# High Speed Motor Test Rig

Design for Manufacturing, Reliability, and Economics

4-1-2016


Team 4

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Sponsor: Danfoss Turbocor

Faculty Advisor: Dr. Patrick Hollis

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## Abstract

Danfoss Turbocor has asked Senior Design Team 4 to develop a high-speed motor test rig to qualify their motor performance within the compressors. They have asked Team 4 for a motor-generator rig that uses one compressor motor to transmit power to another that can act as a variable load. The original designs were rather expensive and Team 4 has offered a more affordable alternative to prove alignment within the system and to also eventually run the compressors at full speed output. The total cost of the proposed design is $1,040.76 and this design is also suited for eventual input of torque transducers to run at max speed or max torque. The test rig is set to be complete the week of April 8th, 2016 and be ready to undergo testing.

**Acknowledgements**

Senior Design Team 4 would like to thank our instructors for the course, Dr. Nikhil Gupta and Dr. Chiang Shih, as well as the Teachers Assistants for their help. This project would not be possible without the support of our sponsor Danfoss Turbocor. Team 4 would also like to thank William Sum, Julio Lopez, and Kevin Lohman from Turbocor, for their guidance through the project.

## 1. Introduction

Danfoss Turbocor is the market leader in oil free compressors for different systems. The company designs compressors for heat, vacuum, and air conditioner industry. They achieve a high quality due to a combination of magnetic bearings, which uses magnetic fields to create a contact free system between the shaft and bearings allowing high speeds (up to 40,000 RPM), and variable-speed centrifugal compression, which allows the use of the compressor with the rotation for the best efficiency.

In order to test all the TT-Series compressors, Turbocor is looking for a system that can qualify their compressor's electric motor more accurately and more efficiently for power, efficiency and heat management. Danfoss's current test process is done in a chiller room, which is very expensive to operate.  A motor-generator system could save test engineers time and money. Therefore, team 4 proposed to Turbocor a use of a new Motor-Generator Test Rig.

A Motor-Generator test rig is a system that couples two motors; one working as a motor and the other one as a motor load or generator, in this case they are using compressor motors. To connect the compressors to each other the use of a flexible coupler, which can handle misalignments, is required.

Our team designed a test rig that can handle the high-speed rotation with a considerable torque. To do so the team considered that the test rig should be well fixed to the ground, the compressors should be rigidly fixed to the base frame and it would require a precise method to move the compressor so the quality of the balancing would be guaranteed. The team designed a system that uses setscrews and shims to move the compressor horizontally and vertically.

For safety reasons it is required that the natural frequency should be at least higher than the operational frequency with a safety factor. The team assumed it too be at least 700 Hz, this because the theoretical natural frequency could be higher than the actual one.

Currently our design is complete and the team is awaiting the fabrication of the base frame. All other components have been acquired.  As soon as the frame is completed, the final assembly will be made. As the test rig is made to test different compressors with simple installation, we are expecting that the assembly process should take only a couple hours.

## 2. Design for manufacturing

Before starting the assembly the team had to order the raw material and other components, such as the couplers. With the components in hand, some were machined and welded while others came prepared from the vendor. The ordering process took place through Danfoss Turbocor, who received a document with all price quotes of the components. The initial project considered a torque transducer between the two compressors, the project changed due the high cost this equipment ($8,000 each and the system requires two of them).

The base frame is made of 2x2x0.25" steel and its main function is to settle the compressors in their right position and rigidly fix the system to the ground. The raw materials were received at Turbocor's facilities and were machined there as well. The machining process mainly leveled the surface to minimize any inconsistencies on the base frame runners, make the holes to settle the compressors and the ones to fix it to the ground, and weld the structure to guarantee the stiffness required. Figure 1 shows the structure as well as the welding lines, which are represented in red. Turbocor has some distributors of the raw material that they use (McMaster-Carr) and they also use this material in their facilities so the ordering process took less than one week and the machining process is still ongoing.

**Figure 1: Base Frame with the weld lines indicated in red.**

The rigid coupler selected by the team is the Re-Machinable Rigid Coupler supplied by McMaster-Carr. Its main function is to connect the compressor's shaft to a thicker shaft, which will go inside the flexible coupler. The inner bores came originally with 22.25mm (which is the diameter of the shaft of the compressor). To increase the natural frequency of the system the team decided to increase the stiffness of the system by increasing the diameter of the shaft that connects the rigid coupler to the flexible coupler. To do so one of the inner bores was re-machined so it has 25.4mm diameter. After the bores were resized to the final diameter the rigid coupler needs to be balanced to deal with the high operational speed rotation. This system needs 2 rigid couplers and the ordering process ran through Turbocor and it took around 10 business days. Currently the rigid couplers are re-machined and the process took 5 business days, the balancing process should take 4 business days.

