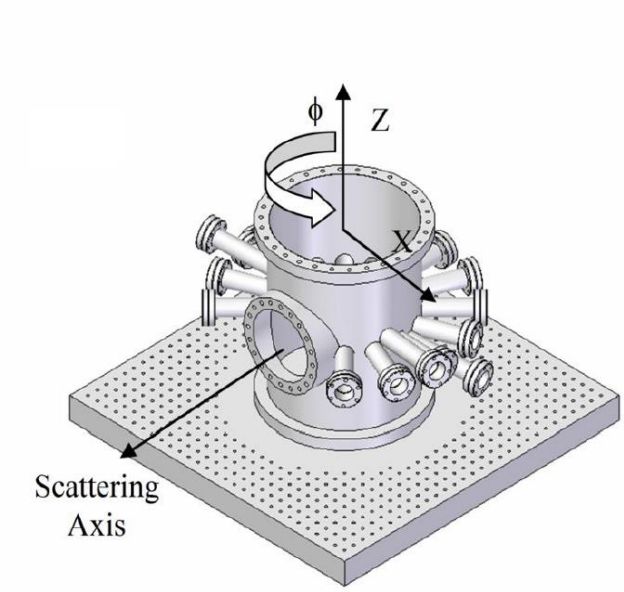
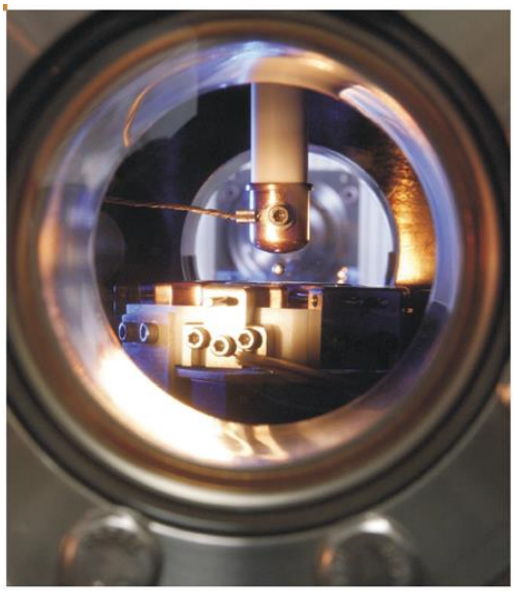
Structural and Modal Analysis of Camera Additions to Vacuum Chamber Port with Design Modification Recommendations





N. Mauro

3/7/2021 Original
2/20/2025 Review

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St. Norbert College
3/7/2021 Original
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Summary

The electrostatic levitator (ESL) high vacuum chamber has numerous Conflat™ ports with visual access to the electrode assembly at the center of the chamber. In order to reduce the footprint of the apparatus it is advantageous to attach camera assemblies (~50 lbs) to the ports, which protrude from the chamber approximately 10 inches from the chamber wall. Mechanical loading on the weld to the chamber is a concern as is the change in the resonance frequencies of the configuration. Transverse displacements of the port at 2.0 ±0.2 kHz affect camera sampling rate.

We conducted a load stress analysis and modal analysis in Inventor to identify likely changes in the resonances. While the static load stress is well within the Von Mises Stress limit for stainless steel (302) we find that modifications to the chamber design are recommended to remove a resonance mode that is instigated with the static load. Several different welded support elements were tested and a design fix is proposed. This document outlines the analysis leading to the fix and includes the dimensions of a weldment additions.

Table of Contents

Introduction

As a matter of course, all components that are modified on the equipment are subject to loading analysis. In this case, the equipment is a camera with high frame rates (~2 kHz) for motion capture that require an understanding of how the resonant modes are affected by the camera assembly, weighing approximately 50 lbs. Mechanical equipment in the vicinity of the experiment are at risk to excite resonances at this frequency. Typically, sensitive equipment would be mounted on the vibration isolation chamber but the confines of the equipment area, shown for context in Appendix A, make this impractical and a compact design is required. Further, and engineering solution can involve welding but should not involve disassembly and remachining of the assembly.

Methods

Autodesk Inventor was used to modify the original design model for the ESL. The port assembly was isolated and shown below in Fig. 1. A static load of 50 lbs was applied to the flat to simulate the camera assembly load.

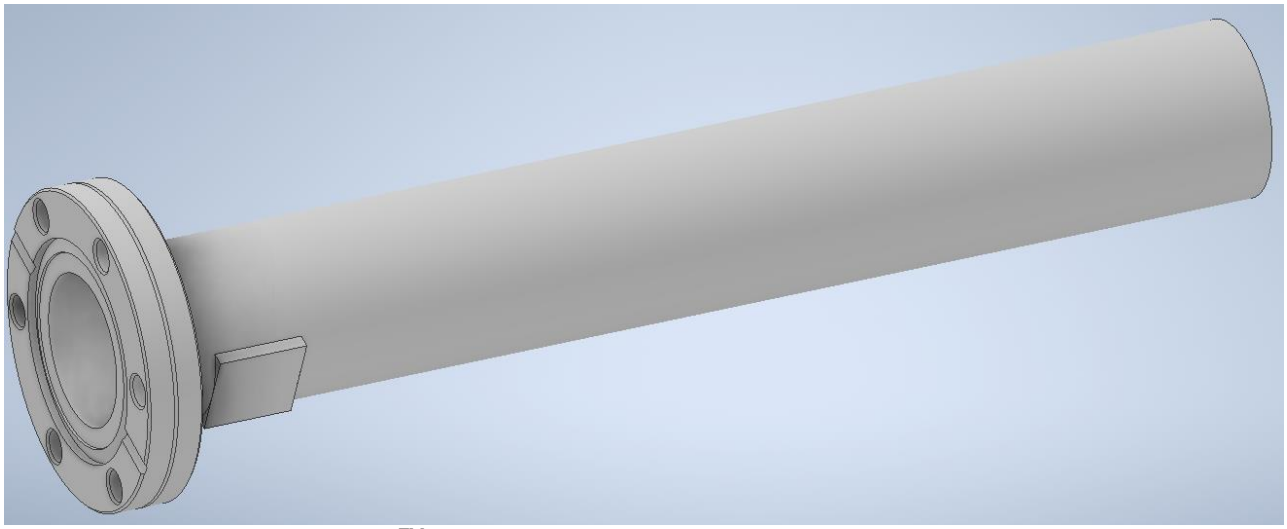


Figure 1 Chamber port with Conflat™ flange on a 10 inch thick-walled (1/8”) stainless steel tube. The flat on the tube will be used to mount the camera, localizing its load on the port.

Methods: Static Loading Analysis

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

Material settings:

Name	Stainless Steel	
General	Mass Density	0.289018 lbmass/in^3
	Yield Strength	36259.4 psi
	Ultimate Tensile Strength	78320.4 psi
Stress	Young's Modulus	27992.3 ksi
	Poisson's Ratio	0.3 ul
	Shear Modulus	10766.3 ksi
Part Name(s)	CF275_ESL_Connector_To_Chamber_with_tube_final_2023.ipt	

Operating conditions

Force:1

Load Type	Force
Magnitude	50.000 lbforce
Vector X	0.000 lbforce
Vector Y	50.000 lbforce
Vector Z	0.000 lbforce

The static load, approximating the weight of the camera apparatus, is shown in Fig. 2. The attachment to the larger chamber was modelled in the simulation as a fixed constraint.

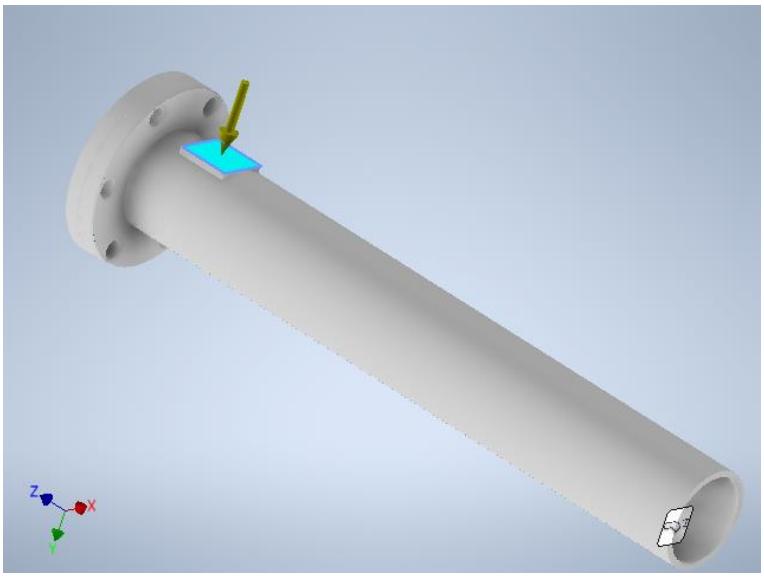


Figure 2 – Static load on the camera assembly point with a fixed constraint modelling the attachment to the chamber.

Methods: Modal Analysis

Four different configurations were tested: 1.) The static load alone, 2.) A thin (2mm), short ventral support fin, 3.) A thicker (4mm) long ventral support fin, and 4.) Two thicker long fins on the ventral side and mounted horizontally. The fins were modelled as a weldment with 0.125" fillet welds. Eight normal modes were identified in the analysis.

General objective and settings:

Design Objective	Single Point
Study Type	Modal Analysis
Model State	[Primary]
Design View	Default
Positional	[Primary]
Number of Modes	8
Frequency Range	Undefined
Compute Preloaded Modes	No
Enhanced Accuracy	No

Mesh settings:

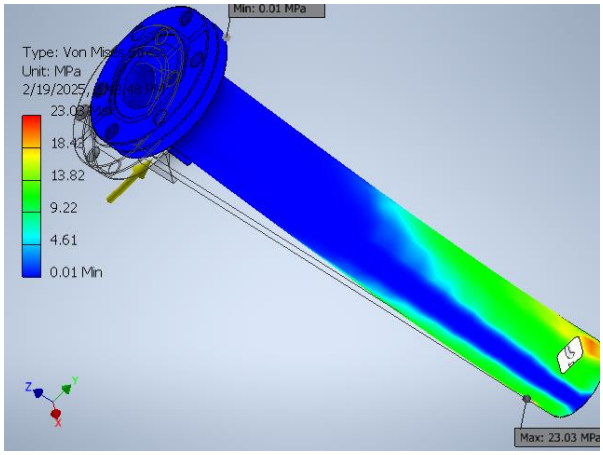
Avg. Element Size (fraction of model diameter)	0.08
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg

Create Curved Mesh Elements	No
Use part based measure for Assembly mesh	Yes

Results

Static Loading Results

The simulation results are shown below in Fig. 3.



Name	Minimum	Maximum
Von Mises Stress	0.00735008 MPa	23.0308 MPa
1st Principal Stress	-8.92281 MPa	29.0466 MPa
3rd Principal Stress	-25.7486 MPa	10.5855 MPa
Displacement	0 mm	0.132474 mm
Safety Factor	10.855 ul	15 ul

Figure 3 – Summary stress and displacement results for 50 lb load. The results are well within tolerances for stainless 302.

Maximum deflection and Von Mises are above engineering limits; the full report is available in Appendix B. No further discussion is necessary as the ventral support fin only serves to reduce the von Mises and displacement.

Modal Analysis Results

I. Static load alone

The frequency values are shown below:

F1	**313.31 Hz**
F2	**316.46 Hz**
F3	**1679.11 Hz**
F4	**2043.78 Hz**
F5	**2065.23 Hz**
F6	**3495.85 Hz**
F7	**4999.44 Hz**
F8	**5053.26 Hz**

There are two frequencies of concern: F4 and F5. In Fig. 4 the maximum displacements are shown for the respective frequencies:

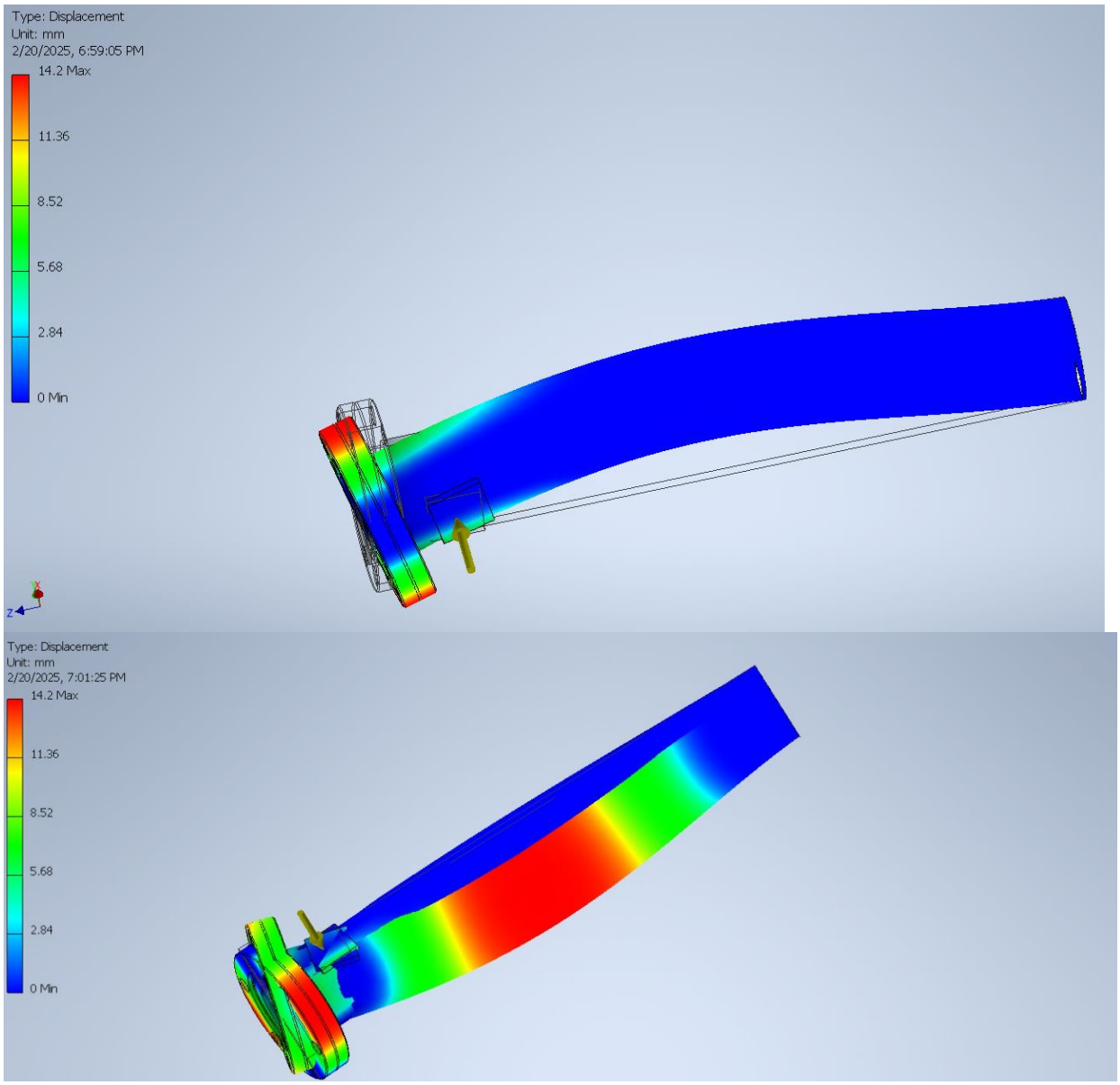


Figure 4 – Displacement modes for F4 and F5, 2043.78 Hz and 2065.23 Hz, respectively.

We see substantial deflection at the frequencies that would affect camera operation, necessitating modification.

II. A thin (2mm), short ventral support fin

A thin short fin is welded to the tube, as shown in Fig. 5. The modal analysis is conducted with the static load (50 lbs) and holding the tube surface and fin surface fixed to the chamber.

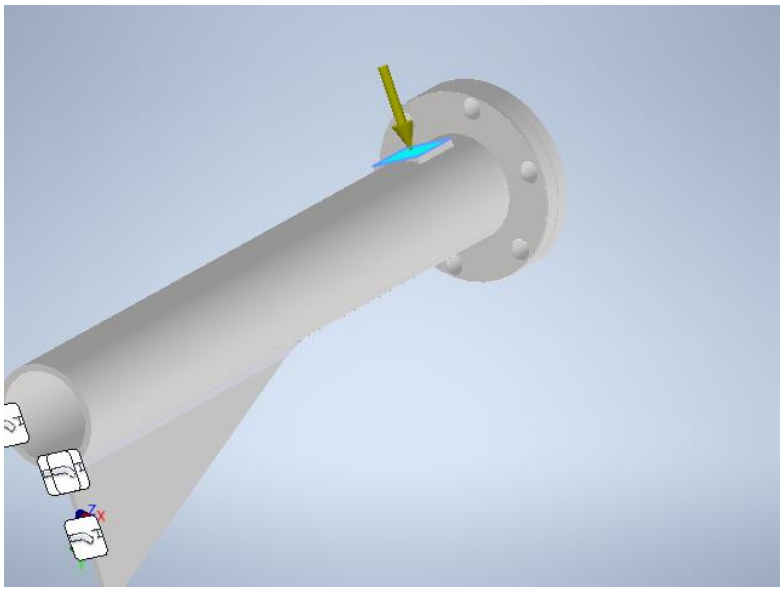


Figure 5 – Short fin attachment.

When the modal analysis is conducted, the frequency values are as shown below:

F1	**293.72 Hz**
F2	**421.95 Hz**
F3	**1578.86 Hz**
F4	**1920.09 Hz**
F5	**2309.53 Hz**
F6	**2475.33 Hz**
F7	**3592.54 Hz**
F8	**4329.39 Hz**

While the modes shift and only one concerning frequency remains (F4) we observe, in Fig. 6, significant transverse displacement, exceeding 8mm at the face. While these displacements are likely exaggerated in practice, we attempt reduction in the displacements and shifts in the frequency.

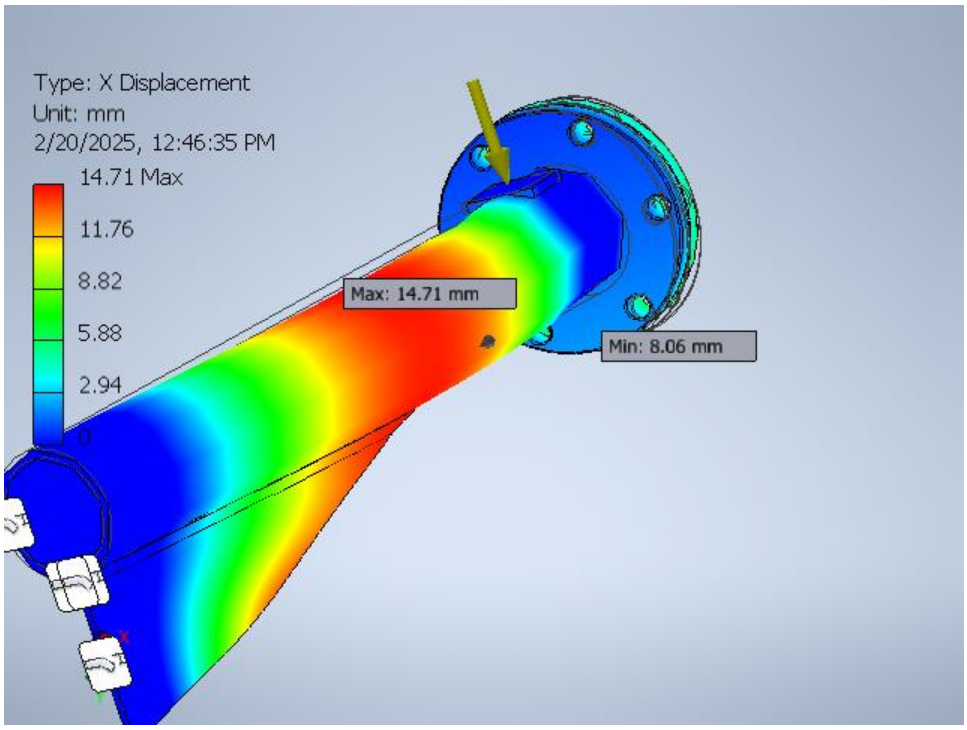


Figure 6 – The displacement mode associated with F4, near 2 kHz. Displacements at the face above 8mm are concerning.

III. A thicker (4mm) long ventral support fin

A thicker (4mm) long fin is welded to the tube, as shown in Fig. 7. The modal analysis is conducted with the static load (50 lbs) and holding the tube surface and fin surface fixed to the chamber.

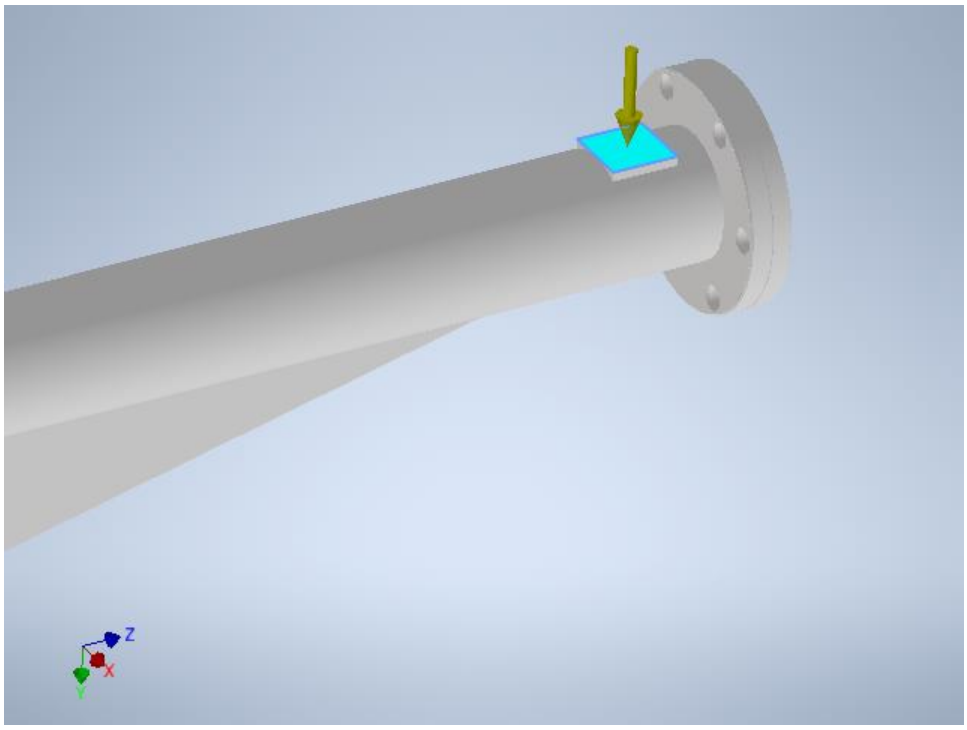


Figure 7 – A thicker (4mm) long fin attachment.

When the modal analysis is conducted, the frequency values are as shown below:

F1	**292.03 Hz**
F2	**541.78 Hz**
F3	**1560.91 Hz**
F4	**1824.98 Hz**
F5	**2530.85 Hz**
F6	**3294.30 Hz**
F7	**3802.89 Hz**
F8	**4666.13 Hz**

The modes continue to shift in frequency, and no modes resonate at a frequency of concern., in Fig. 8, significant transverse displacement, exceeding 8mm at the face. While these displacements are likely exaggerated in practice, we attempt reduction in the displacements and shifts in the frequency.

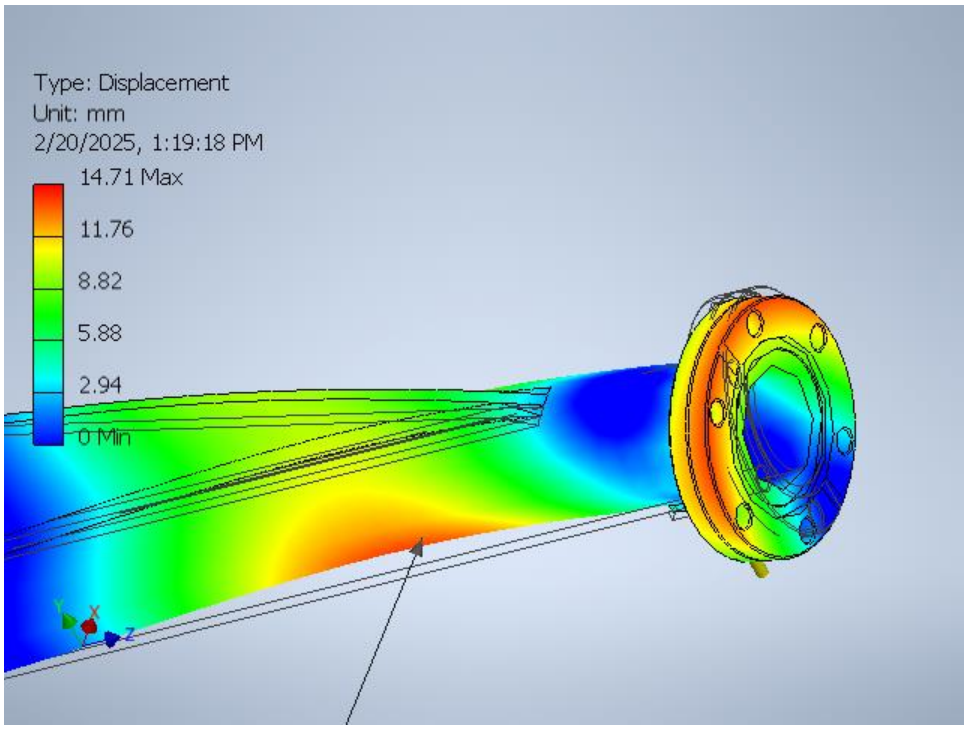


Figure 8– The displacement mode associated with F4, near 1.82 kHz. Displacements at the face above 8mm are concerning.

