\frac{g(m_1 w_1 + m_2 w_2)}{(m_1 w_1^2 + m_2 w_2^2}\right]^{1/2}$
End



734.55
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82.90
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100
126.90
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285.80
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1676.55
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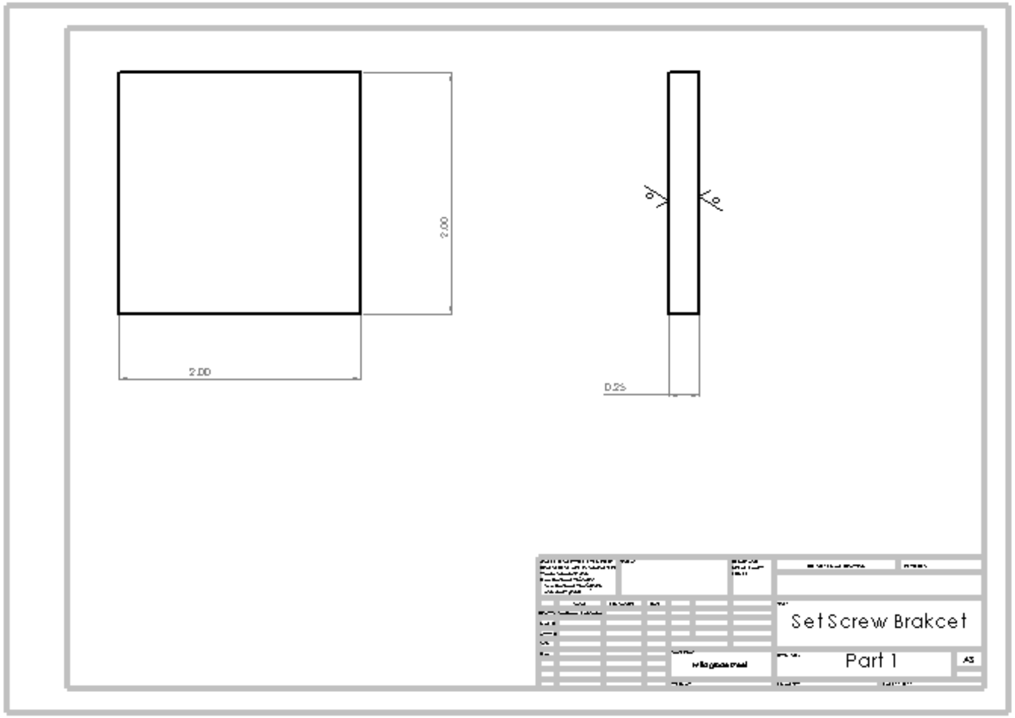
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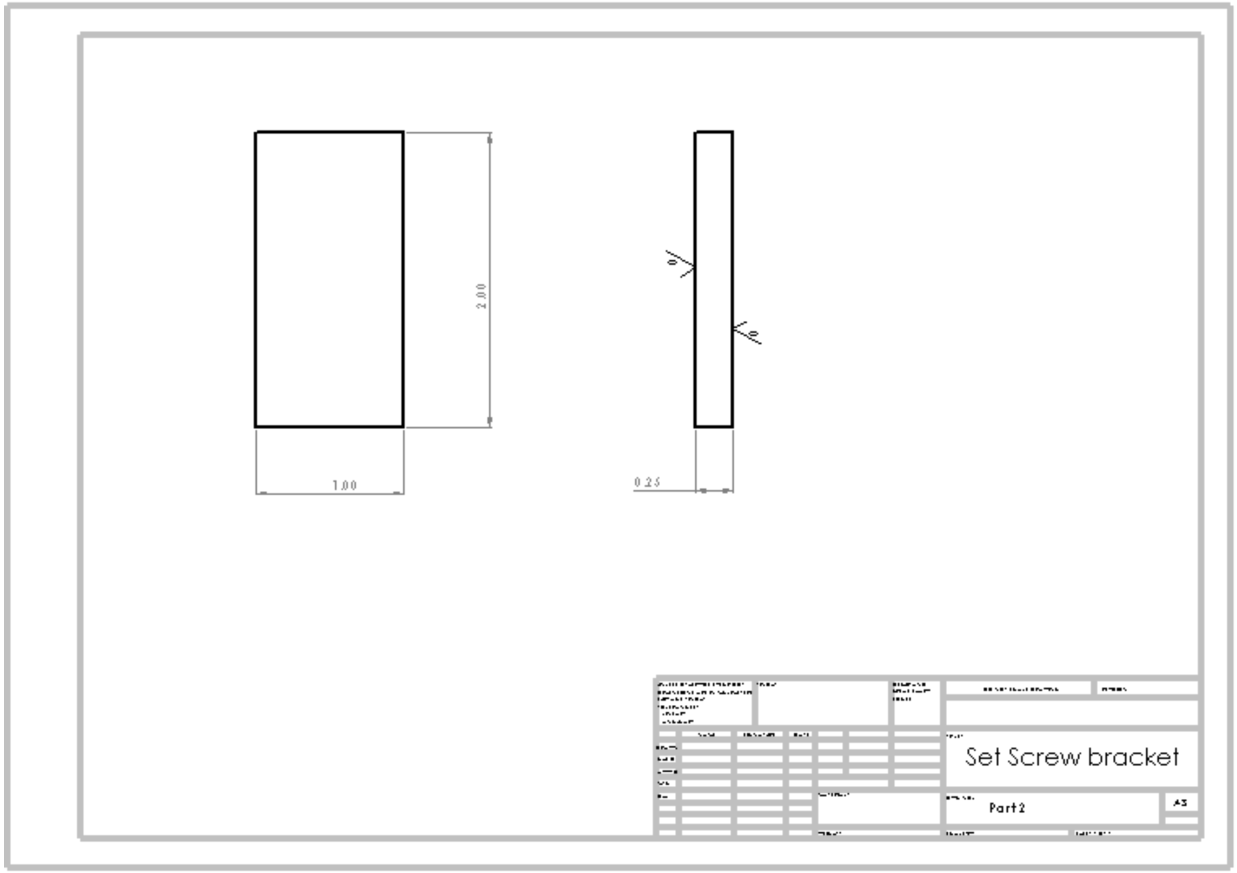
Set Screw Brakcet
Part 1