The flexible coupler selected by the team is the Bellow Coupler BK2 150, this component has been ordered through Turbocor and the senior design received this component. The coupler came with the desirable diameter so it does not require a re-machining process. This process should have taken 15 days but it has took longer than expected, we received this component only this week, it supposed to be delivered last week.

The shaft to connect the rigid coupler to the flexible coupler is made of 1566 hardened steel. The system requires 2 shafts. Turbocor has ordered the raw material and machined the shaft so they have an overall diameter is 25.4 with a 50µm precision. Figure 2 shows a section view of the rotating assembly, the yellow component represents the flexible coupler, the grey component represents the shaft and the blue component represents the rigid coupler.

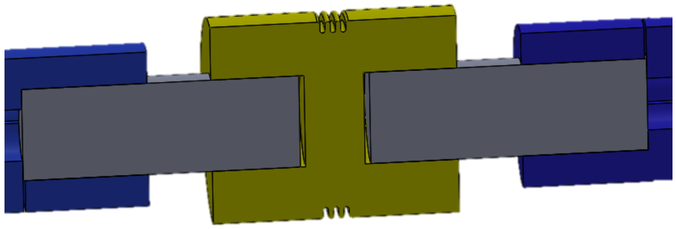

**Figure 2: Section View of Rotating Assembly**

To move the compressor during the alignment process the team designed brackets and tabs, which perform the horizontal and vertical movement respectively. Both parts are made of 1/4” steel and are welded to the structure. The tabs were simple to manufacture because they were designed to be a plate with a hole in the middle. The brackets were a little more complex to manufacture because each bracket is made with smaller plates, which needed to be cut and welded to be one final part. The manufacturing ran through the FSU/FAMU College of Engineering Machine Shop and took around 5 business days to cut all the pieces; the welding process will take a few days. A view with the brackets and the Tabs can be seen in the Figure 3, the red lines indicate the welding lines.

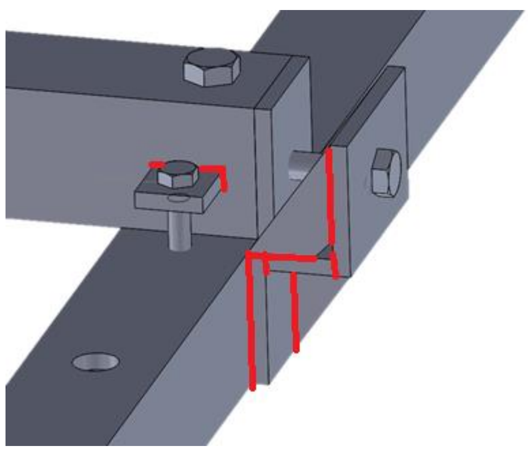

**Figure 3: Brackets and tabs with the welding line indicated in red.**

During the design process the team faced some problems. The first big problem was the budget constraint, initially the team designed the system to support one torque transducer between the two compressors. This was our ideal design but there is no torque transducer in the market that can handle different scenarios, high speed and low torque (40,000 RPM and 20 Nm) and low speed and high torque (10,000 RPM And 50Nm), so it would be necessary for two different torque transducers, one for each scenario. Another problem was that each transducer has a different shaft diameter, so again it would require different shafts and two more rigid couplers to connect the shafts to the torque transducer. Each torque transducer costs approximately $8,000. Our sponsor proposed to us to first prove the alignment system than buy the transducers.

To prove the alignment system we extended the shaft so it would fill the transducer space, reducing the costs and eliminating extra components, such as the second pair of rigid couplers. We presented this idea to our sponsor and then we faced another problem. If we replace the transducer by the shaft the system would not be rigid enough, which yields a small natural frequency (around 500 Hz). The maximum operational frequency is 40,000 RPM (667 Hz). For safety reasons the team assumed the minimum natural frequency for the system to be 700 Hz. To solve this problem we arranged the compressors to be closer to each other, to do so we designed the shaft to be shorter and thicker, which will increase the stiffness of the system and consequently the natural frequency. Our final design has a theoretical natural frequency of 708 Hz; the real value will be measured after the assembly in Turbocor's facilities.