IV. Two orthogonally placed support fins

A thicker (4mm) long fin is welded to the tube, as shown in Fig. 9 on the ventral side with an additional fin to stiffen the orthogonal transverse direction in an attempt to shift F4 away from the resonance concern area. The modal analysis is conducted with the static load (50 lbs) and holding the tube surface and fin surface fixed to the chamber.

.

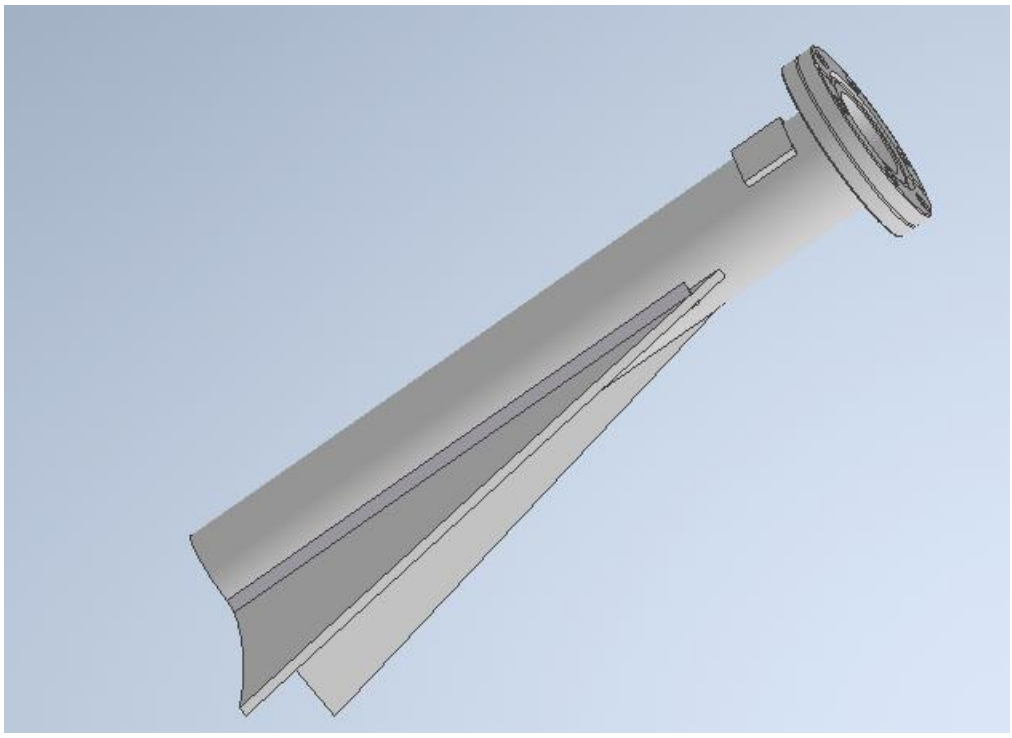


Figure 9 – Two orthogonally, transverse mode-damping, thick, long fin attachments.

When the modal analysis is conducted, the frequency values are as shown below:

F1	**515.15**
F2	**591.67 Hz**
F3	**1666.07 Hz**
F4	**2378.91 Hz**
F5	**2460.78 Hz**
F6	**3244.25 Hz**
F7	**3388.78 Hz**
F8	**4149.03 Hz**

The modes continue to shift in frequency and no modes persist in the frequency range of concern. In Fig. 10, we observe that the transverse displacements add into what appears to be a torsional-dominant mode. The full modal analysis is provided in Appendix B.

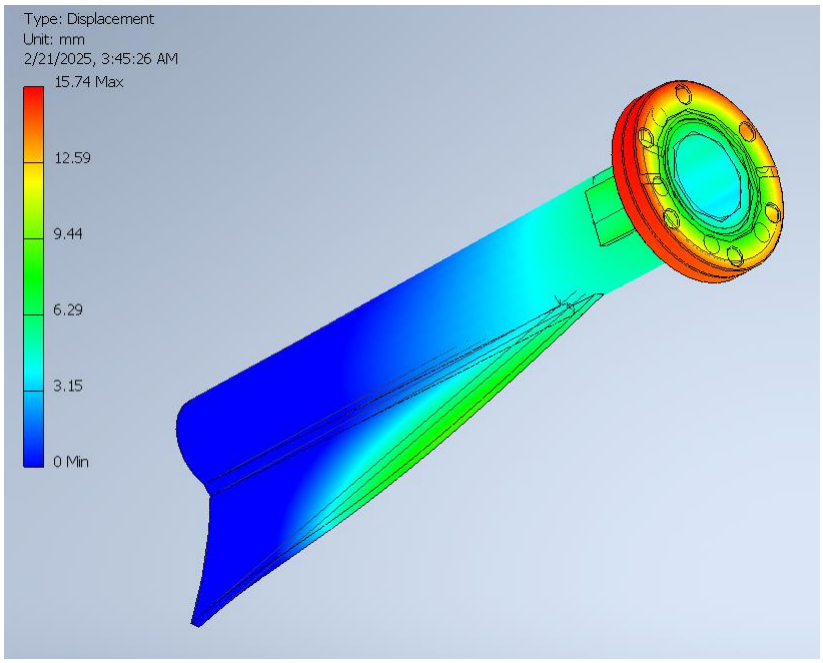


Figure 10– The displacement mode associated with F3, near 1.67 kHz. Displacements at the face above 8mm are concerning, however, the mode is nearly torsional.

Discussion

With relatively minor modifications to the chamber assembly, we find that the resonant mode frequencies are shifted out of the frequency range of concern, 2.0 ±0.2 kHz. With all modal analyses, the absolute deviation of the displacement is likely inaccurate, however, frequency identification and change in modal frequency with parameter adjustment are good metrics to inform design change. This, combined with the requirement that the chamber not be removed *ex situ*, the welding modifications are quite feasible *in situ*. As always, we are concerned about overtones in the resonance. In this case, F8 is in the vicinity of a multiple of the 2.0 ±0.2 kHz expected driving frequencies. This mode, shown below in Fig. 11 is almost completely longitudinal. Upon data acquisition with the camera the researchers should be cognizant of the potential for F8 mode excitation.

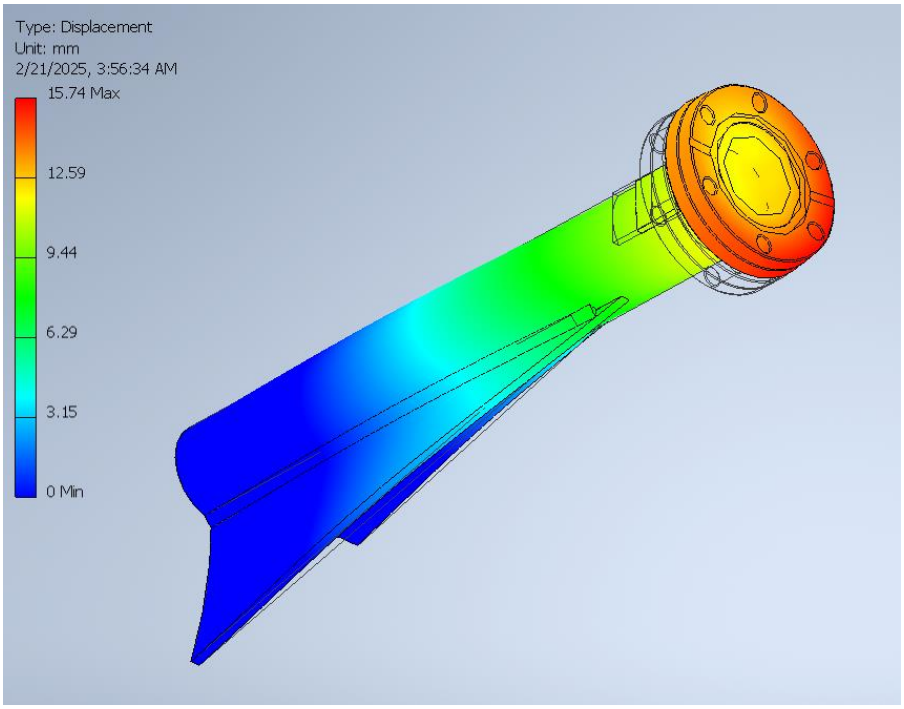
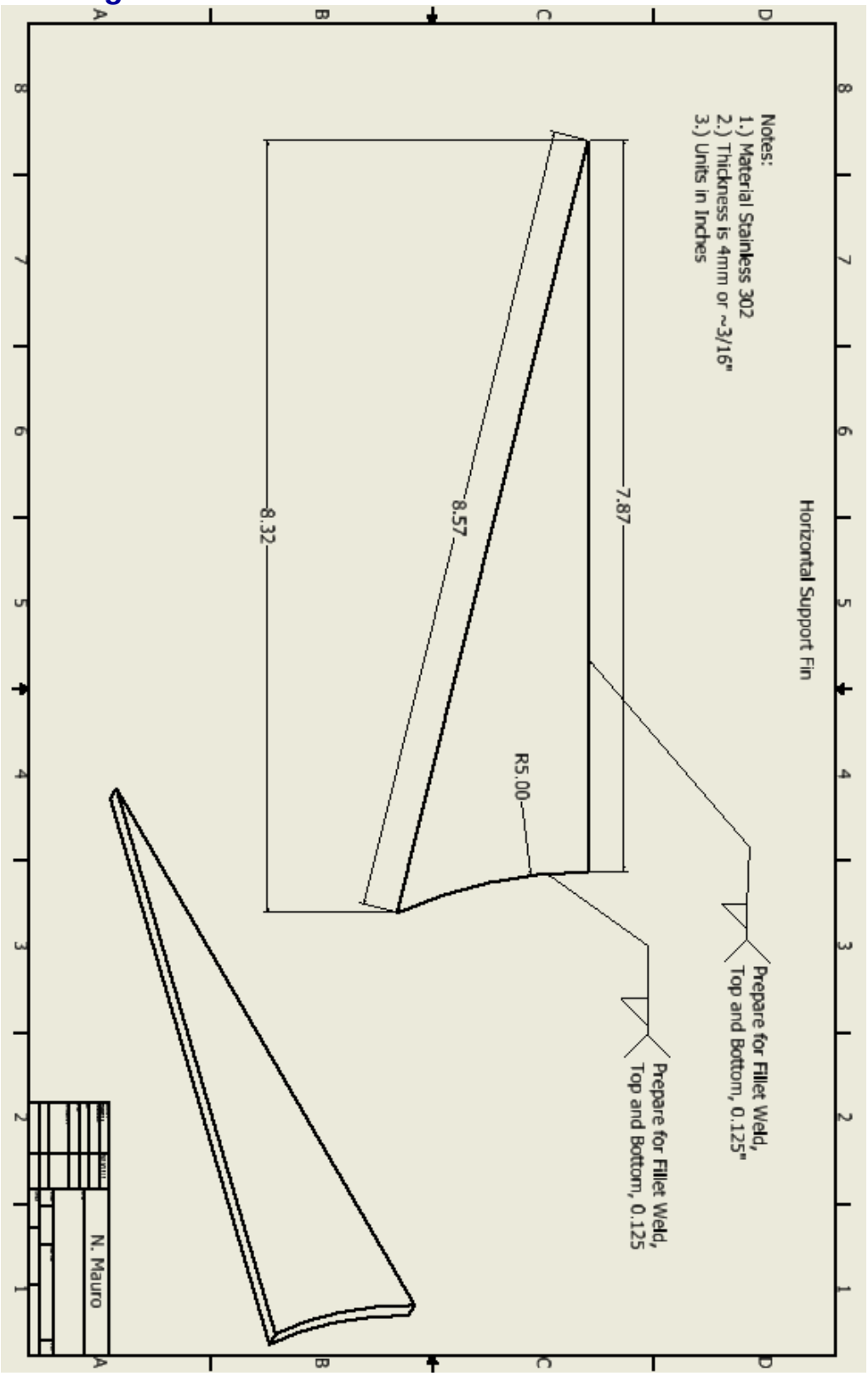


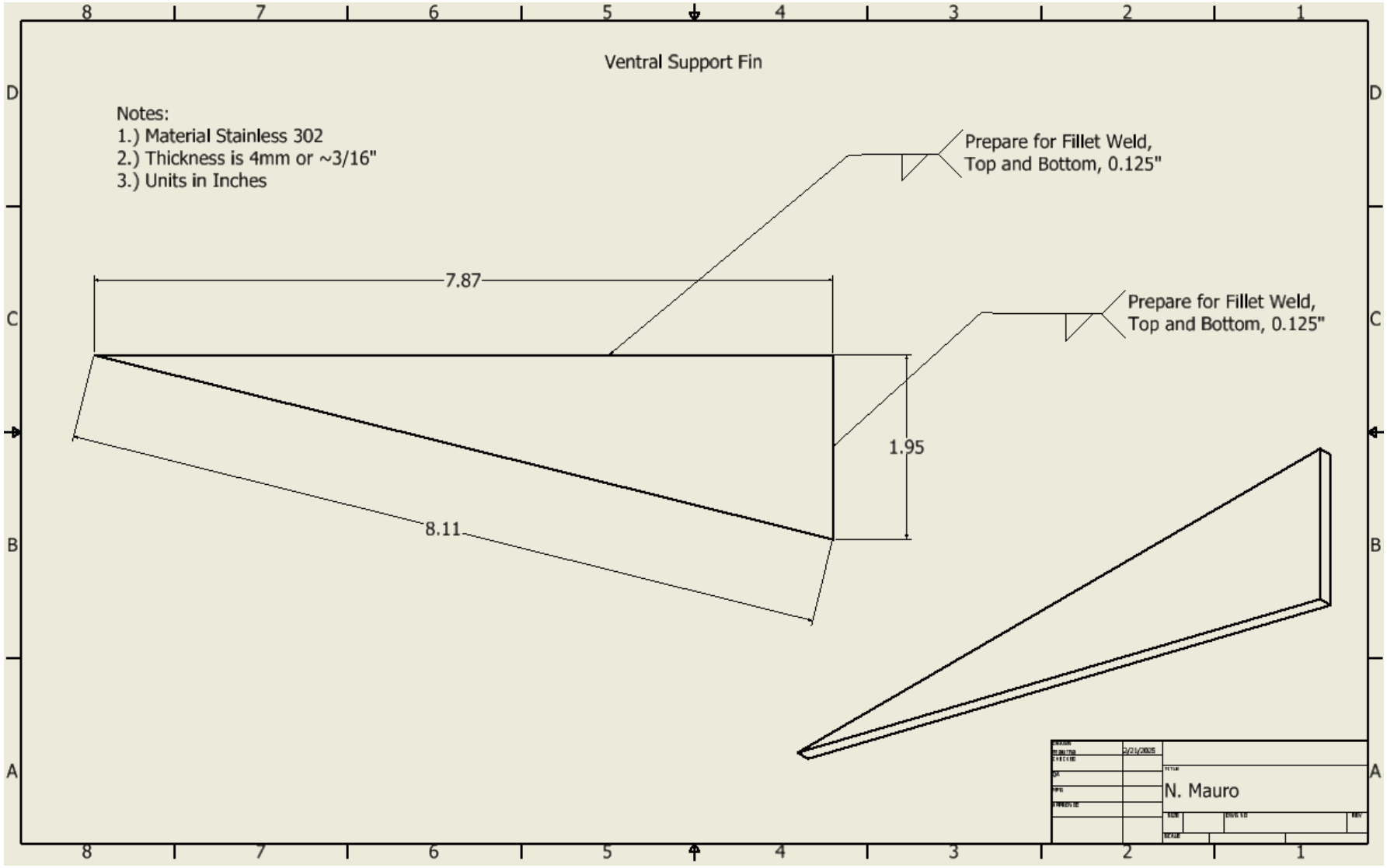
Figure 11– The displacement mode associated with F8, near 4.2 kHz. Displacements at the face above 8mm are concerning, however, the mode is nearly entirely longitudinal.

Conclusions

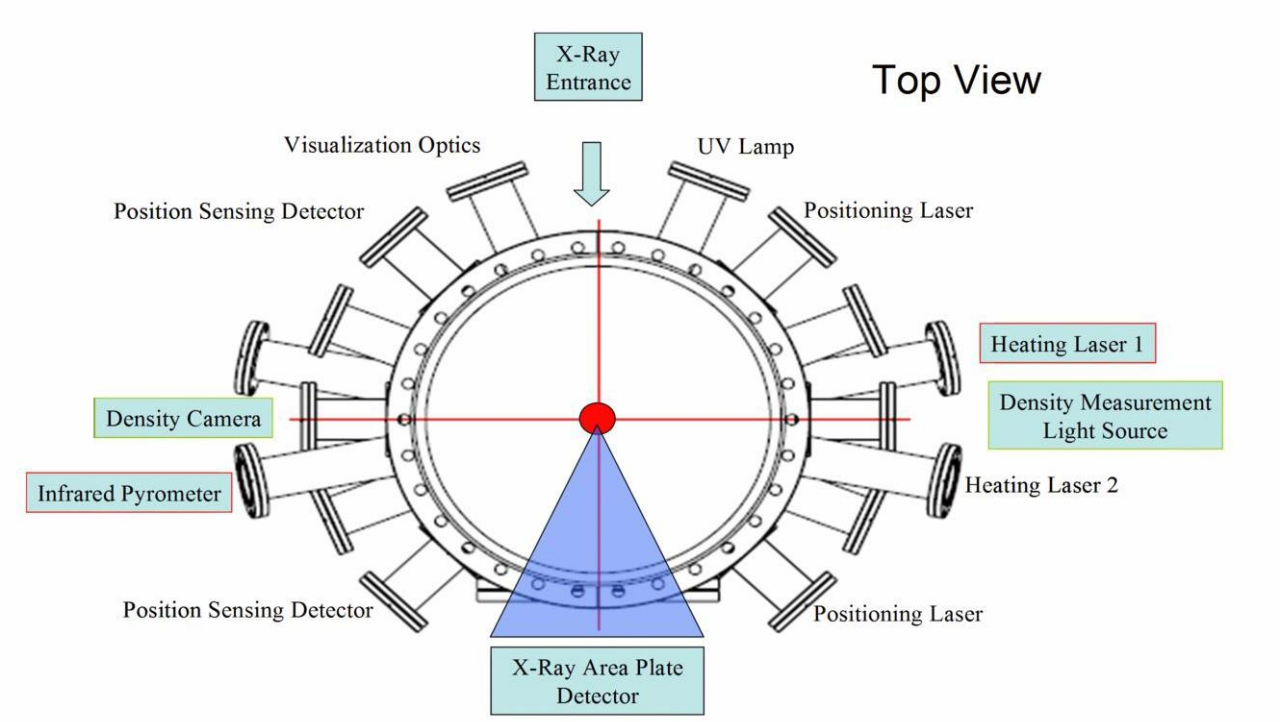
Drafting documents have been provided for the two stainless steel (302) support fins for production and welding. Performance analysis should be conducted before full apparatus deployment to validate the efficacy of the solution.