A3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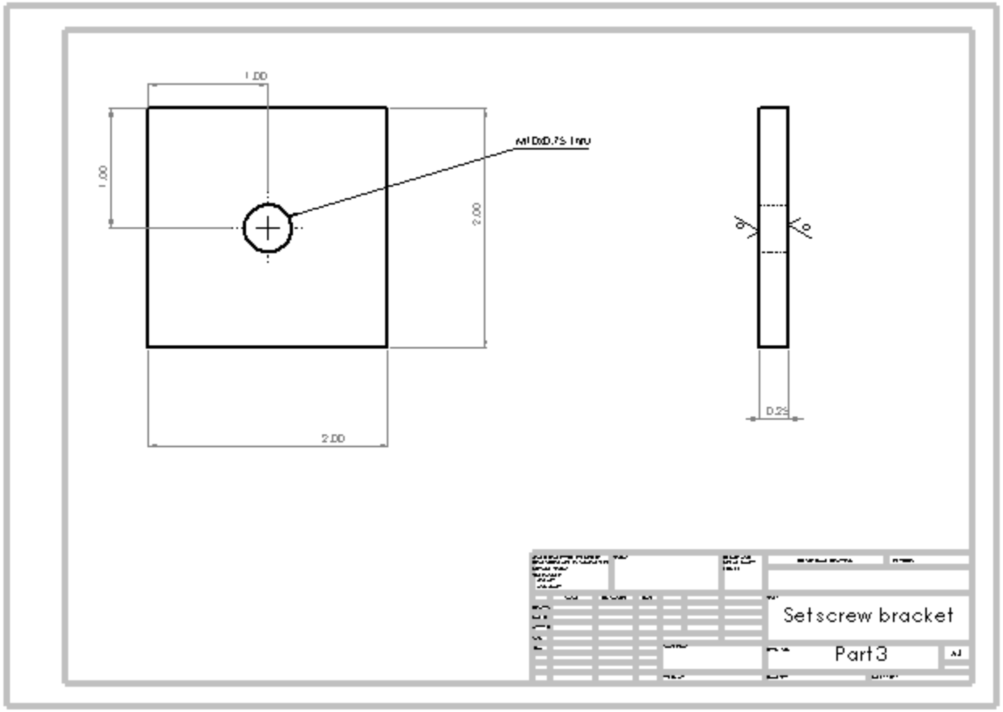
Set Screw bracket
Part2
A3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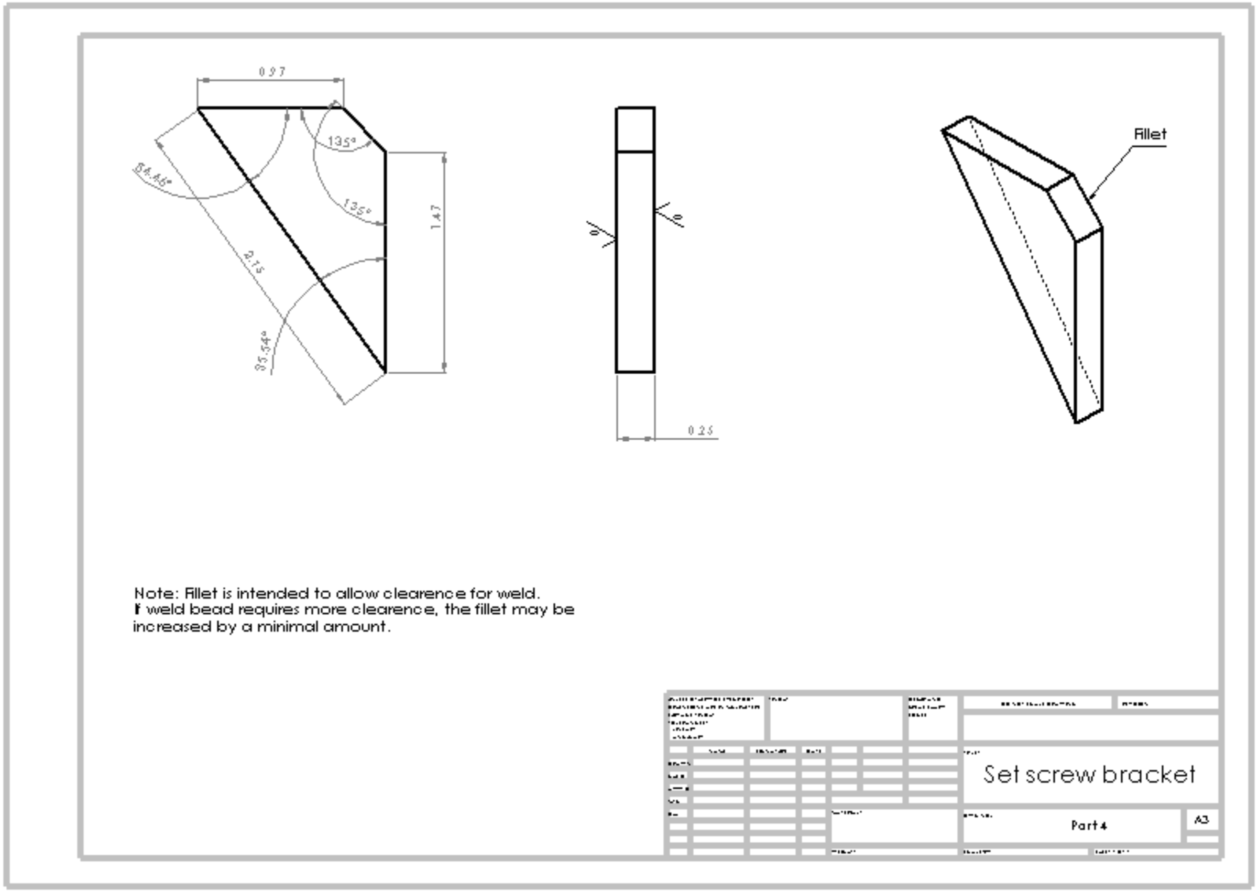
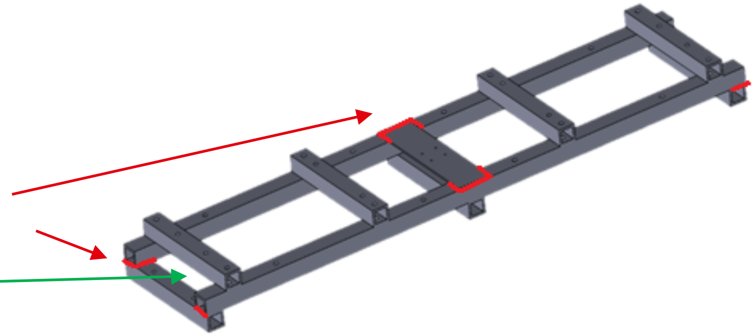
Setscrew bracket
Part3