After the design process the team came up with our final design, which is shown on the Figure 4.

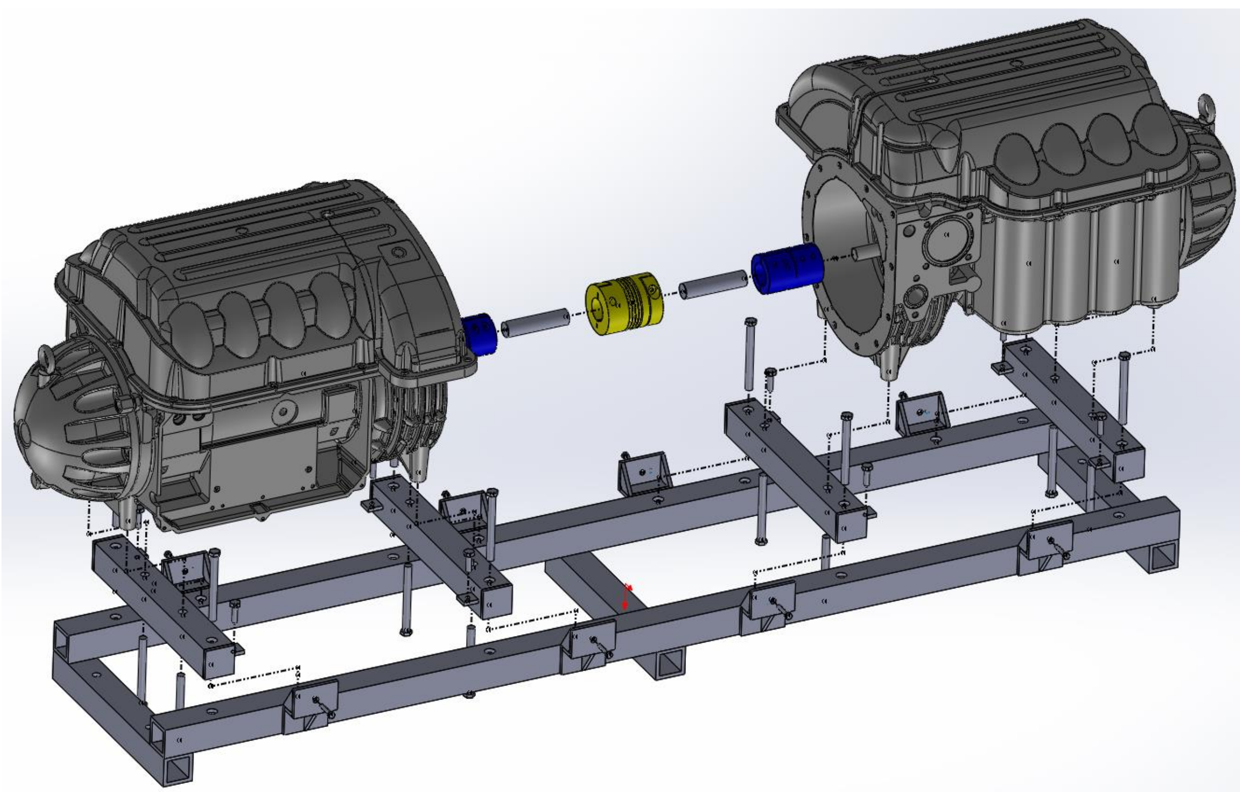

**Figure 4 Exploded view of the final design.**

With all the parts ready the assembly process can start, this implies that the base frame is machined, all the brackets and tabs are welded to the base frame, the rigid couplers are machined and the arrival of the flexible coupler is complete. The final assembly process should occur within one business day. The test rig will be used to test different compressors, so a fast assembly time is desirable, we estimate that the assembly time should take a couple hours, it would be interesting for a continuation of this project to develop a better way to assembly the system so it can be faster.

The actual way to move the compressors during the alignment process does not indicate how much the compressor has been moved so another suggestion for a continuation would be to develop a system that indicates how much the compressor is moving.