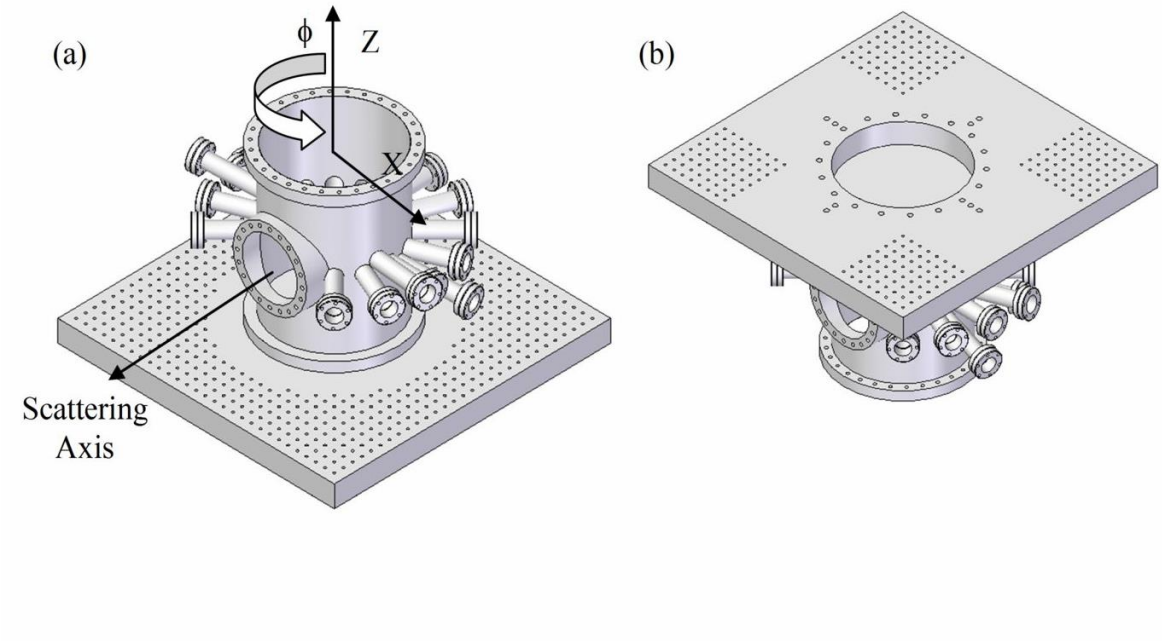
Drafting Documents

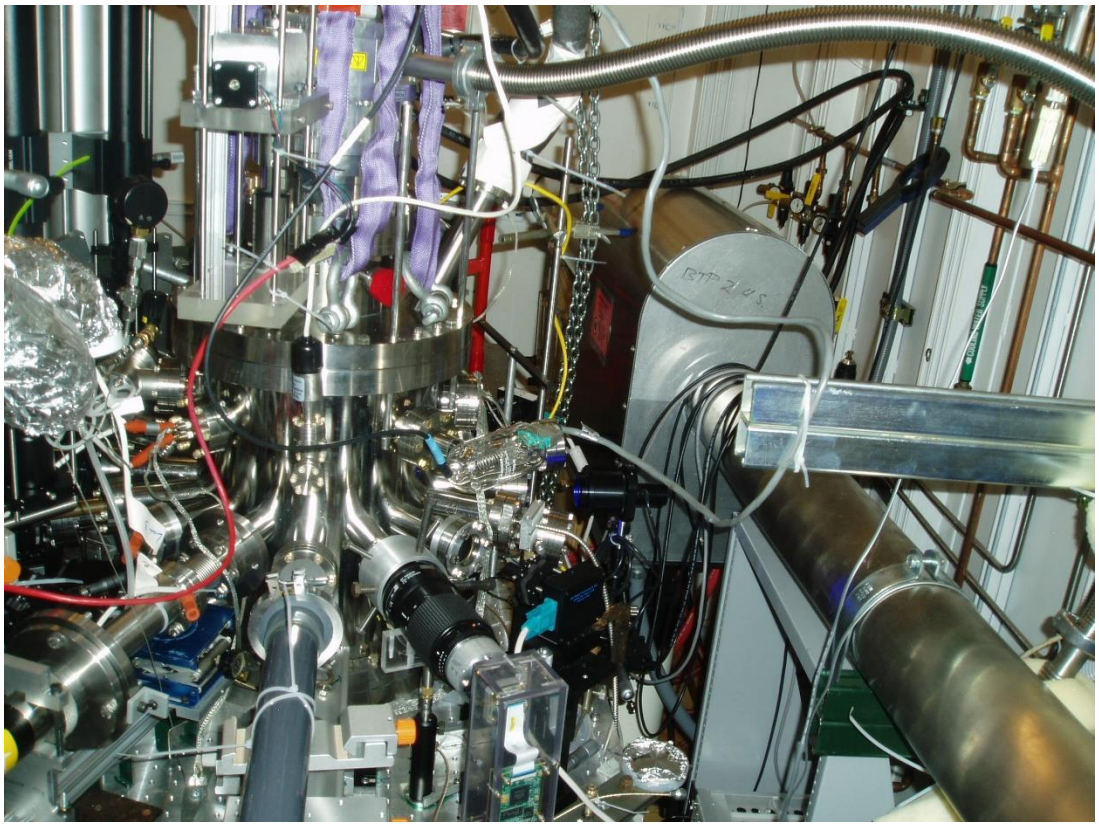


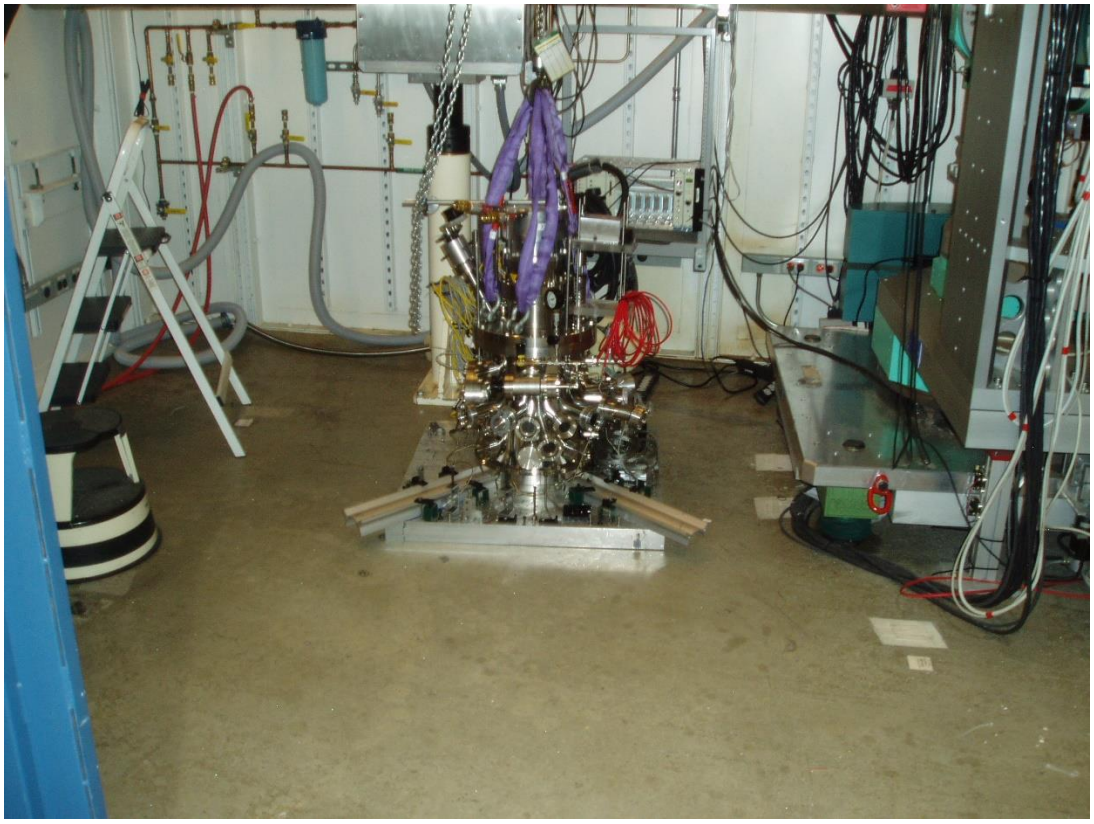

Ventral Support Fin
Notes:
1.) Material Stainless 302
2.) Thickness is 4mm or ~3/16"
3.) Units in Inches
Prepare for Fillet Weld,
Top and Bottom, 0.125"
7.87
Prepare for Fillet Weld,
Top and Bottom, 0.125"
1.95
8.11
N. Mauro

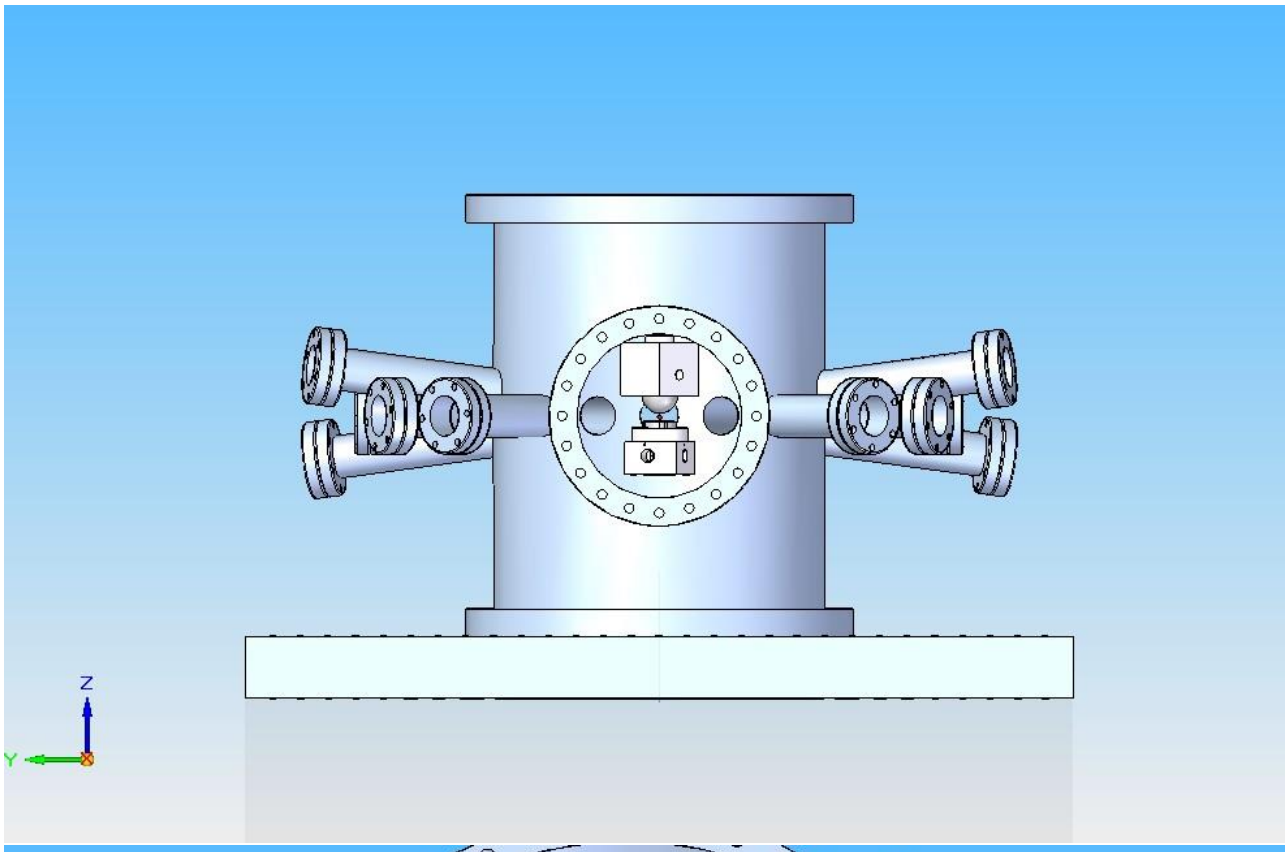
Appendix A:
Chamber Images for Component Context

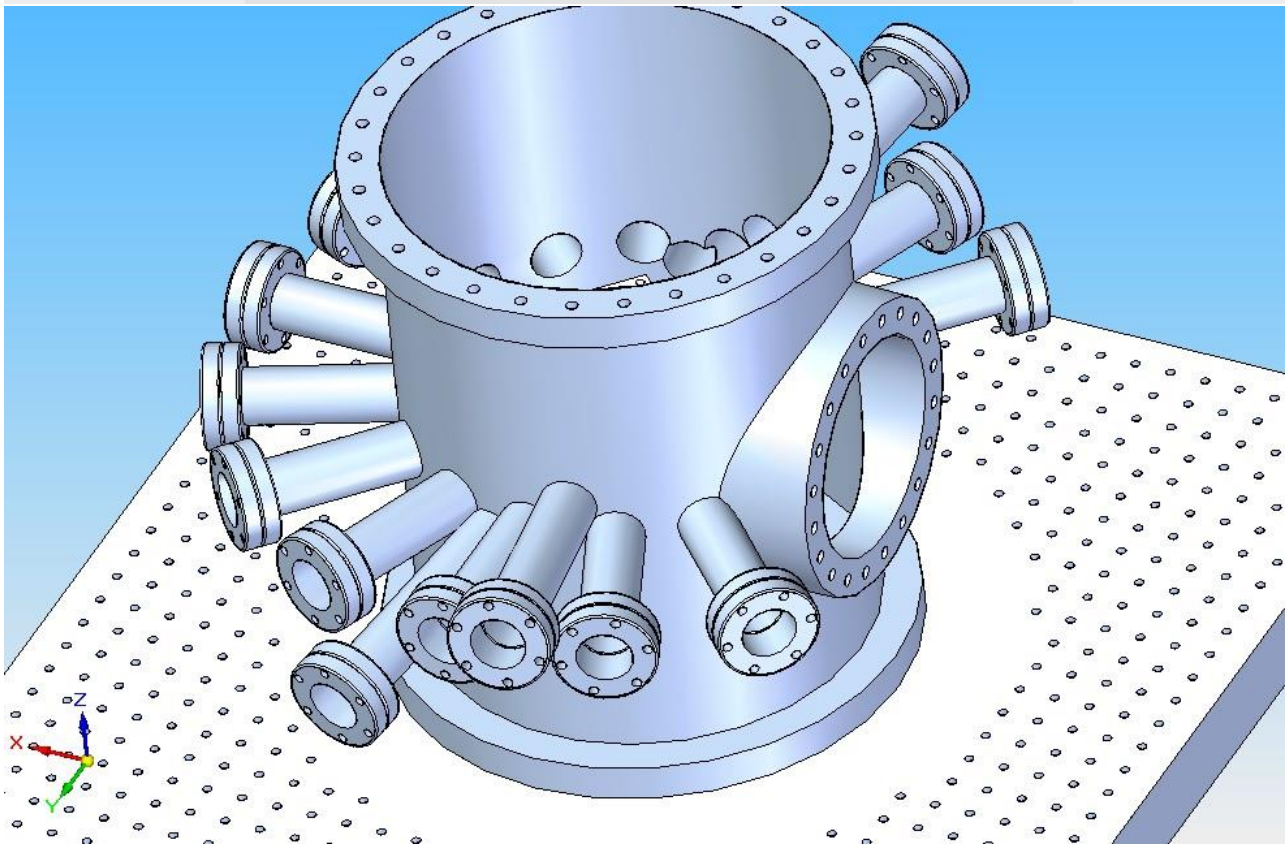









Z
Y


Z
X
Y

Appendix B:
Stress Analysis Ventral Horizontal Weldments (Reproduced from original on 2/20/2025)

Stress Analysis Report

AUTODESK.

Analyzed File:	weld assembly_rev1.iam
Autodesk Inventor Version:	2025.2 (Build 292293000, 293)
Creation Date:	2/20/2025, 6:38 PM
Study Author:	maurna
Summary:	

Modal Analysis:1
General objective and settings:

Design Objective	Single Point
Study Type	Modal Analysis
Last Modification Date	2/20/2025, 6:29 PM
Model State	[Primary]
Design View	Default
Positional	[Primary]
Number of Modes	8
Frequency Range	Undefined
Compute Preloaded Modes	No
Enhanced Accuracy	No

iProperties
Summary

Author	maurna

Project

Part Number	weld assembly_rev1
Designer	maurna

Estimated Cost	$0.00
Creation Date	2/20/2025

Status

Design State	WorkInProgress

Physical

Mass	0.342649 lbmass
Area	100537 mm^2
Volume	149117 mm^3
Center of Gravity	x=-79.0642 mm y=8.05852 mm z=42.7776 mm

Note: Physical values could be different from Physical values used by FEA reported below.

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.08
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	No
Use part based measure for Assembly mesh	Yes

Material(s)

Name	Steel	
General	Mass Density	0.283599 lbmass/in^3
	Yield Strength	30022.8 psi
	Ultimate Tensile Strength	50038 psi
Stress	Young's Modulus	30457.9 ksi
	Poisson's Ratio	0.3 ul
	Shear Modulus	11714.6 ksi
Part Name(s)	weld assembly_rev1.iam	

Name	Stainless Steel	
	Mass Density	0.289018 lbmass/in^3

General	Yield Strength	36259.4 psi
	Ultimate Tensile Strength	78320.4 psi
Stress	Young's Modulus	27992.3 ksi
	Poisson's Ratio	0.3 ul
	Shear Modulus	10766.3 ksi
Part Name(s)	CF275_ESL_Connector_To_Chamber_with_tube_final_weld_piece_2023_MIR.ipt CF275_ESL_Connector_To_Chamber_with_tube_final_2023.ipt	

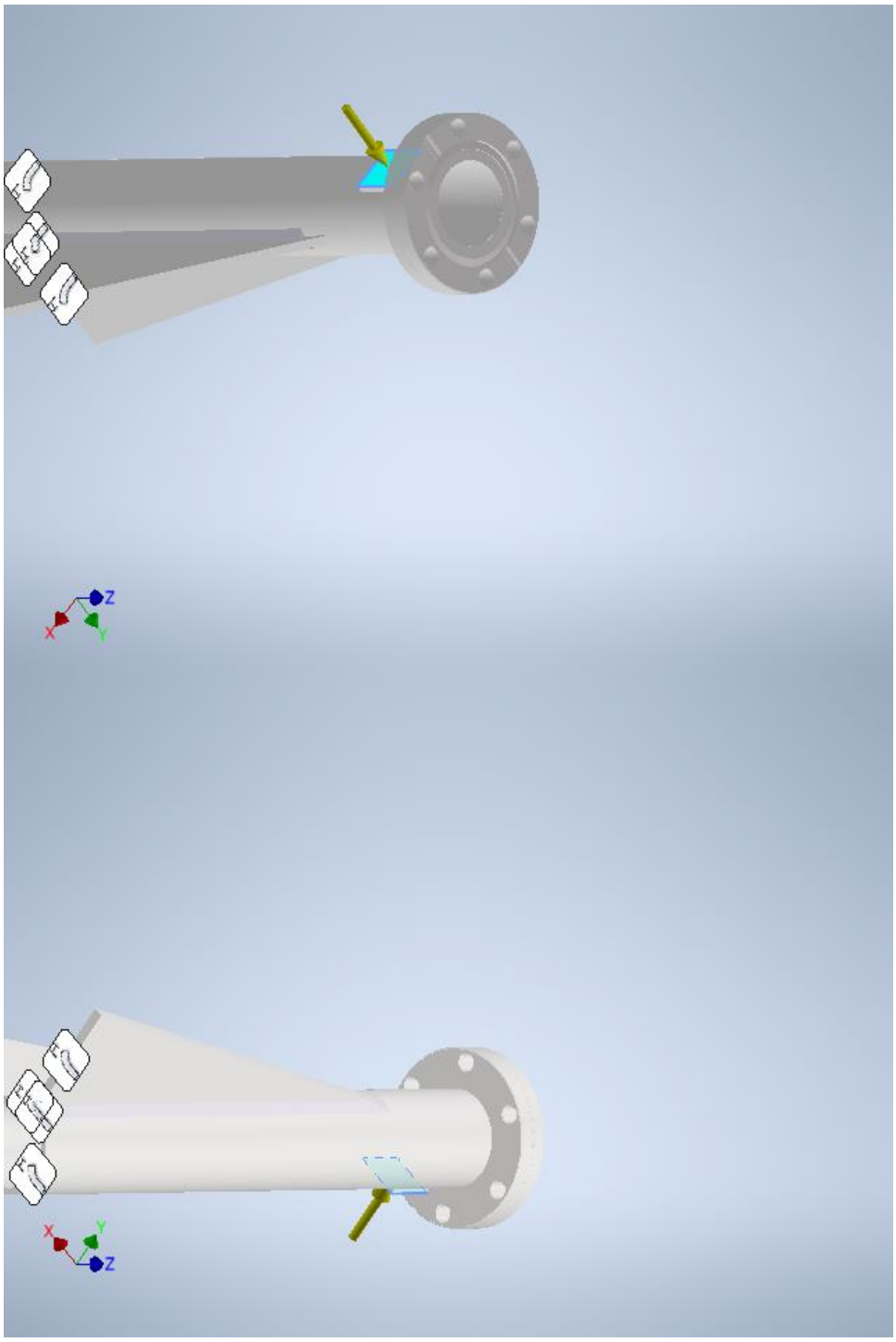
Name	Generic	
General	Mass Density	0.0361273 lbmass/in^3
	Yield Strength	0 psi
	Ultimate Tensile Strength	0 psi
Stress	Young's Modulus	0.0000145038 ksi
	Poisson's Ratio	0 ul
	Shear Modulus	0.00000725189 ksi
Part Name (s)	CF275_ESL_Connector_To_Chamber_with_tube_final_weld_piece_horizontal2023.ipt	

Operating conditions

Force:1

Load Type	Force
Magnitude	50.000 lbforce
Vector X	-0.000 lbforce
Vector Y	50.000 lbforce
Vector Z	-0.000 lbforce

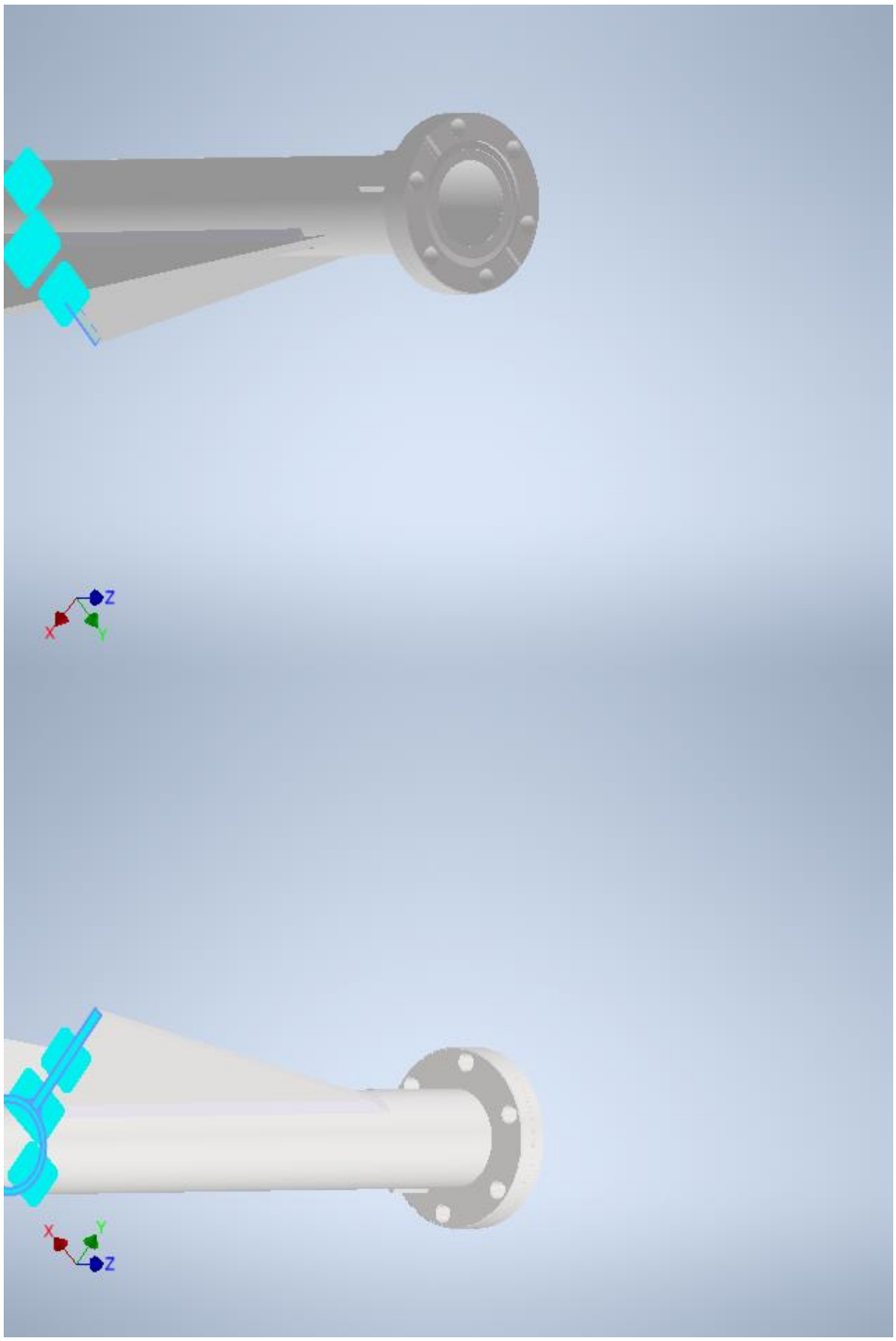
Selected Face(s)



Fixed Constraint:1

Constraint Type	Fixed Constraint

Selected Face(s)



Contacts (Bonded)

Name	Part Name(s)
Bonded:1	CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1 CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1

Bonded:2	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1
Bonded:3	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1
Bonded:4	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1
Bonded:5	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1

Results

Frequency Value(s)

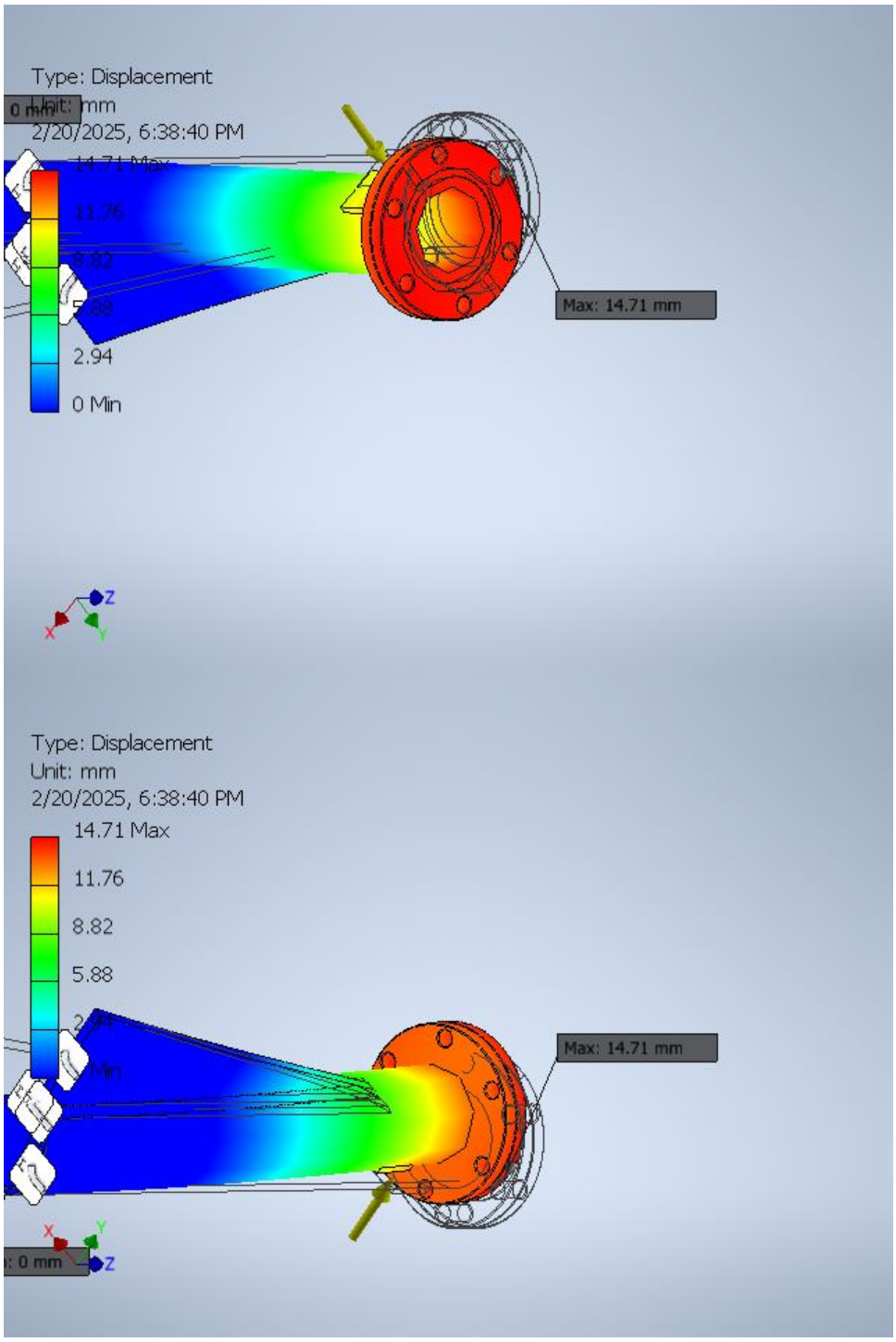
F1	292.03 Hz
F2	541.78 Hz
F3	1560.91 Hz
F4	1824.98 Hz
F5	2530.85 Hz
F6	3294.30 Hz
F7	3802.89 Hz
F8	4666.13 Hz