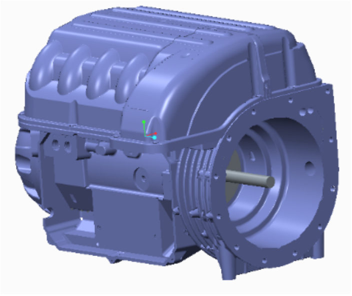
Note: Fillet is intended to allow clearence for weld.
If weld bead requires more clearence, the fillet may be increased by a minimal amount.

Assembly Process

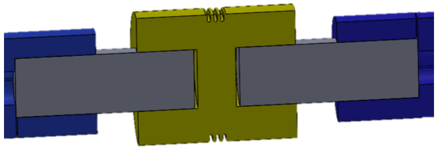
- 1. Base frame: Welded components first.
  - Cross members bolted.



2. First compressor is mounted (assistance with crane required) to cross members.



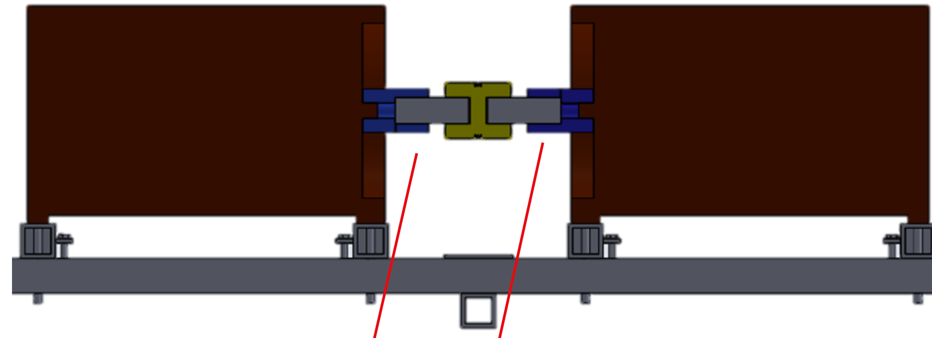
3. Rigid couplers, steel dowels, and flexible couplers are secured together to first compressor.



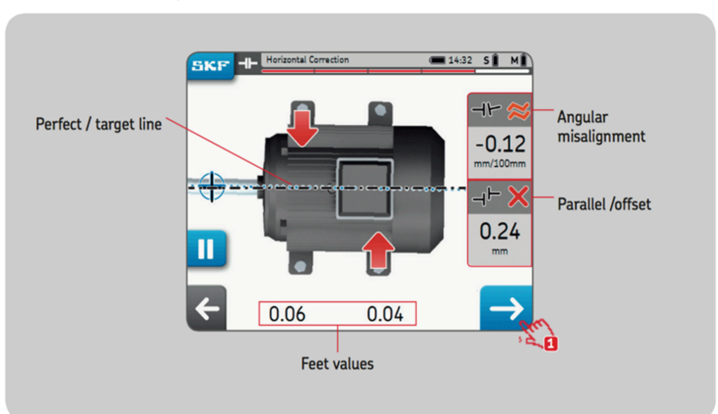
4. Second compressor is mounted to cross members, and shaft is coupled to rotating assembly.

Alignment Process

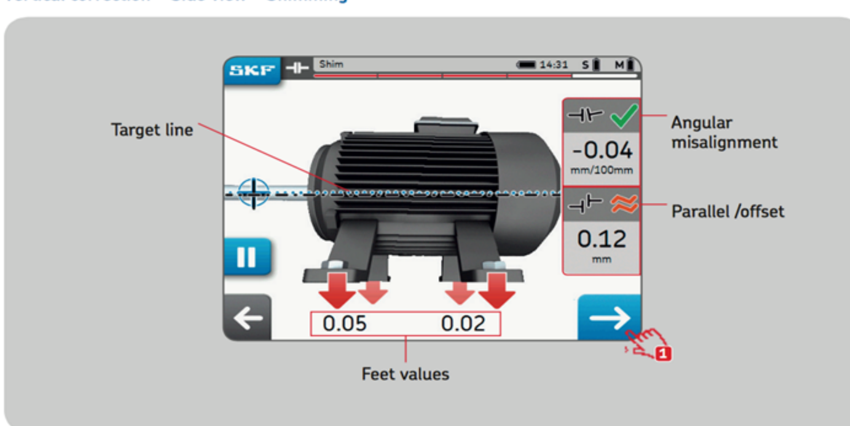
- Tool mounts to both rigid Couplers after assembly. Secured by using clamps.
- Shafts are rotated together, as this happens the laser guides process data.
- Live readings are displayed directing the user which direction to align system.



Horizontal correction – Top view



Vertical correction – Side view – Shimming



Pricing:

- 2″x2″x1/4″ Steel quantity 26 ft.
  - $110.88
- ¼″x2″x4′ Steel bar.
  - $9.16
- BK2 coupling (flexible)
  - $289.40
- SUA coupling (rigid) (2)
  - $80
- 3′ 1060 Steel dowel shaft (2)
  - $106.25
- TKSA 31 Laser Aligner
  - $2,155.00
- Fasteners: Provided by Danfoss

- Total: $2,936.94

Safety Shielding Frame

- Safety shield framing, to be filled with steel plate.
  - Plate thickness to be determined.
- Frame material: 90° angled steel.
  - A=2”, B=2”, C=3/16”
- Dimensioned for assembly without transducer (transducer shown)