### 3. Design for Reliability

Being that most of the components of this test-rig are made of steel, the machining process was relatively simple. Low carbon steel was chose for it's high yield stress and for the purposes of the test rig there have been no forces of concern that will even come close to causing plastic deformation in the steel components. The max stress calculated from the FEA analysis shown in Appendix E gives a maximum stress value of 0.3 MPa in the base frame and 118 MPa in the setscrew alignment mounts. Looking at the fatigue limit of steel below in Figure 5, the carbon steel endurance limit is beyond the actual maximum load stresses on the steel components so it can be determined that there is no load life cycle concern with the test-rig.

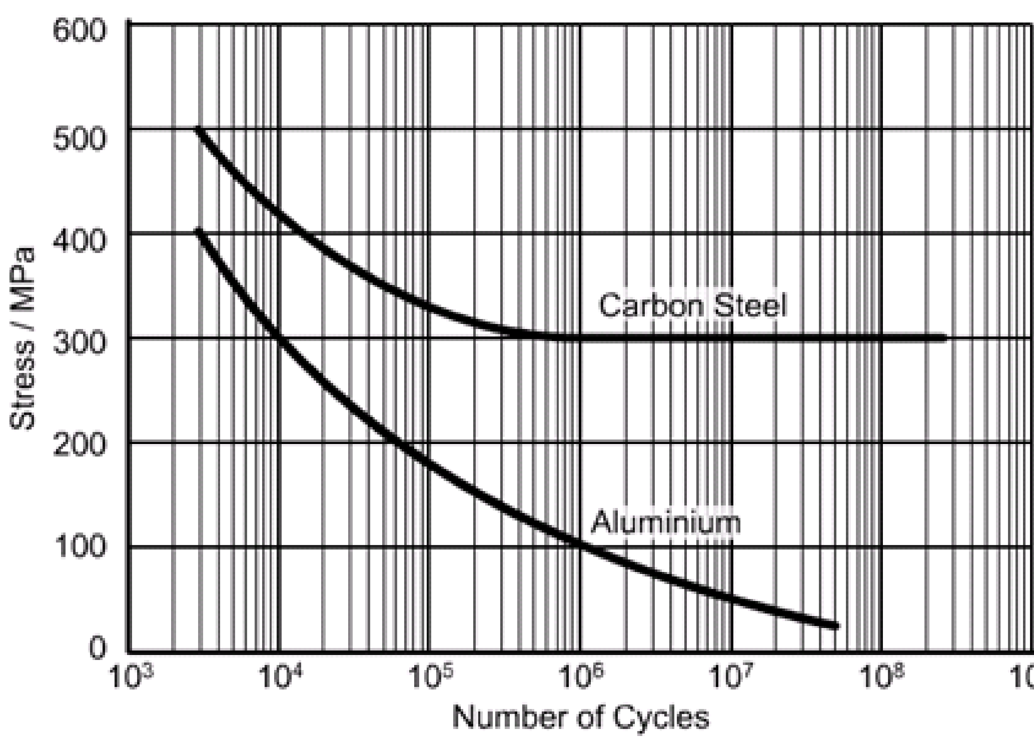


**Figure 5: Stress (MPa) per number of cycles**

Looking at the FMEA analysis performed by team 4, there are some areas of concern, which are unlikely but were deemed to have a 10 in severity. These potential issues are observed in the base frame, compressors, and shafts. In the base frame, the possible modes of failure are structural defects, rusting, and vibrations. Being that the base frame carbon steel runners are machined and welded, the processes could have adverse effects on the material's integrity. It is highlighted that fracture and bending could possibly occur due to mishandling and warping. This is not something that can be detected easily but the machinery and welders at Danfoss are of the highest caliber and the cause for a structural defect is highly unlikely (it received a 1 in occurrence). To go along with potential mishandling, rust can possibly plague this base-frame being that it isn't made of stainless steel. It is recommended that much care go into this frame; maintenance and an anti-rust paint should be applied to protect the rig.

Being that this designed to run at high speeds (50,000 rpm) and also at high torque (100 N-m), vibrational effects must be considered. The team is confident that the system can reach full operation for alignment purposes being that the natural frequency is 708 Hz, when the actual compressor natural frequency at around 667 Hz. Other considerations should be taken when Danfoss decides to run at full speed since the factor of safety calculated is only 1.13.