Result Summary

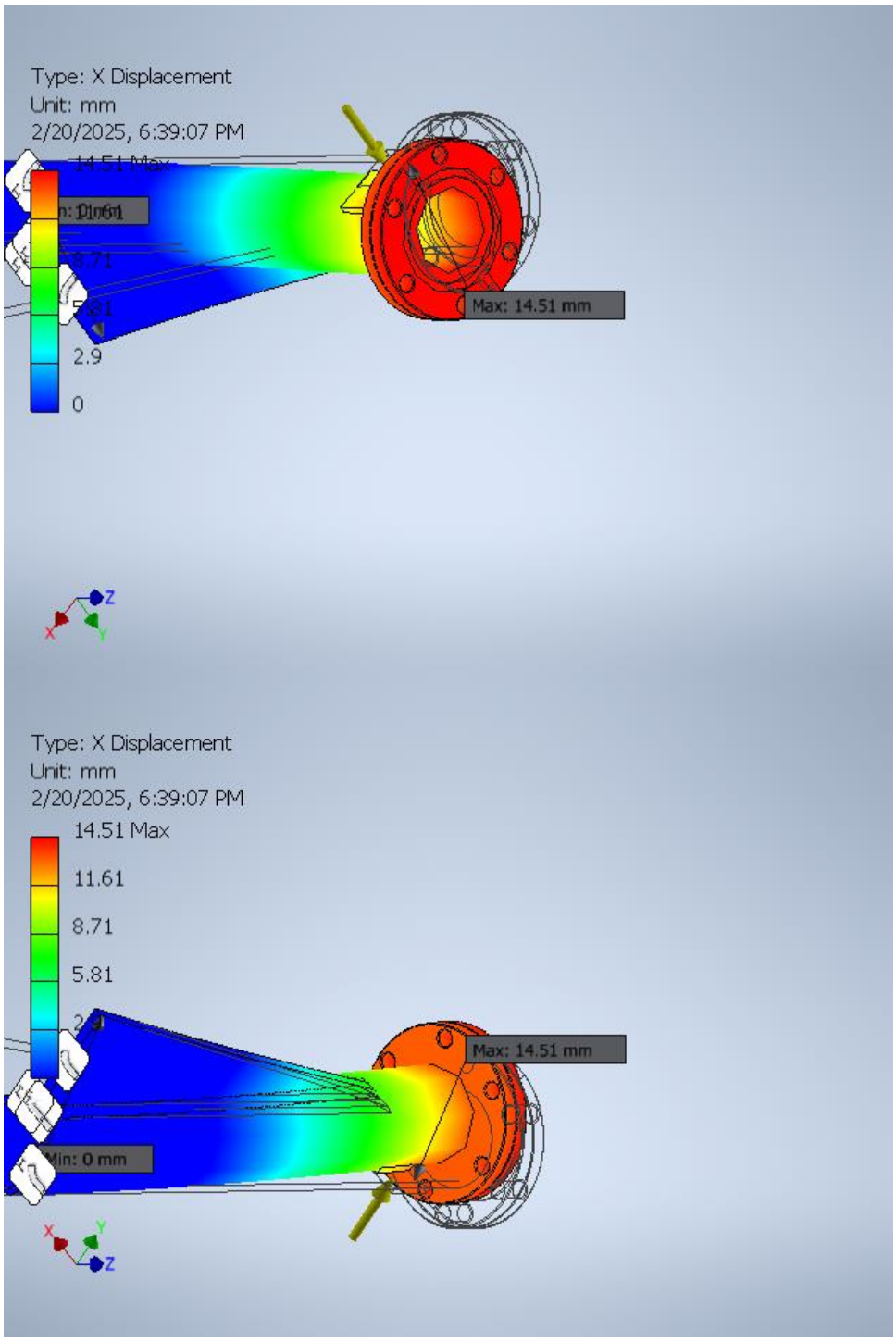
Name	Result Value
Volume	126809 mm^3
Mass	2.2359 lbmass