The compressor shaft and hardened shafts are a very key component to the rotating components of the rig. The hardened steel shafts could potentially fail like the steel in the base frame with a structural defect that could take place in the machining or balancing process. Since these shafts are suspended in air and attached to a flexible and rigid coupler, a structural defect that can cause fracture or bending can potentially launch a projectile. To combat this the team has proposed a safety shielding made of mild grade steel to encase the rotating assembly and protect the operators in the event. The compressor shafts are finely balanced and are attached with sensors that can stop the motors if a radial force of 200 lbf is experienced. The hard stop with all rotating components could cause damage to the compressor if the force is large enough. This is severe since these compressors are very expensive. As long as the machining process and assembly goes according to plan and all operators adhere to the alignment process specified in the operations manual, the test rig should be reliable and safe.

## 4. Design for Economics.

The total cost of the project thus far is $1,046.76. This price includes all hardware (nuts, bolts, washers, etc.), couplers, baseframe steel, and shaft material. As you can observe in Figure 6, the couplers and base frame make up the majority of the cost at $414.48 and $352.14. The shim stock was ordered in large amounts at multiple thicknesses so that the increments of height adjustment would range sufficiently. Fasteners and shafts were not a burden on the team for pricing.

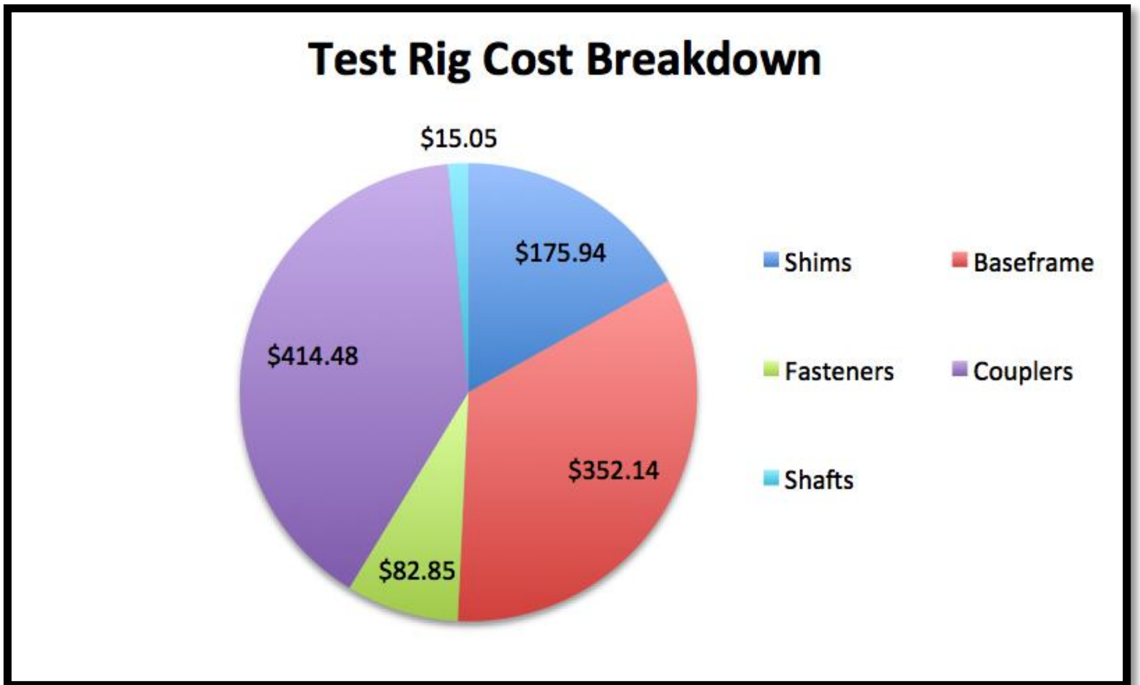


**Figure 6: Test Rig Cost Breakdown chart.**

Team 4 was never given a specified budget for the project and instead selected parts were purchased at Danfoss's discretion. As mentioned previously, the original design proposal called for two MAGTROL torque transducers. Each of these transducers was quoted at $8,000.00 and this would take the total for the design up to around $17,000.00, which was deemed too expensive at the moment by Danfoss. Another component that was omitted in the project due to price was the TSKA-31 laser alignment tool. It was valued at $3,500.00, but as previously stated the double dial indicator method is to be used in place of this. Overall the design has been cut by $19,500.00, but the base frame can still accommodate the original design if Danfoss decides to purchase the laser aligner and transducers.

There is not a current test rig that can handle the speeds that Danfoss requires and it was told to the team that the first phase in designing this test rig rung up a price near $70,000.00 - $80,000.00, as told by our liaison. This current design is simple, economical, and by design it is to be practical. All order forms are formally documented and can be viewed in Appendix B, Appendix C, and Appendix D.

## 5. Conclusion

Danfoss Turbocor is in need of a high-speed motor test rig that can withstand angular speeds up to 50,000 rpm and torques up to 100 N-m. There isn't a current system on the market that can perform under these conditions and Danfoss originally worked through a design running them up to $70,000.00-$80,000.00 in costs. Team 4 has offered an alternative design using a motor-generator set up with possibility for alignment validation and high-speed capability (if Danfoss desires). This design when ultimately completed with all transducers and laser aligners will save Danfoss close to $50,000.00 based on what the first phase was to cost. Fabrication of the prototype should be completed the week of April 8th, 2016 and undergo testing.

## Reference

**[1] http://eng.fsu.edu/me/senior_design/2015/team04/**

# Appendix A

## Table 1: DFMEA Analysis

| Item / Function | Requirement | Potential Failure Mode | Potential Effect(s) of Failure | Severity | Classification | Potential Cause(s)/ Mechanism(s) of Failure | Current design: Controls Prevention | Occurance | Current design: Controls Detection | Detection | RPN | Recommended Action(s) | Responsibility | Action Results: Actions Taken | Sev | Occ | Det | R.P.N. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frame | Support Compressors | Structural Defect (fracture and bending) | Misalignment during system operation | 10 | | High heat from welding (warping), mishandling frame (fracture) | Careful handling and fabrication of components | 1 | | 2 | 20 | Fracture: welding component. Bend: replace | Machinist, Welder Opera | | | | | |
| | | Yielding in the steel components | Destruction of test rig | 8 | | Overloading | Proper assembly of base frame and perform testing within specified | 1 | | 1 | 8 | Shut down rig and replace damaged | Operator | | | | | |
| | | Vibration in steel components | Damage to rig and compressors | 10 | | Improper fastening | Be sure that bolts are torqued properly and rig is secured to floor | 6 | | 6 | 360 | Shut down rig and be sure to fully fasten bolts | Operator | | | | | |
| | | Rust | Could degrade material and cause serious structural issues | 10 | | Lack of maintenance | Paint | 7 | | 7 | 490 | Regularly inspect for rust, re-paint periodically | Operator, machinist | | | | | |
| Set screw brackets | Lateral Alignmet | Bending | Unable to preform lateral alignment, | 7 | | Overlaoding on set screw . | Ensure proper fastening and weld to frame properly | 5 | | 4 | 140 | Shut down rig, re-thread hole and replace screw | Operator, machinist | | | | | |
| | | Fracture | Unable to preform lateral alignment, | 8 | | Overloading on set screw (compression) | Ensure proper fastening | 2 | | 4 | 64 | Shut down rig, re-thread hole and replace screw | Operator | | | | | |
| | | Hole shear | Unable to preform lateral alignment, | 8 | | Overloading and vibrational effects | Ensure proper fastening | 3 | | 3 | 72 | Shut down rig, re-thread hole and replace screw | Operator | | | | | |
| | | Bolt shear | Unable to preform lateral alignment, | 3 | | Vibrational effects and over torqued bolt | Ensure proper fastening | 3 | | 3 | 27 | Shut down rig, re-thread hole and replace screw | Operator | | | | | |
| Shims | Vertical alignment | Warping | Uneven surface for compressor to sit, could compromise alignment | 1 | | Compression from weight of compressor | cut out shims properly to not degrade material's integrity | 1 | | 7 | 7 | Lift compressor and replace shim | Operator, Machinist | | | | | |
| Rigid Coupler | Couple compressor shaft to steel shaft | Vibrations | Could detatch from assembly or cause system to hit reasonance if | 6 | | Improper fastening, improper balancing | Make sure to machine to proper balance specifications, fasten fully | 4 | | 4 | 96 | Remove, balance, and re-fasten | Operator, Machinist | | | | | |
| Flexible coupler | Couple both steel shafts | Vibrations | Could detatch from assembly or cause system to hit reasonance if | 4 | | Improper fastening, improper balancing | Make sure to machine to proper balance specifications, fasten fully | 3 | | 4 | 48 | Remove, balance, and re-fasten | Operator, Machinist | | | | | |
| Steel shafts | Couple both compressors | Structural Defect (fracture and bending) | Could shear and turn into projectile and cause damage to compressor | 10 | | mishandling (fracture), stall torque, poor machining | Careful fabrication and proper test rig operation | 2 | | 2 | 40 | Replace shaft | Operator, Machinist | | | | | |
| Compressor | Motor and generator for test rig | Stall | Could damage inner components or onboard computers | 10 | | improper assembly and coupling of shafts | Follow operations manual and have trained technician running | 3 | | 7 | 210 | Remove compressor, recalibrate | Operator | | | | | |