Figures

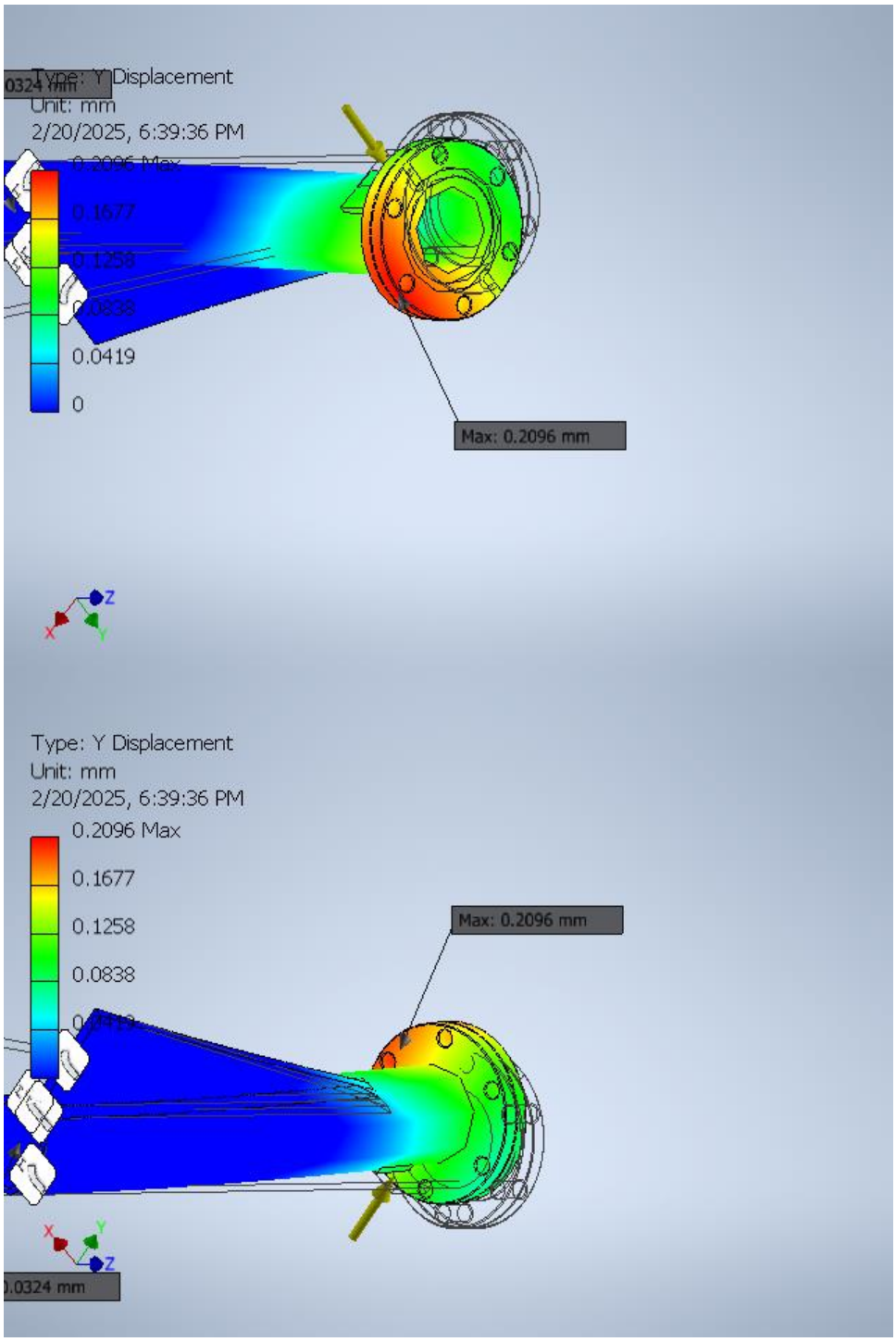
F1 292.03 Hz Displacement



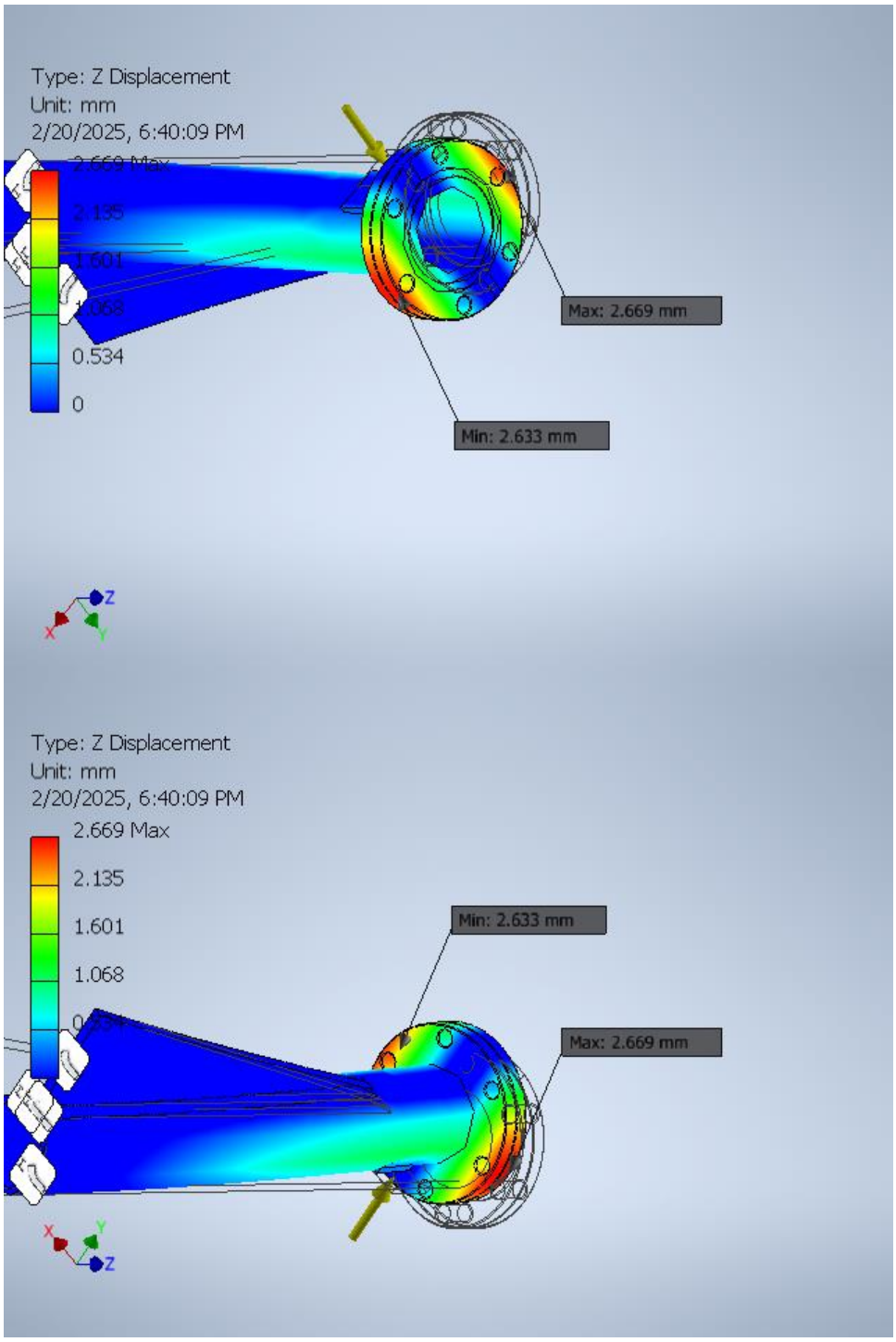
F1 292.03 Hz X Displacement



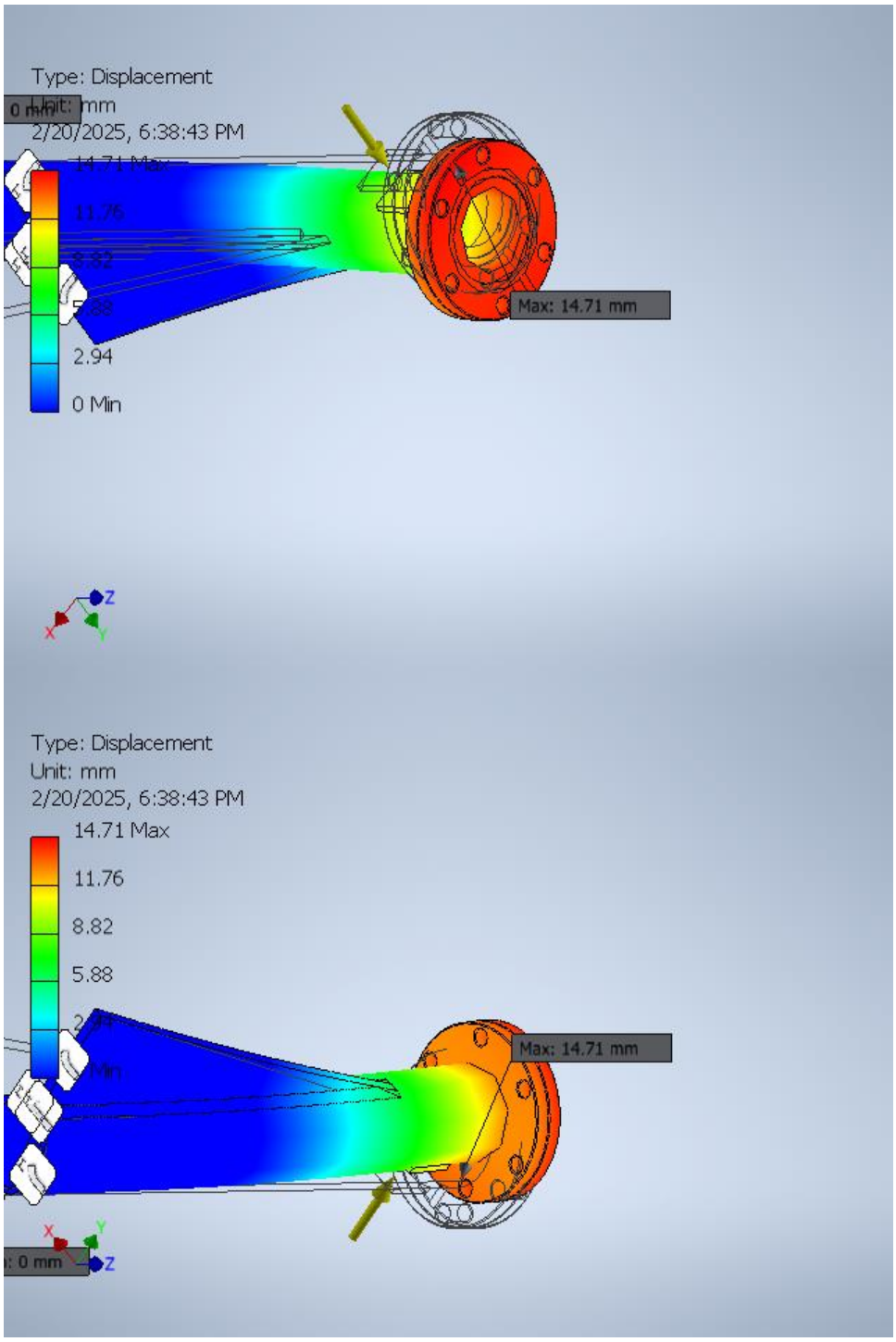
F1 292.03 Hz Y Displacement



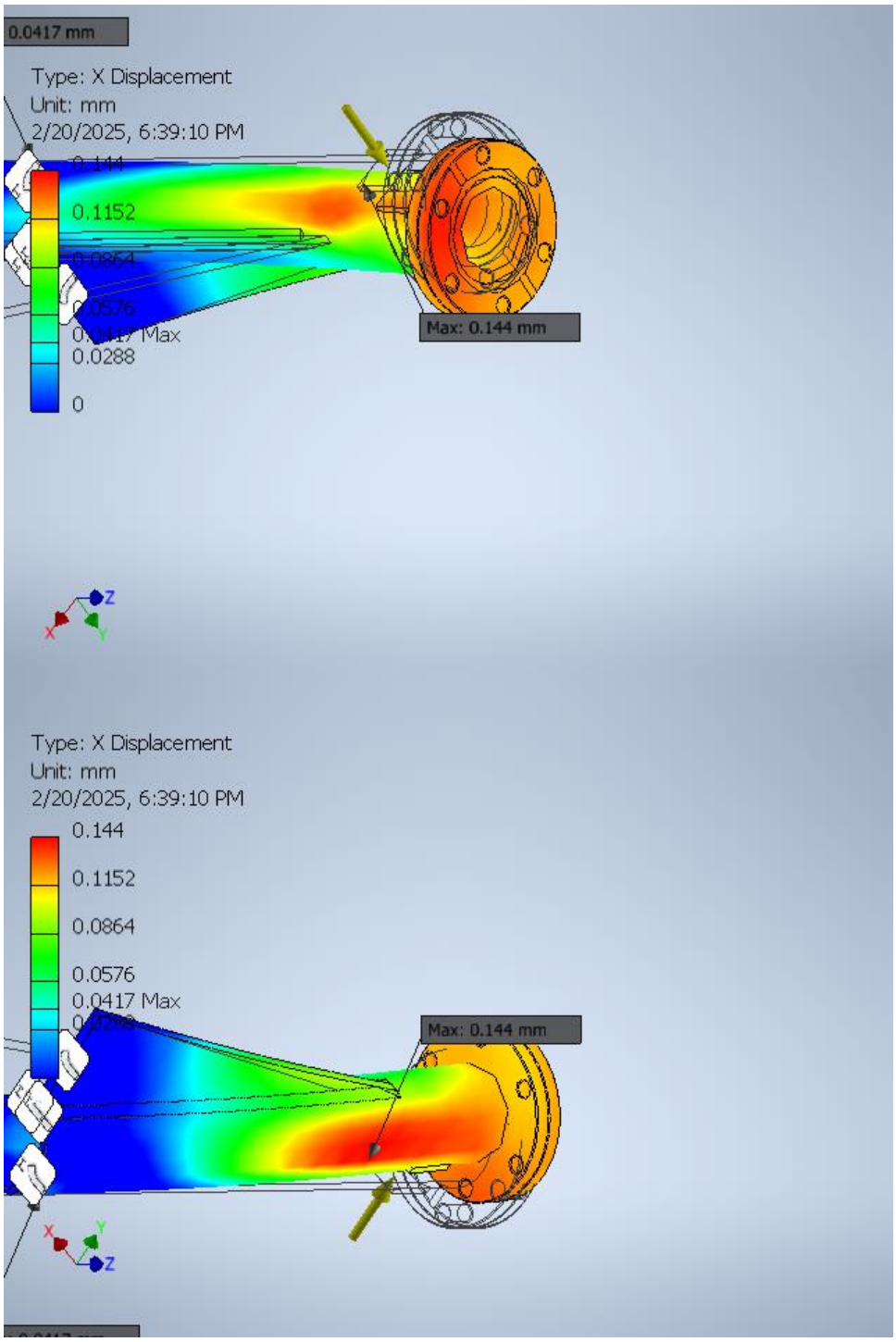
F1 292.03 Hz Z Displacement



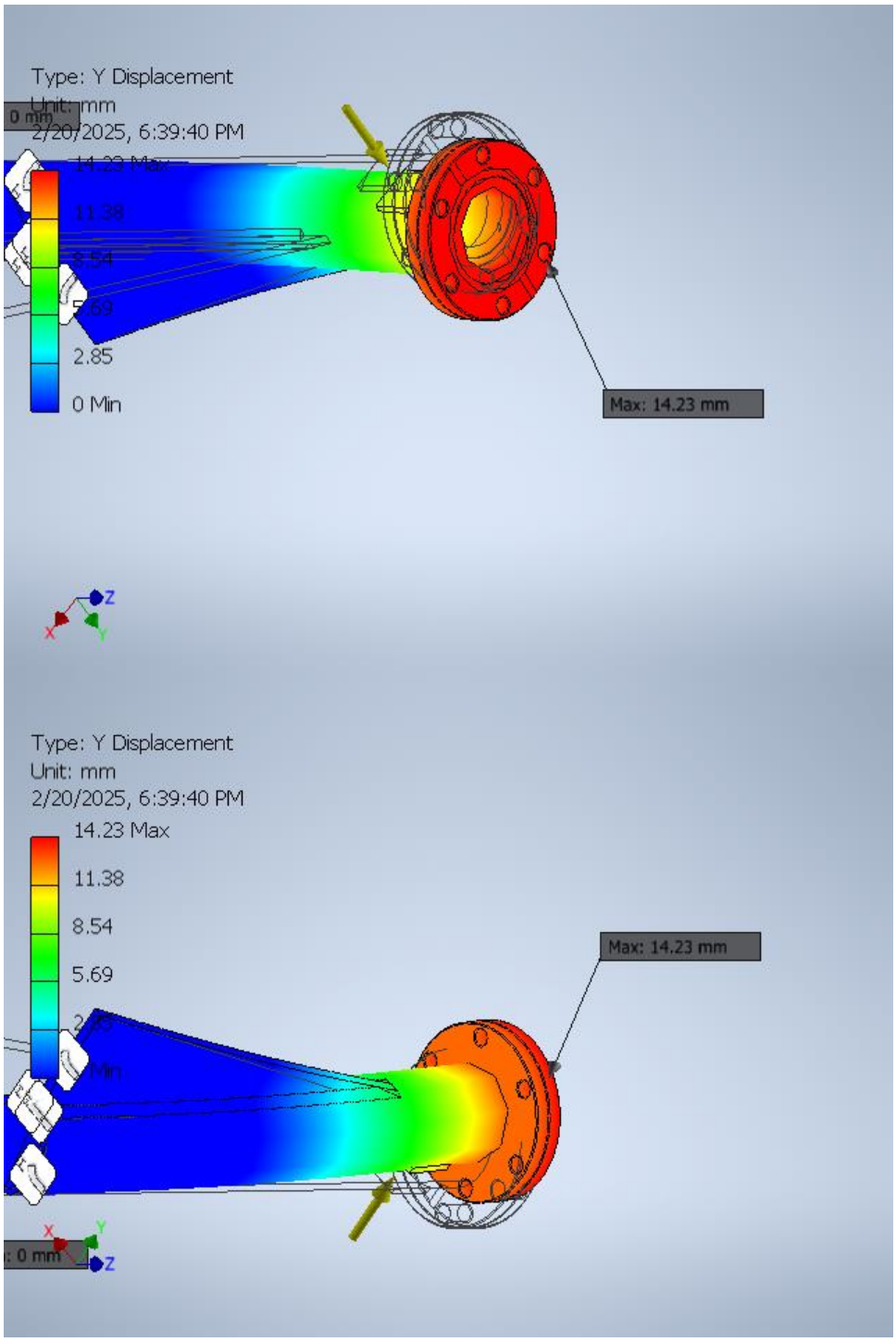
F2 541.78 Hz Displacement



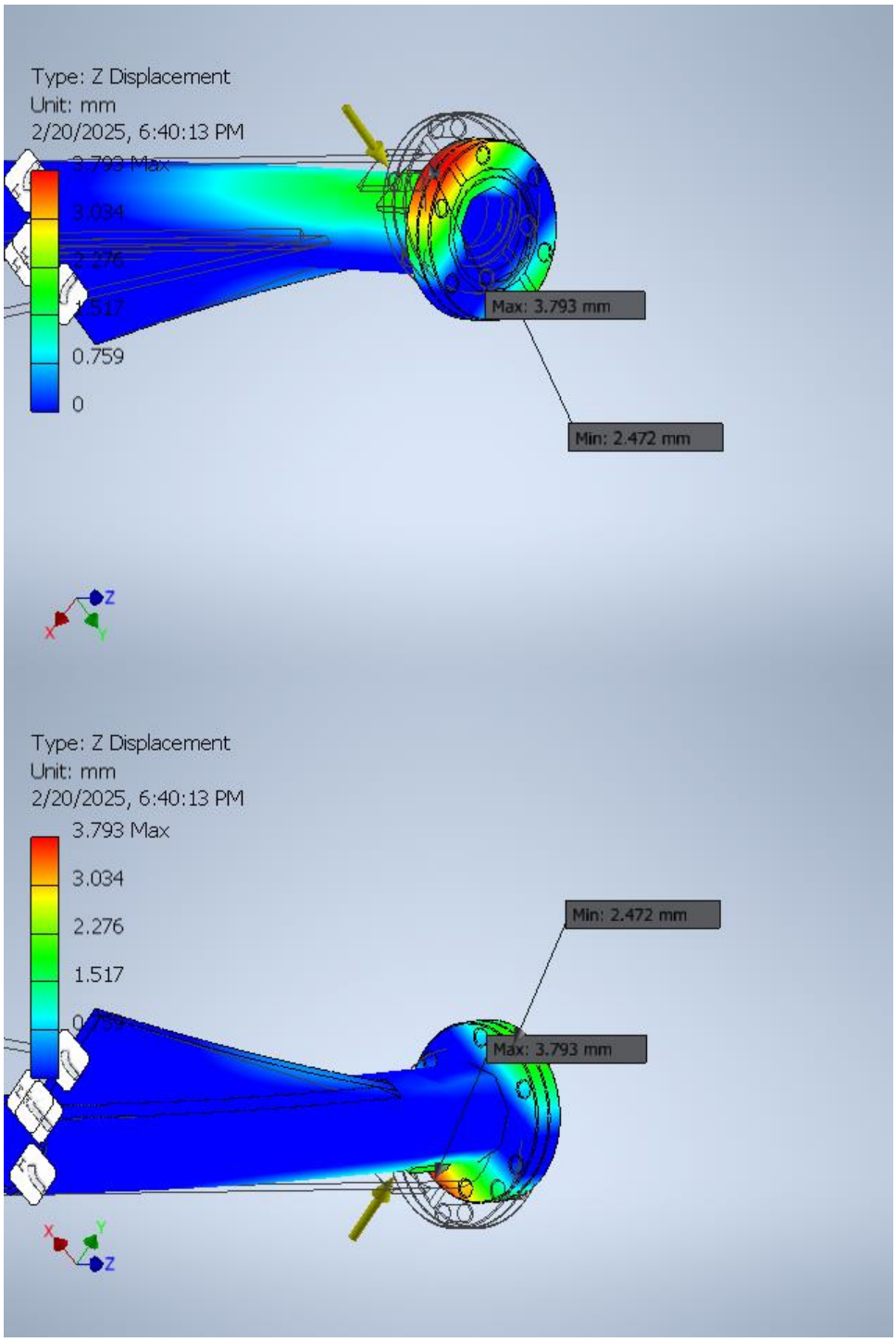
F2 541.78 Hz X Displacement



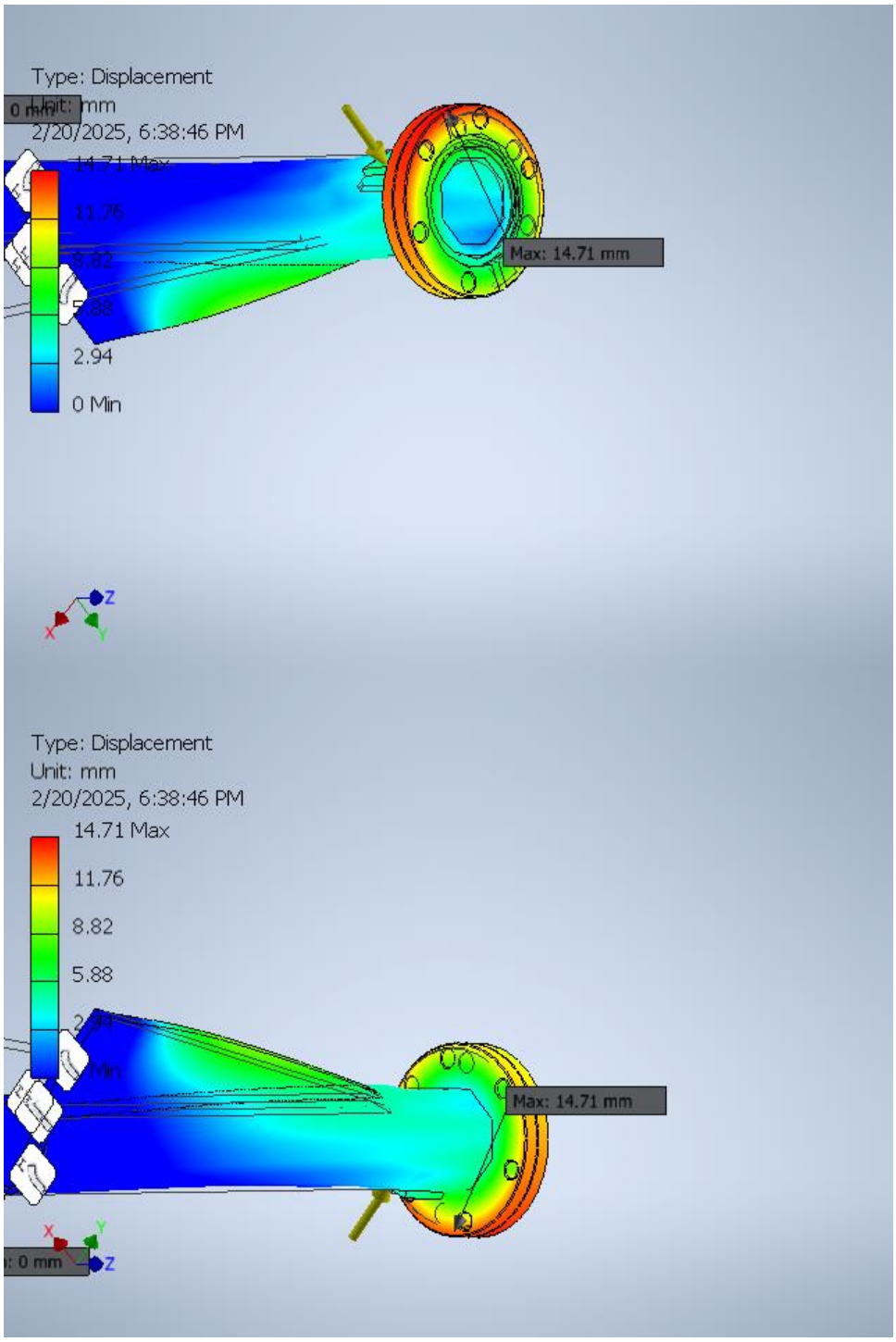
F2 541.78 Hz Y Displacement



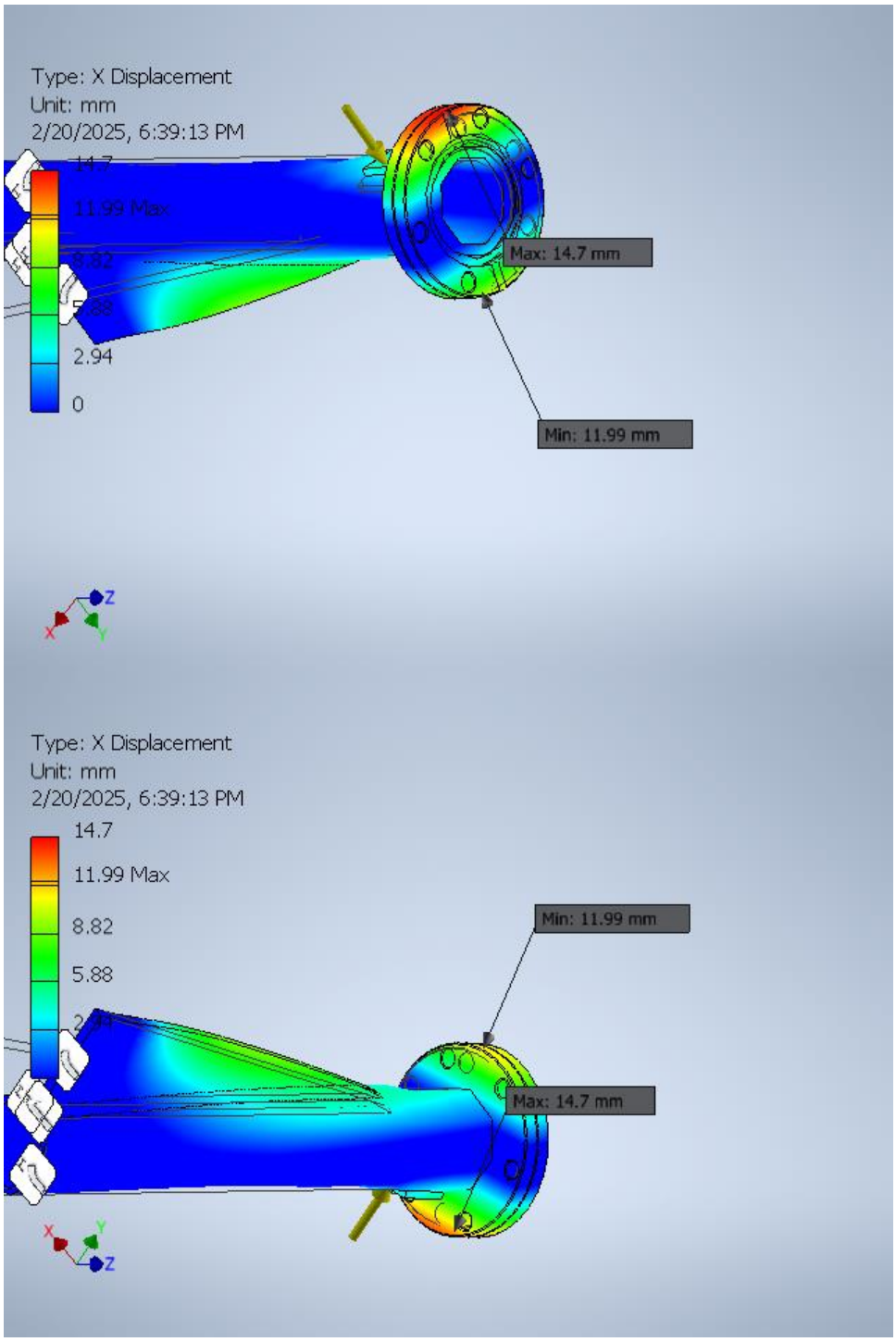
F2 541.78 Hz Z Displacement



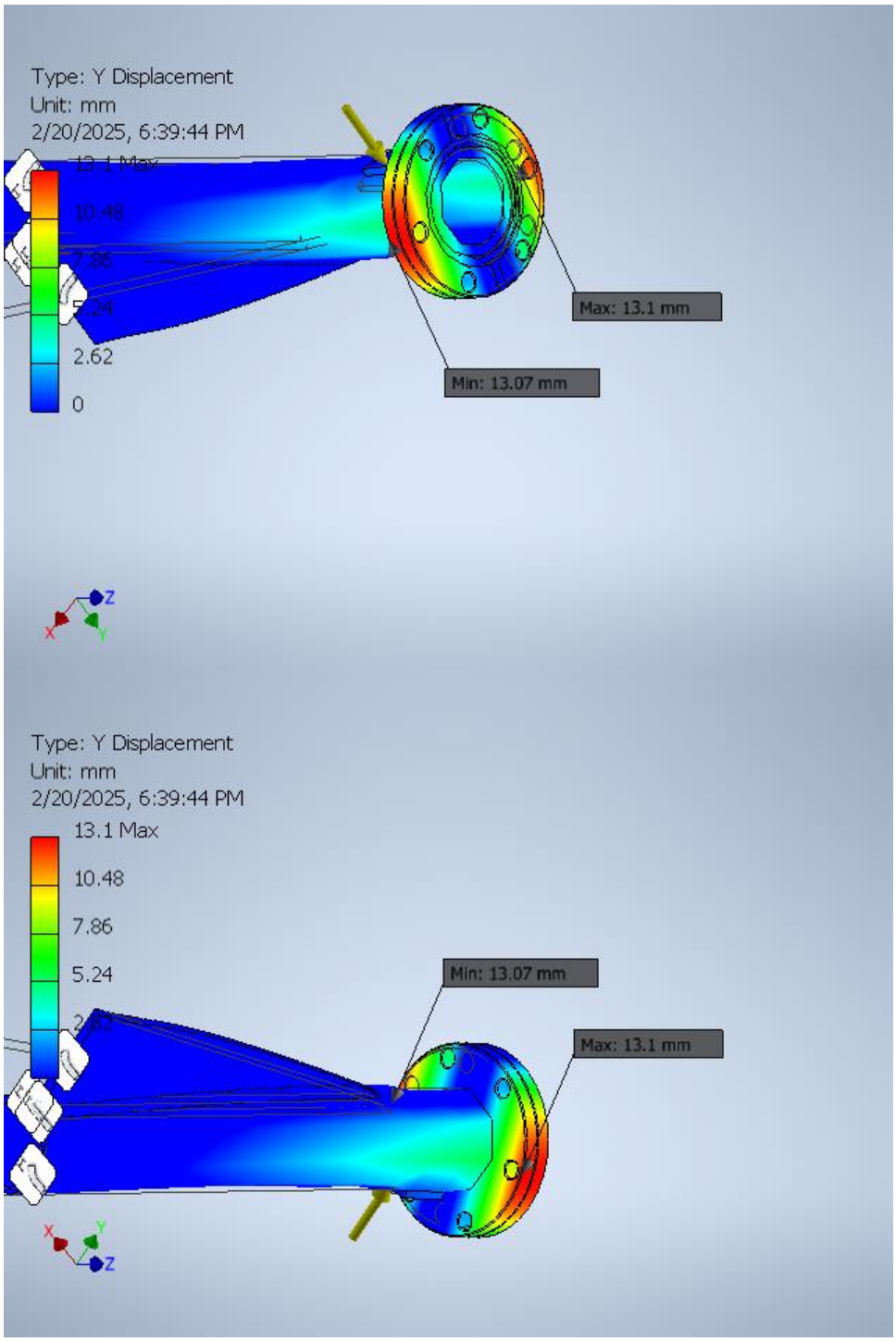
F3 1560.91 Hz Displacement



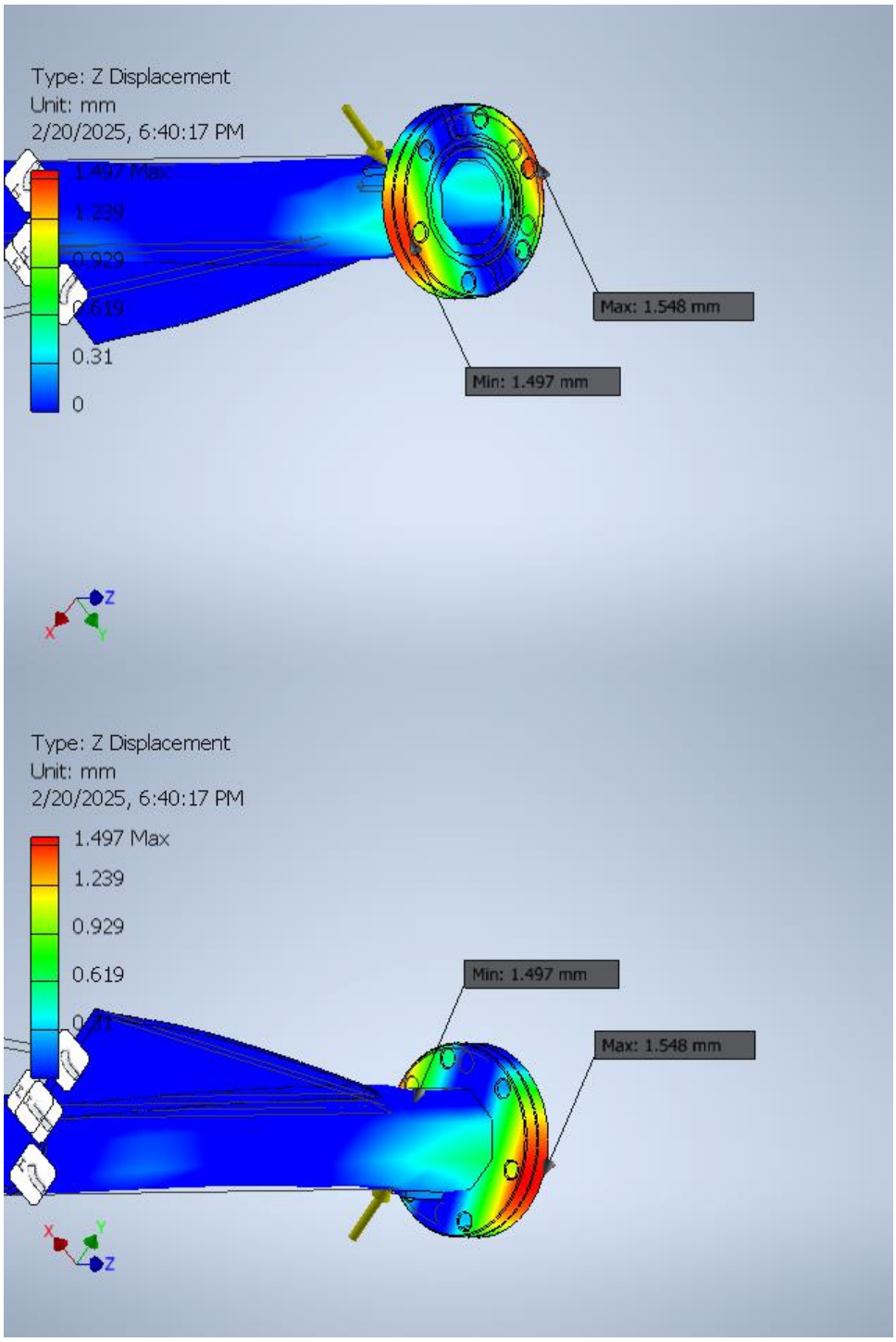
F3 1560.91 Hz X Displacement



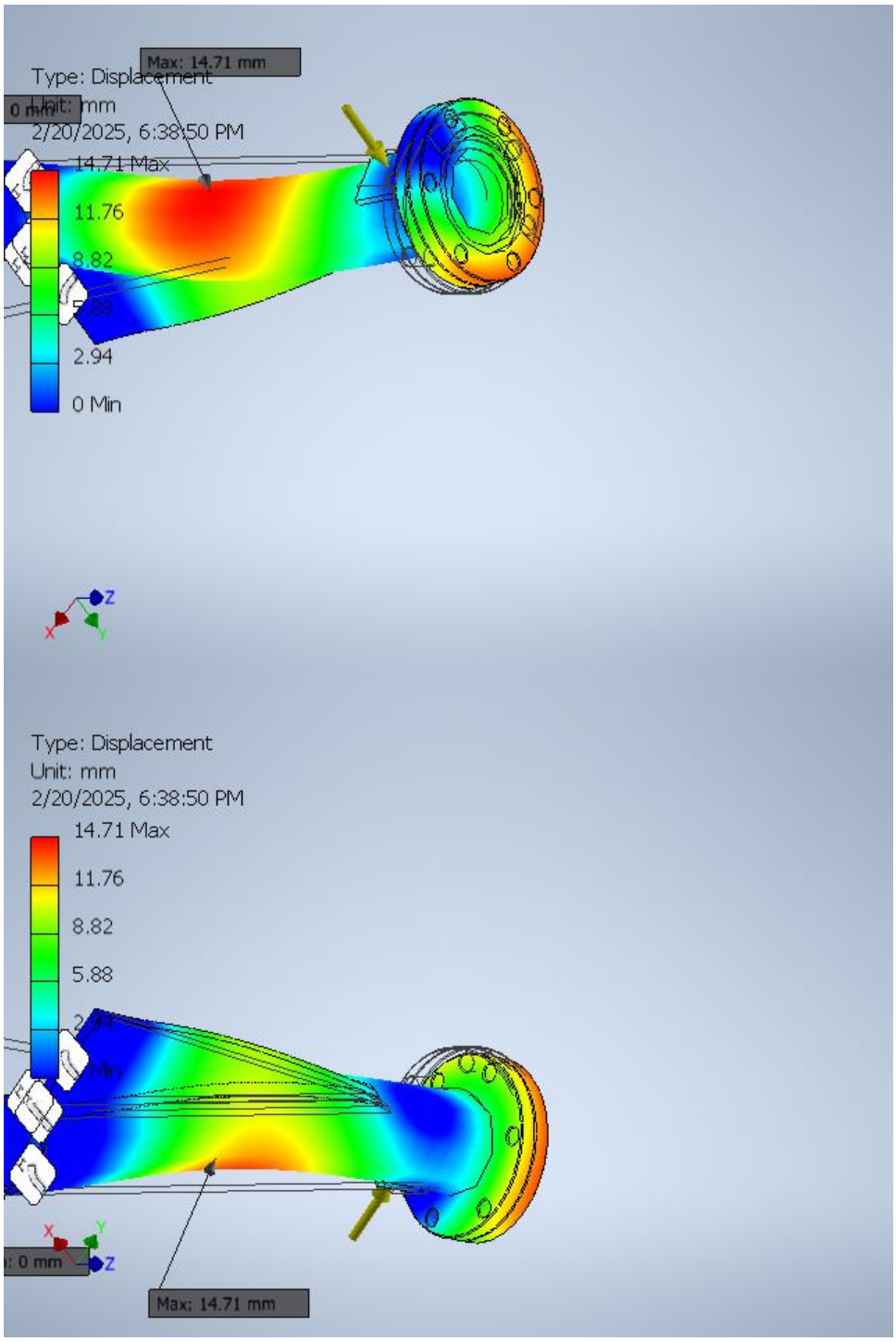
F3 1560.91 Hz Y Displacement



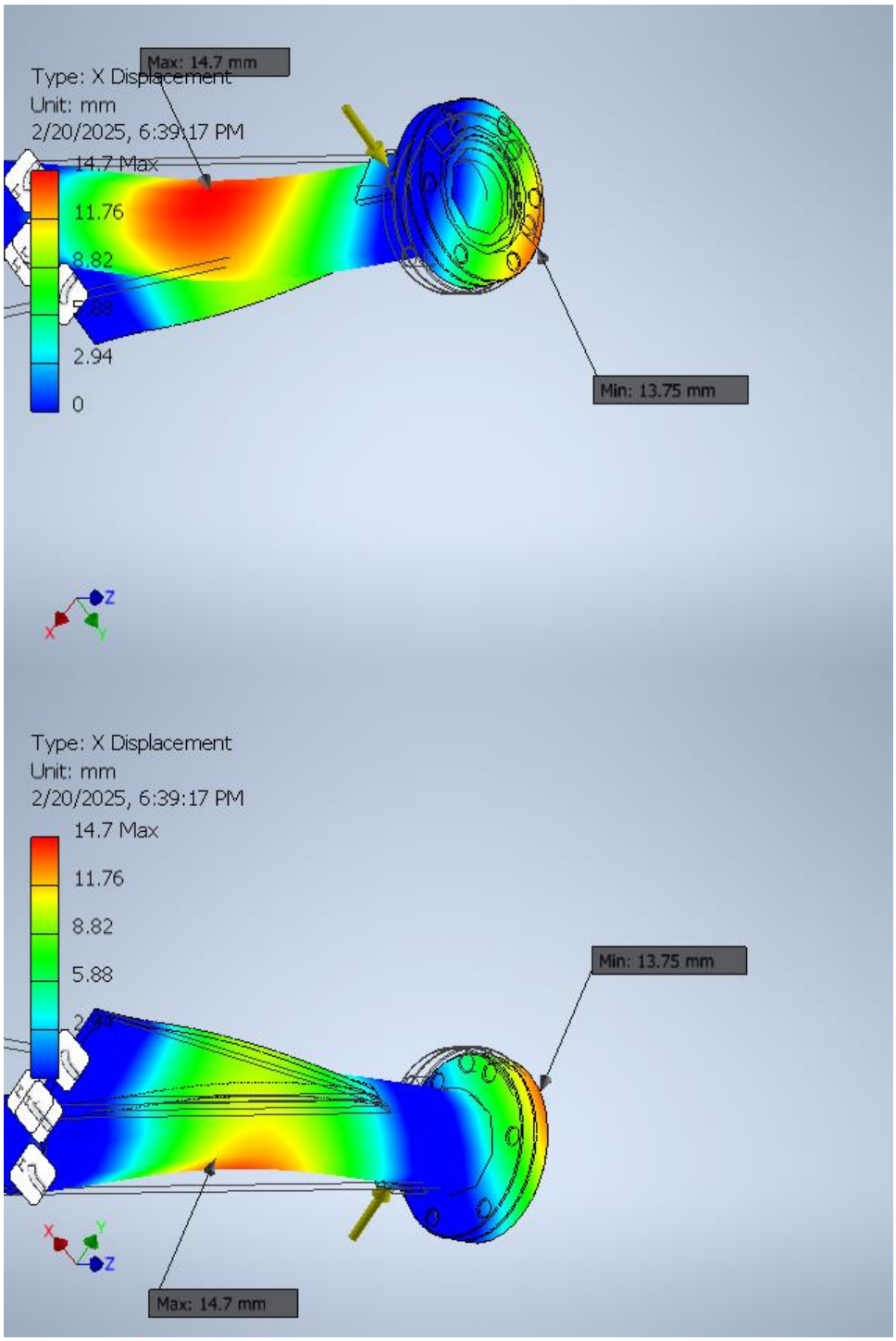