## Appendix B

### Table 2: Price order sheet 1

**PURCHASE ORDER REQUISITION**

Vendor: McMaster Carr

**DATE:** **10-Mar-16**

DATE REQUIRED:

CAPITAL EXPENDITURE (please tick):

**CURRENCY:** **USD**

Contact: www.mcmaster.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 |
|---|---|---|---|---|---|---|---|
| | 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) | 91257A734 | 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 | | |
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**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

## Appendix C

### Table 3: Price order sheet 2

Danfoss TURBOCOR

# 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 | | |
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**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

## Appendix D

**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.# / Cust.# | 65010 / 209644 (40) |
| 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**<br>BK2 / 150 / 95 / 25.4 / 25.4<br>Bore D1: 25.4 H7<br>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.

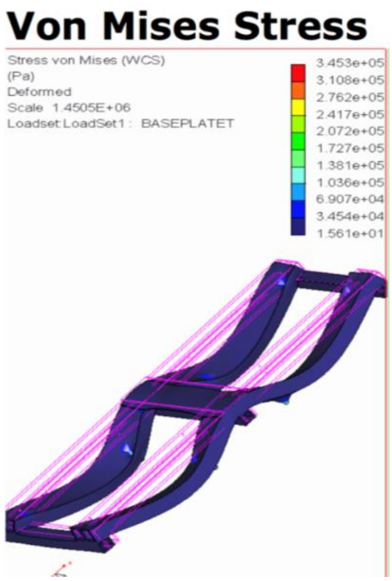
This quote is valid for 3 months and subject to our general terms and conditions.
Terms and conditions can be found at: info.rw-america.com/organization

Best regards,

R+W America
Leon Voskov

**Figure 7: R&W Price quote**

## Appendix E



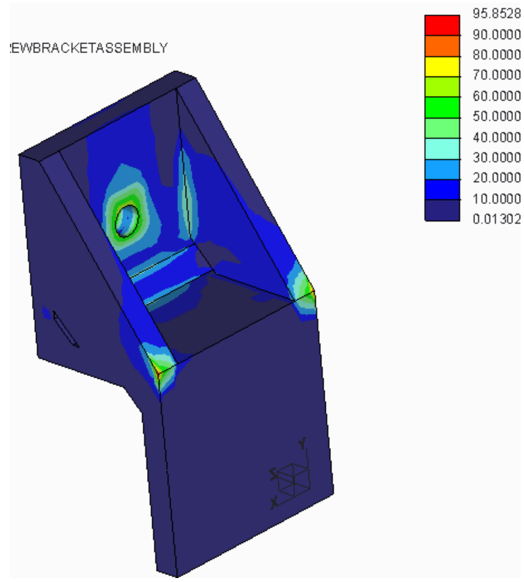




**Figure 8: Base frame**

**Figure 9: Setscrew mount horizontal**

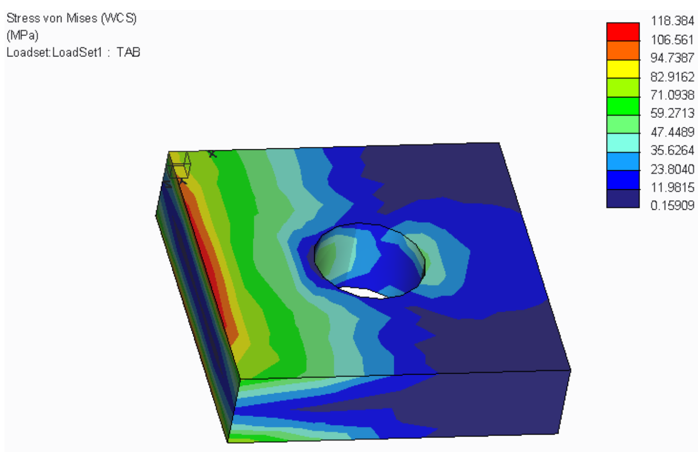



**Figure 10: Setscrew mount vertical**