F3 1560.91 Hz Z Displacement



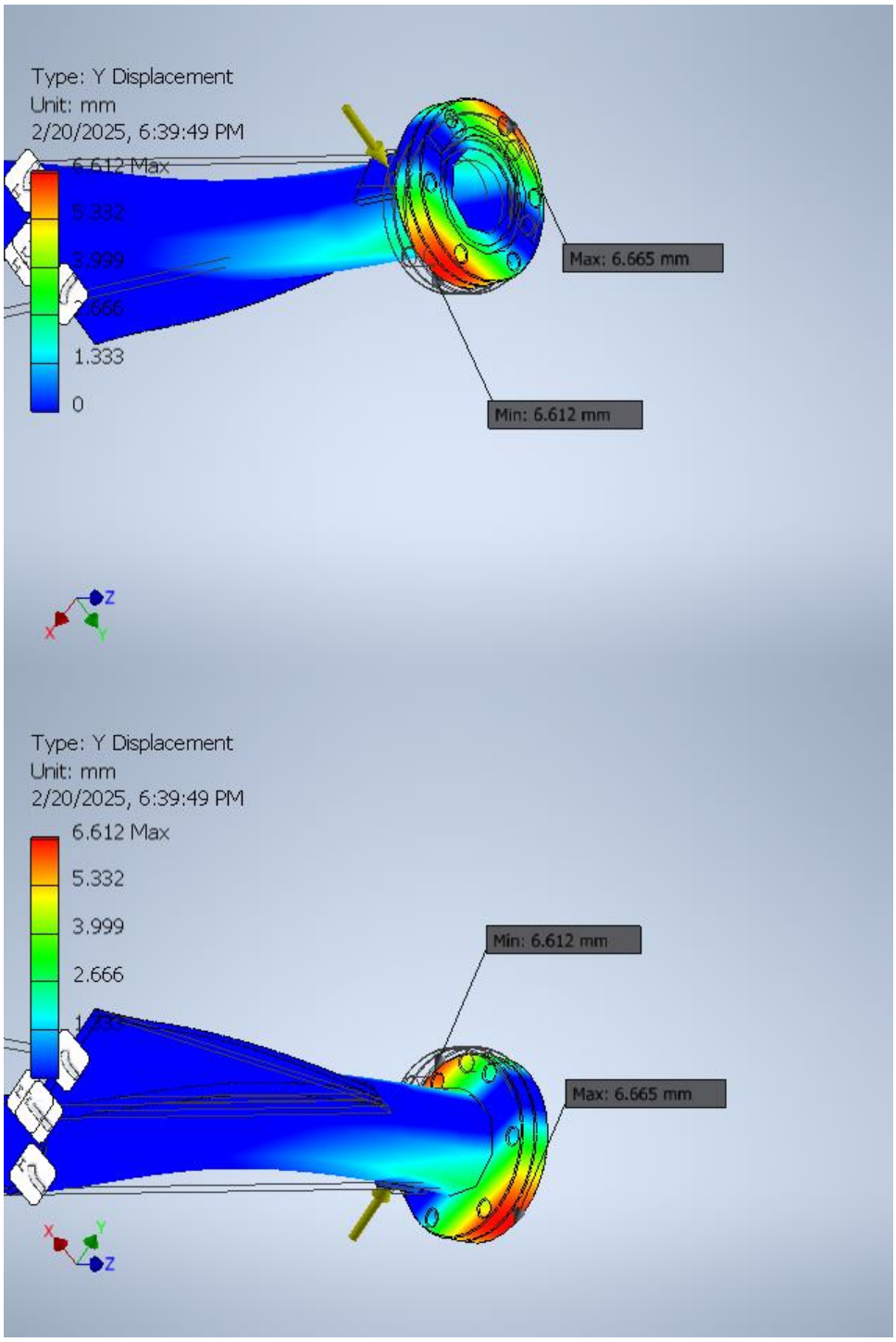
F4 1824.98 Hz Displacement



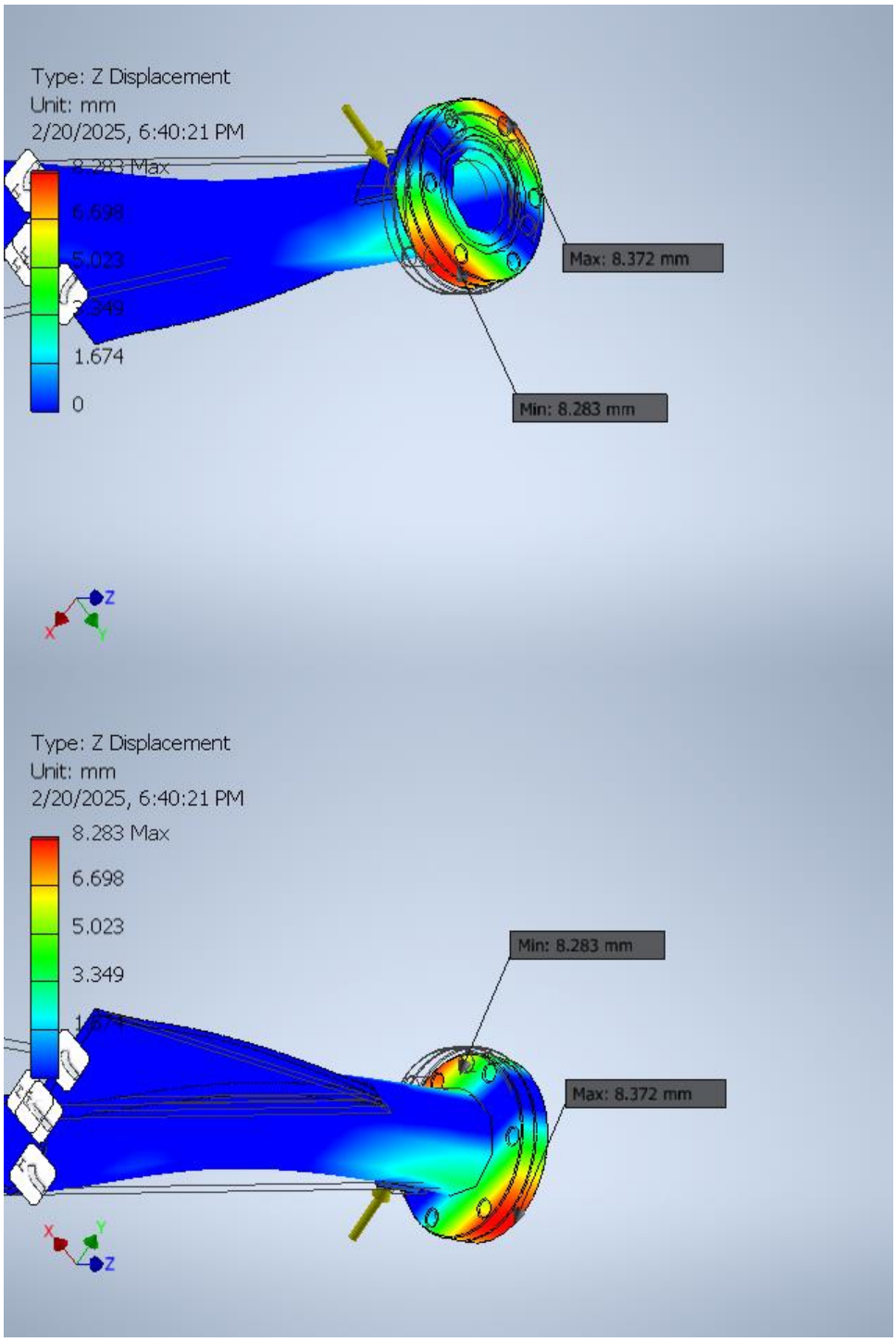
F4 1824.98 Hz X Displacement



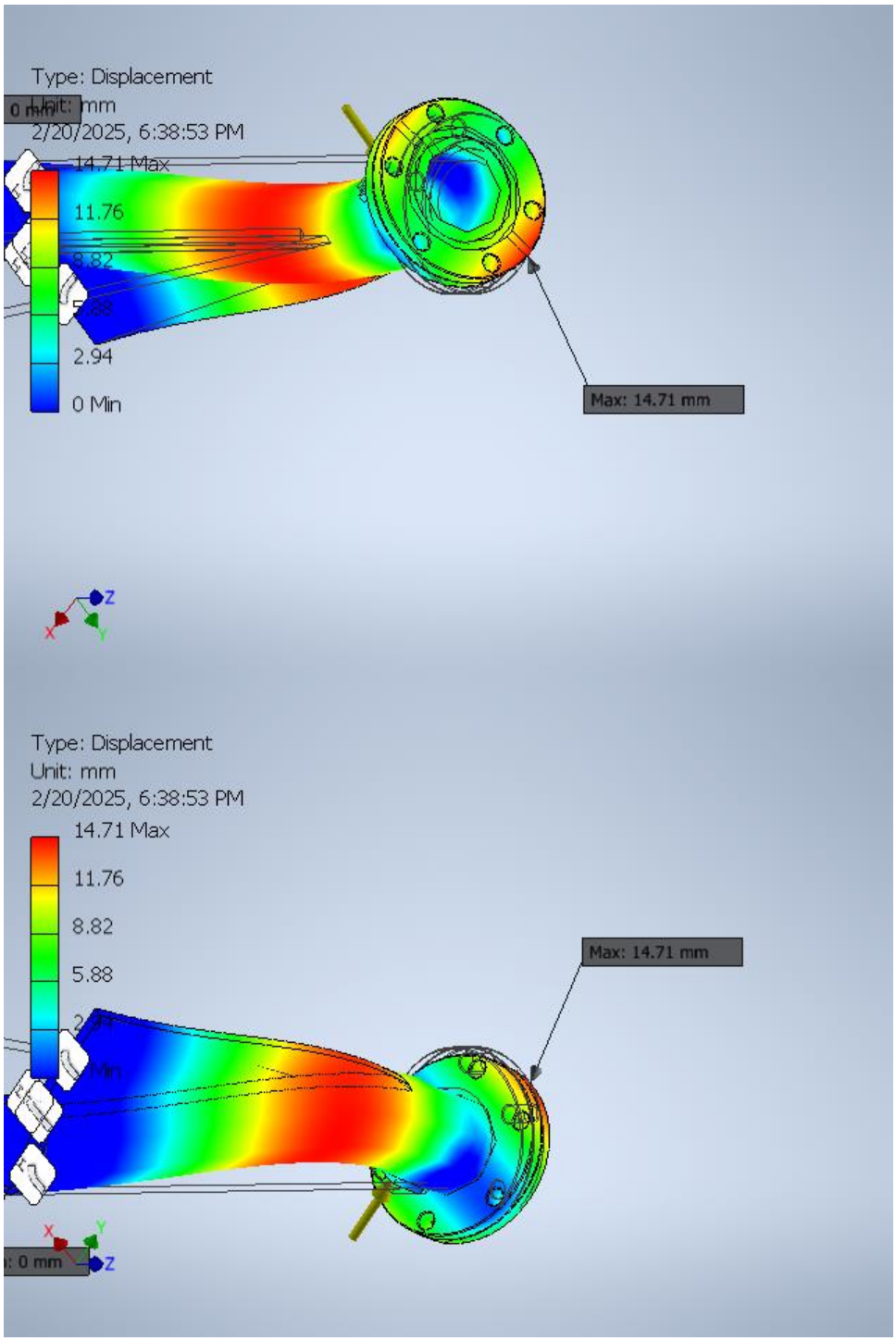
F4 1824.98 Hz Y Displacement



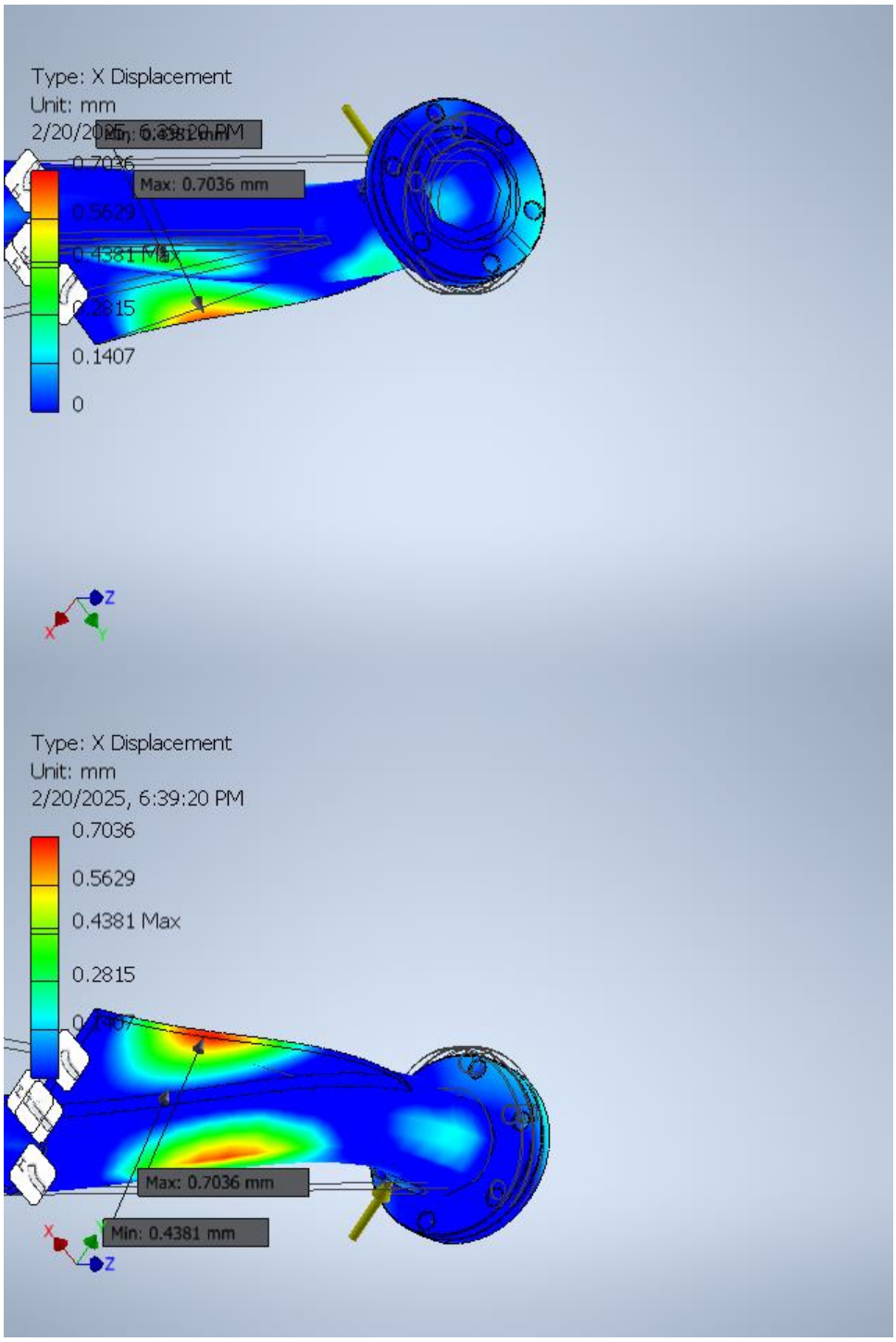
F4 1824.98 Hz Z Displacement



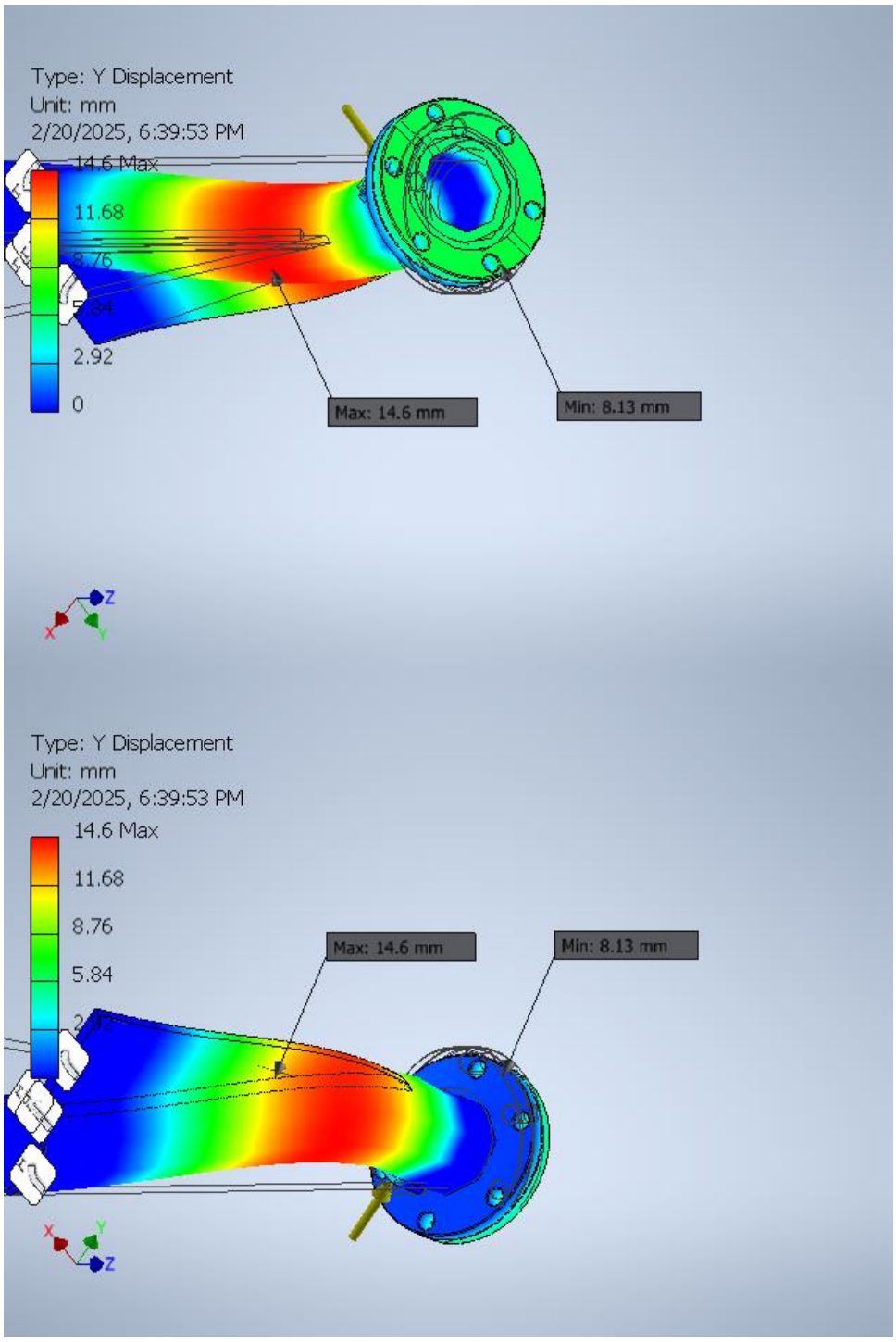
F5 2530.85 Hz Displacement



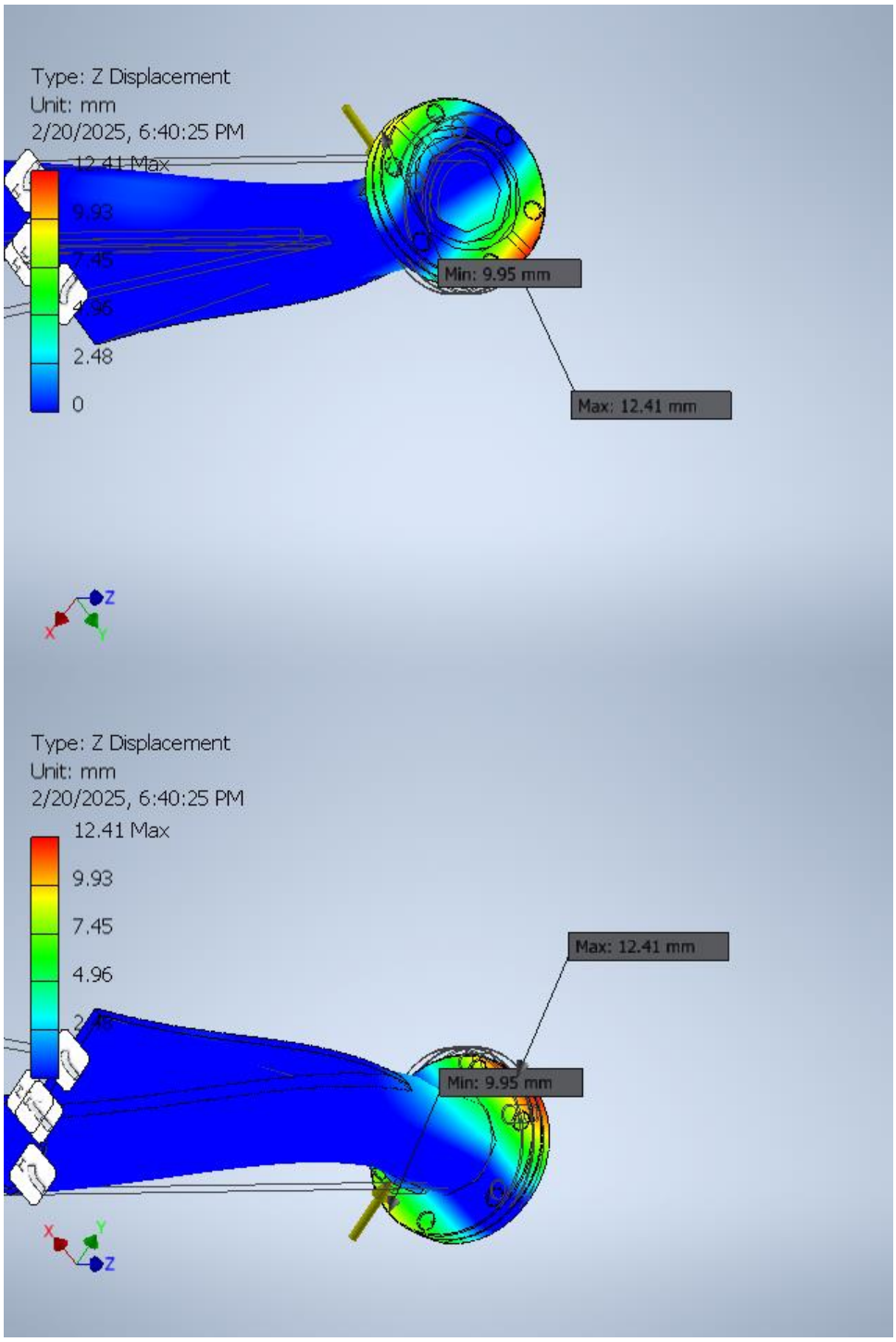
F5 2530.85 Hz X Displacement



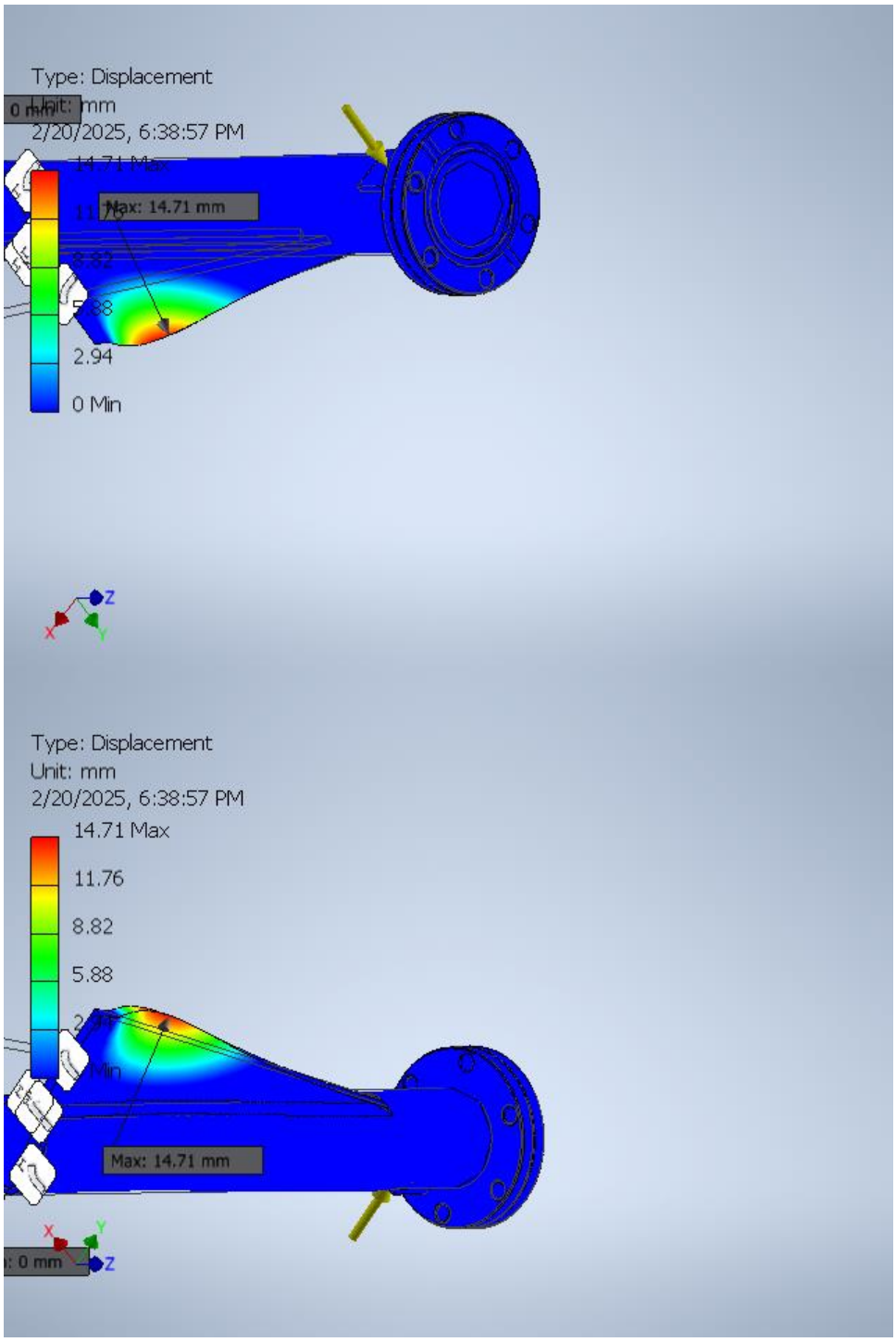
F5 2530.85 Hz Y Displacement



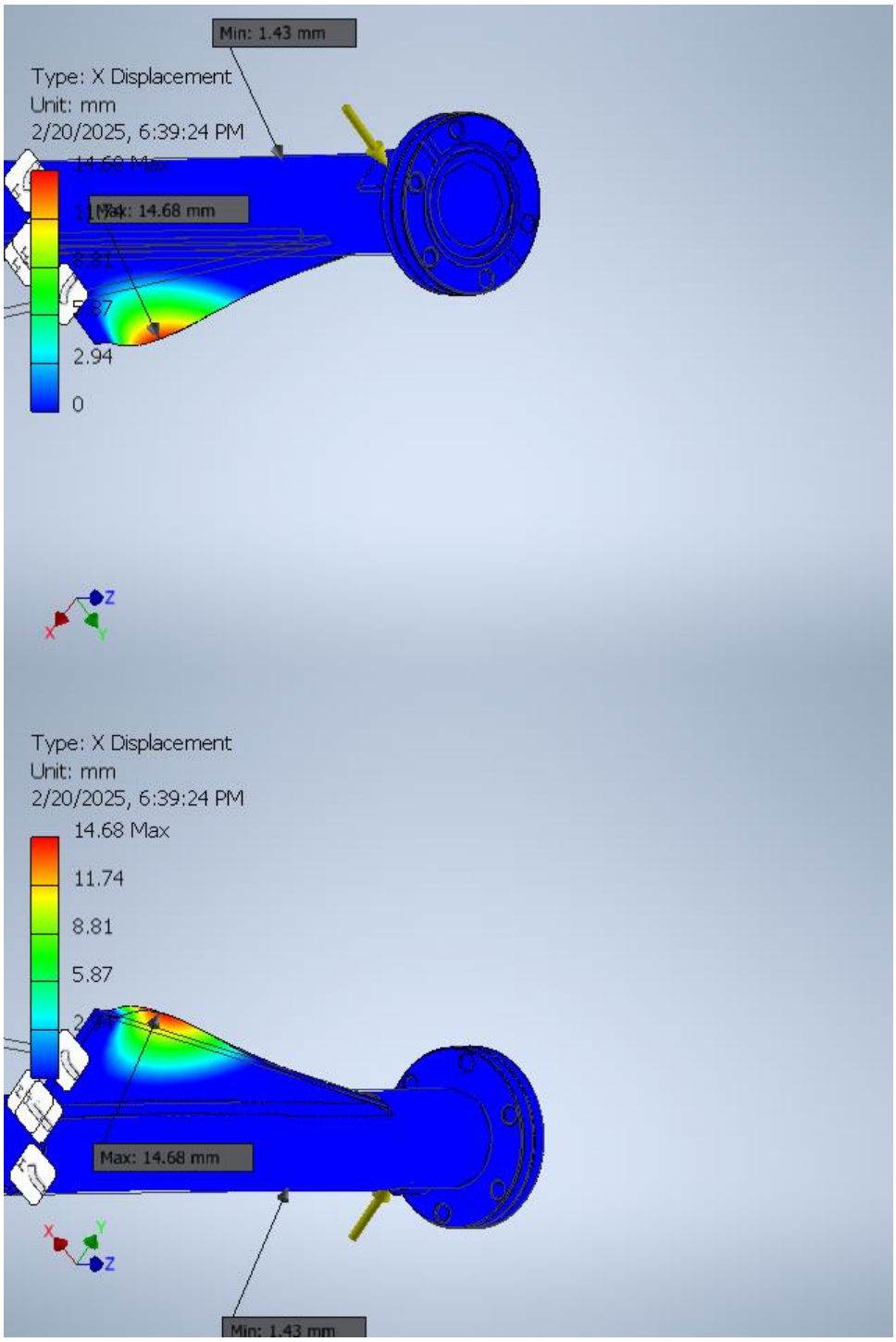
F5 2530.85 Hz Z Displacement



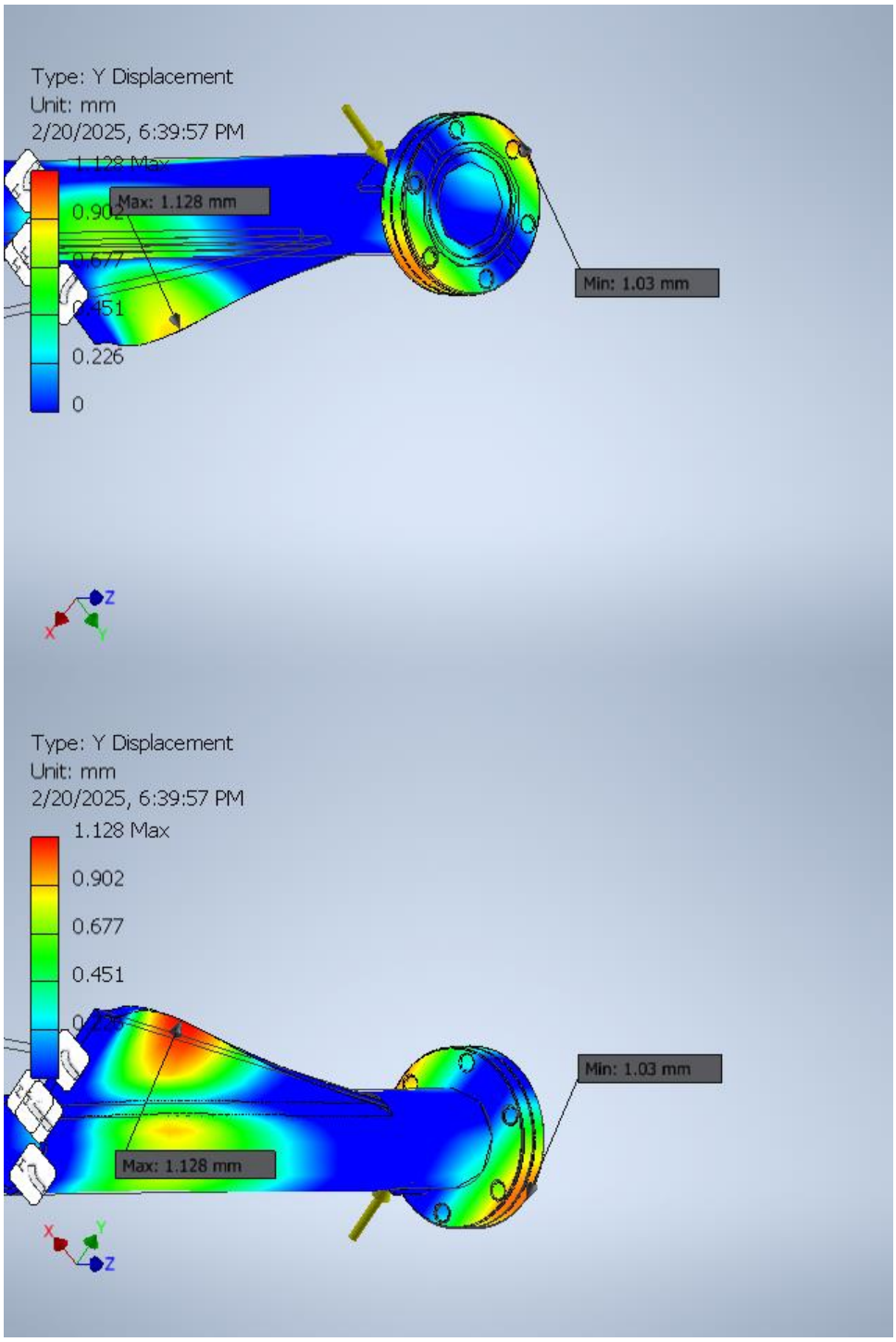
F6 3294.30 Hz Displacement



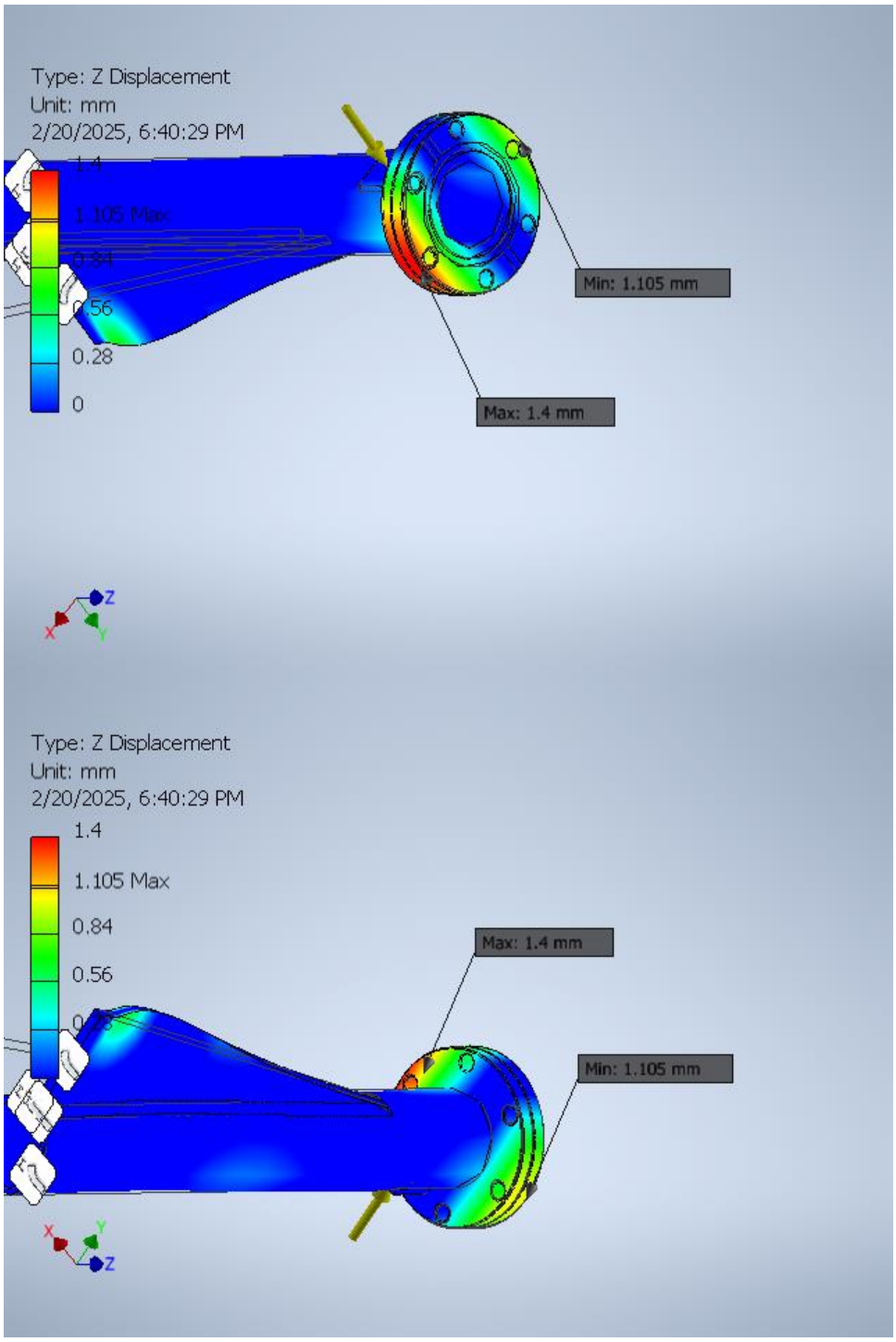
F6 3294.30 Hz X Displacement



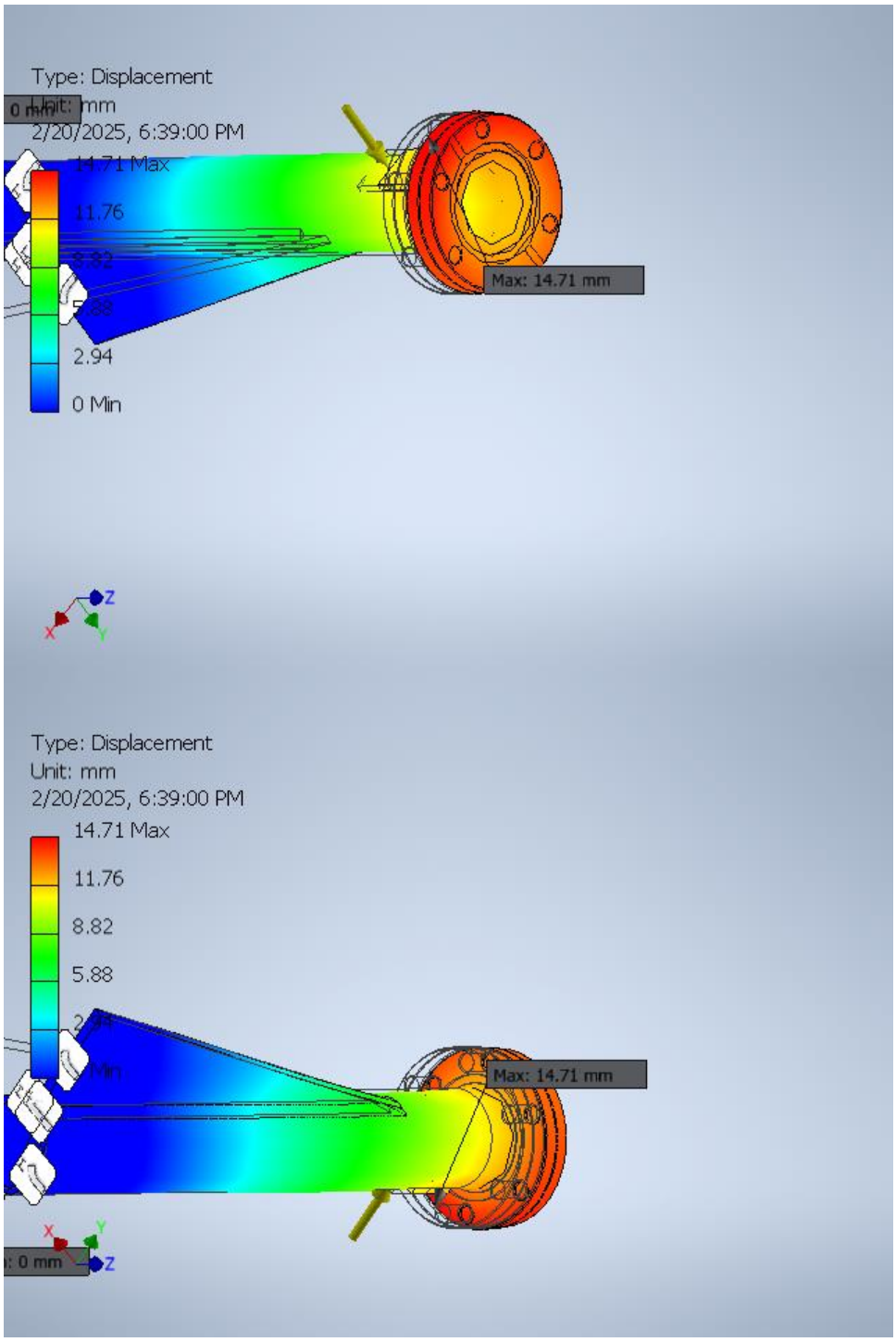
F6 3294.30 Hz Y Displacement



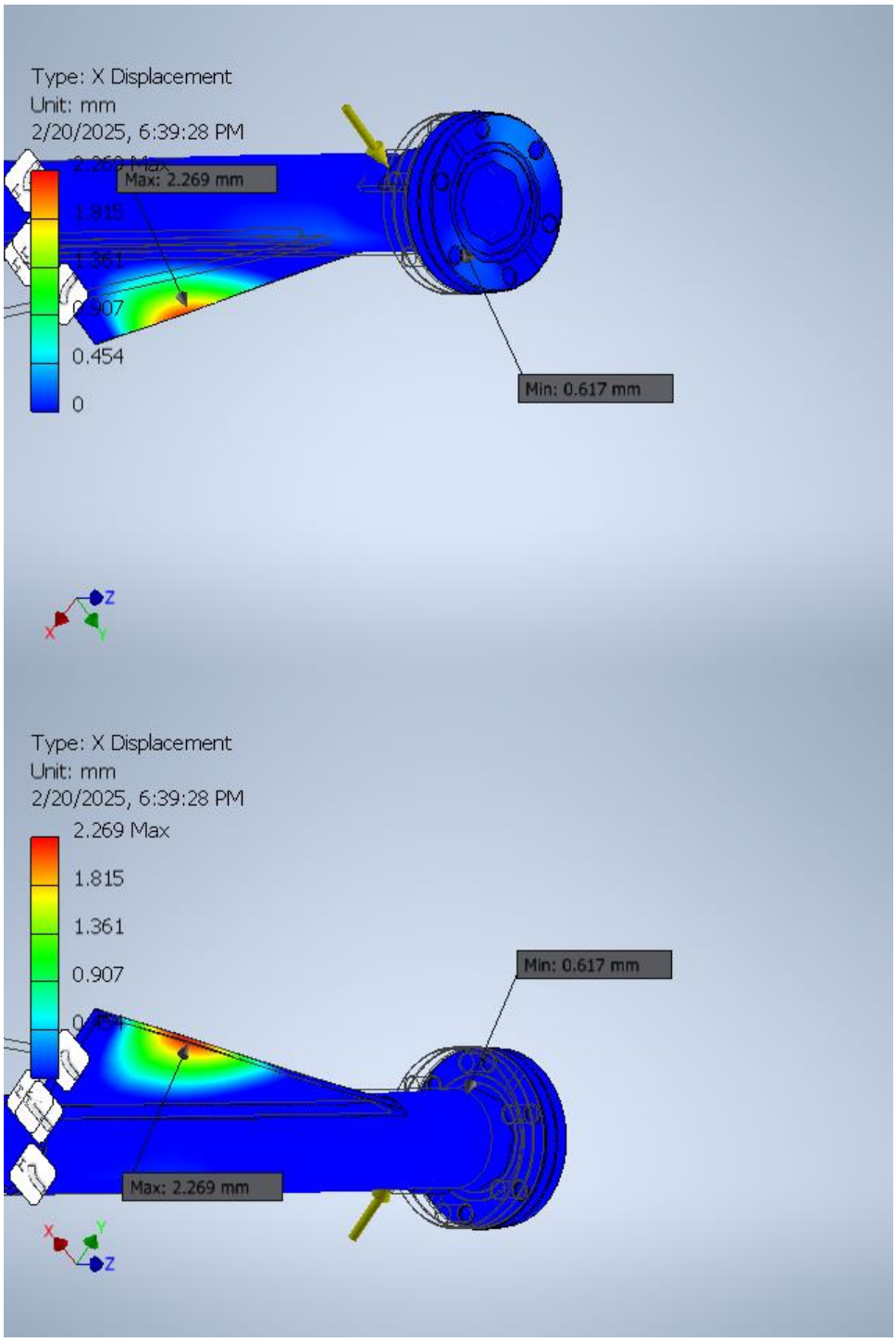
F6 3294.30 Hz Z Displacement



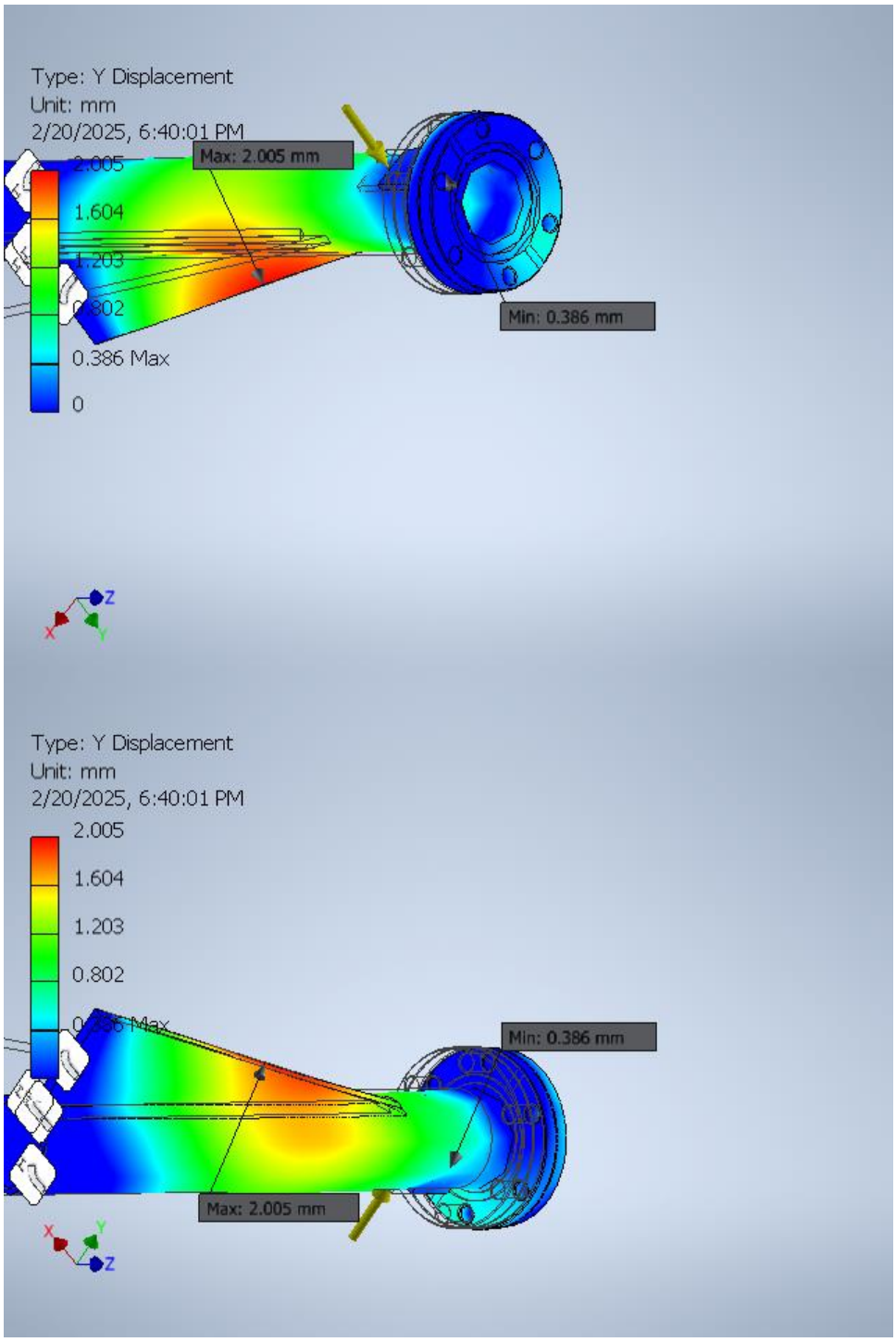
F7 3802.89 Hz Displacement



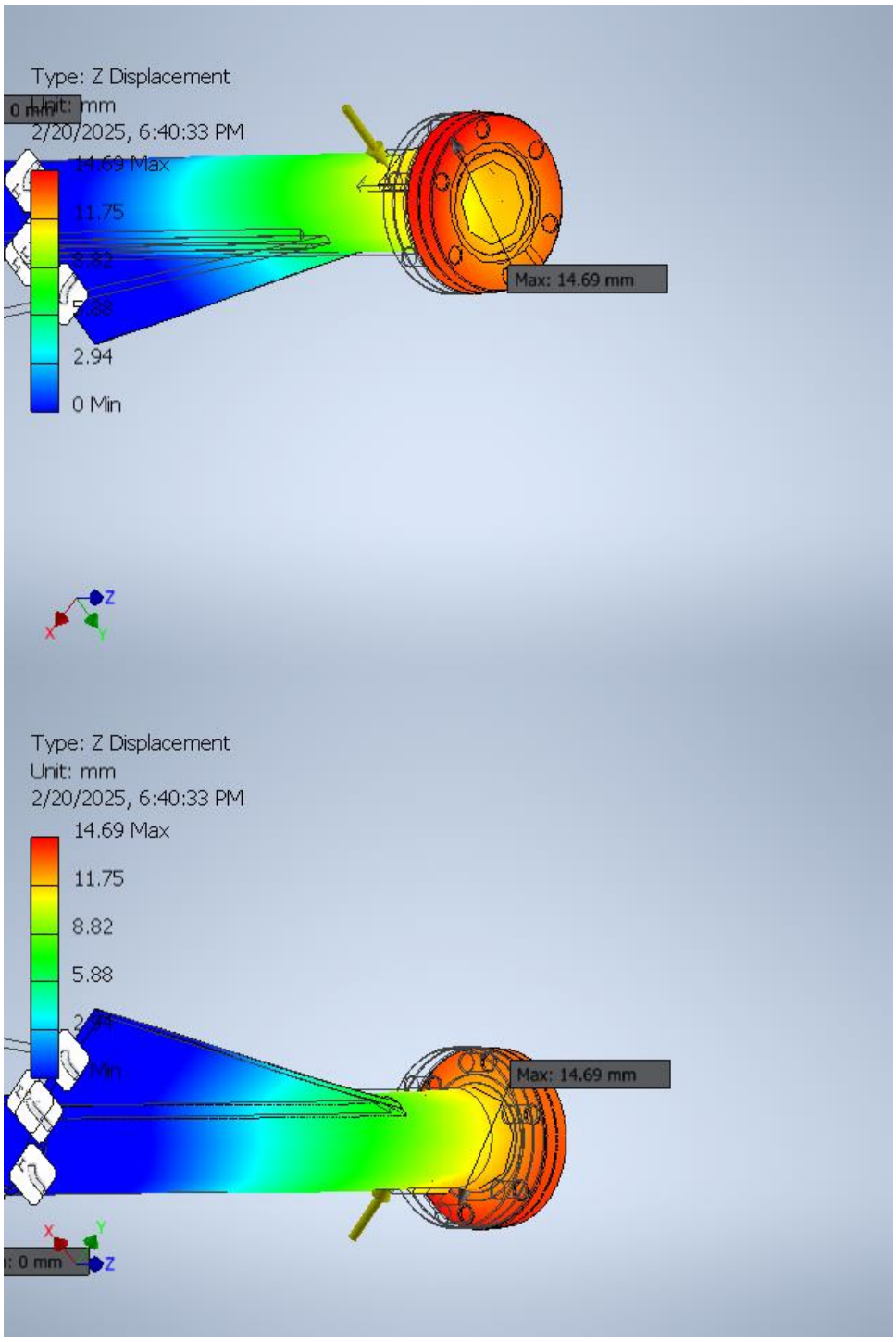
F7 3802.89 Hz X Displacement



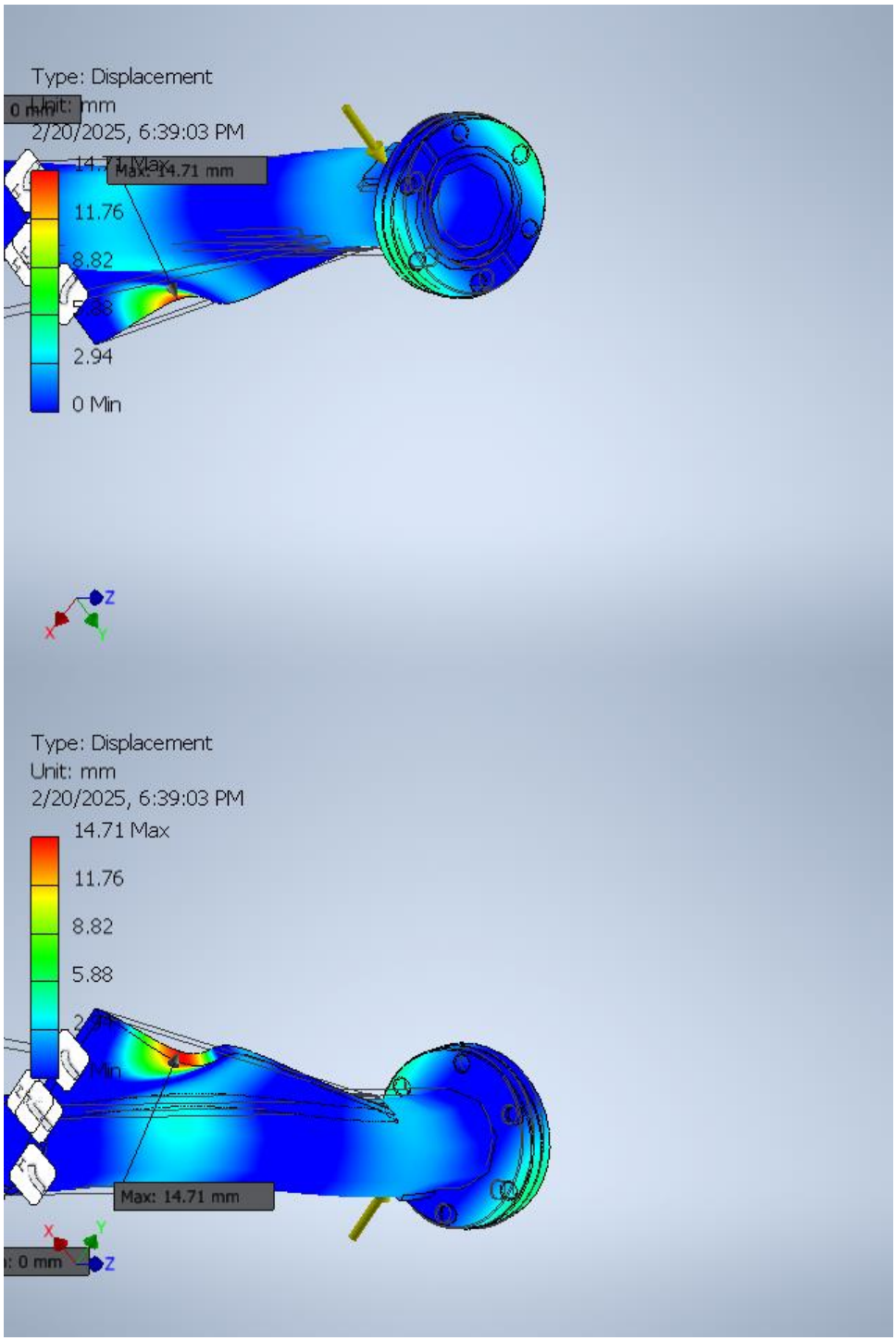
F7 3802.89 Hz Y Displacement



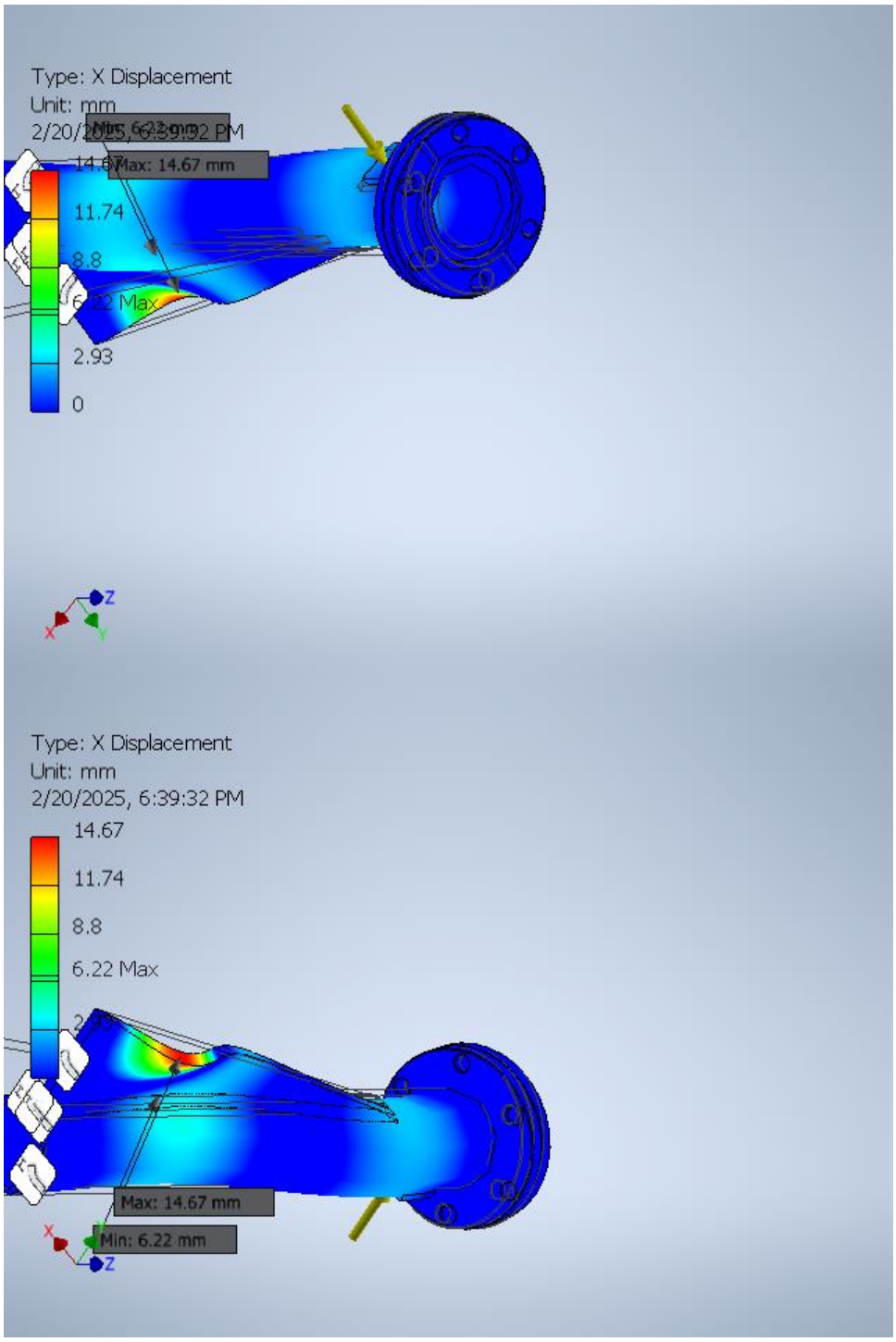
F7 3802.89 Hz Z Displacement



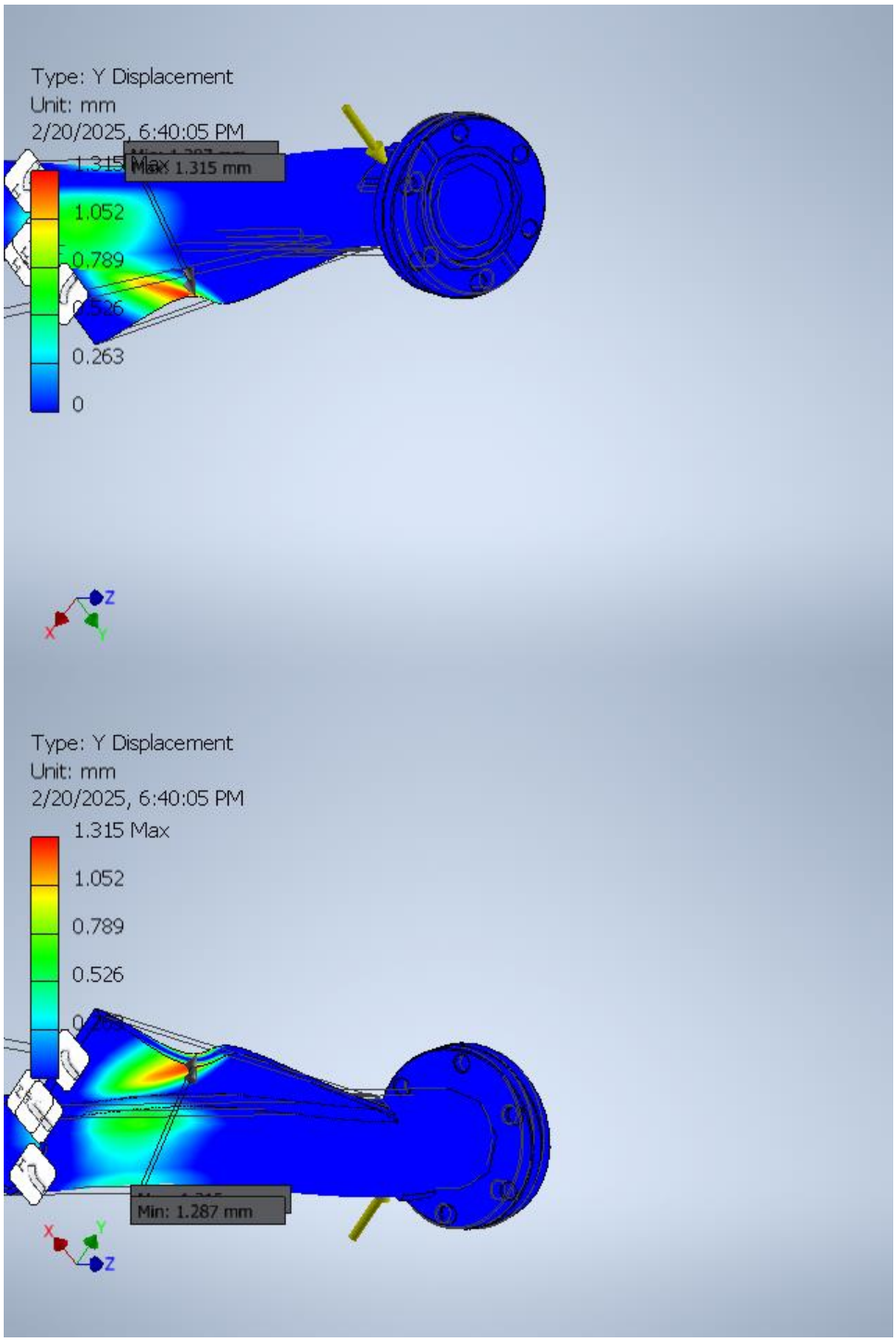
F8 4666.13 Hz Displacement



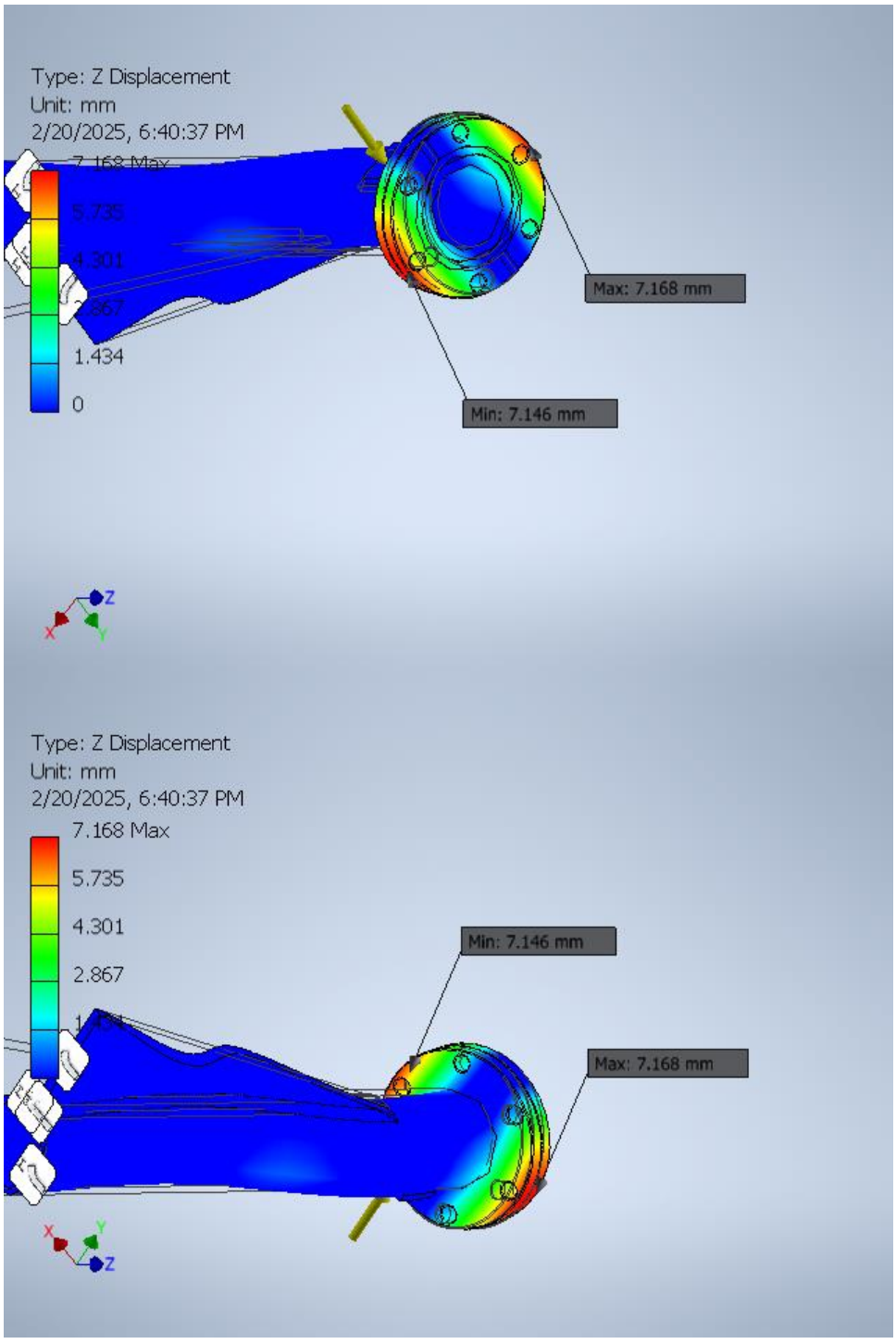
F8 4666.13 Hz X Displacement



F8 4666.13 Hz Y Displacement



F8 4666.13 Hz Z Displacement



Modal Analysis:3

General objective and settings:

Design Objective	**Single Point**
Study Type	**Modal Analysis**

Last Modification Date	2/20/2025, 6:31 PM
Model State	[Primary]
Design View	Default
Positional	[Primary]
Number of Modes	8
Frequency Range	Undefined
Compute Preloaded Modes	No
Enhanced Accuracy	No

iProperties

Summary

Author	maurna

Project

Part Number	weld assembly_rev1
Designer	maurna
Estimated Cost	$0.00
Creation Date	2/20/2025

Status

Design State	WorkInProgress

Physical

Mass	0.342649 lbmass
Area	100537 mm^2
Volume	149117 mm^3
Center of Gravity	x=-79.0642 mm y=8.05852 mm z=42.7776 mm

Note: Physical values could be different from Physical values used by FEA reported below.

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.08
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg

Create Curved Mesh Elements	**No**
Use part based measure for Assembly mesh	**Yes**

Material(s)

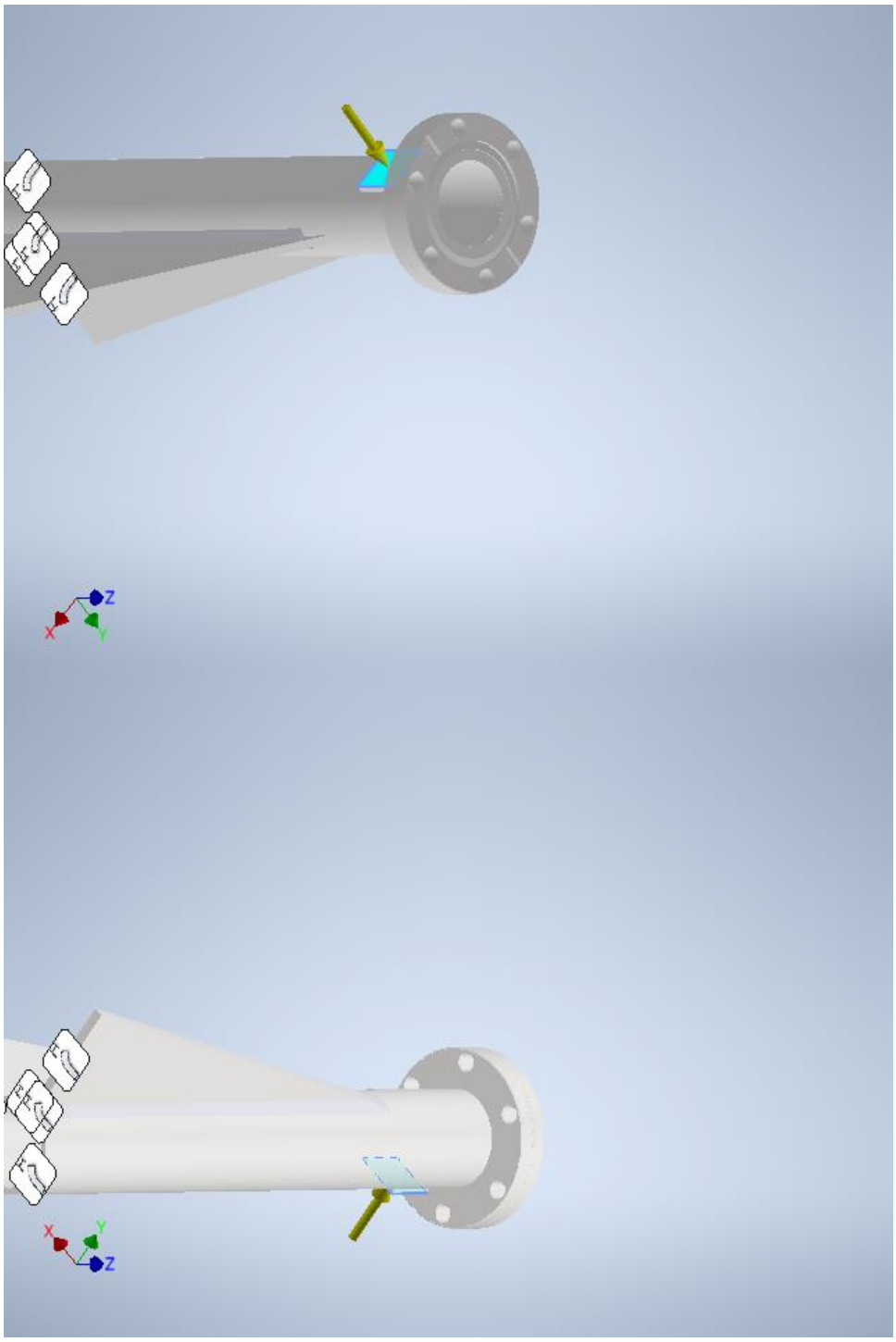
Name	**Stainless Steel**	
General	**Mass Density**	**0.289018 lbmass/in^3**
	Yield Strength	**36259.4 psi**
	Ultimate Tensile Strength	**78320.4 psi**
Stress	**Young's Modulus**	**27992.3 ksi**
	Poisson's Ratio	**0.3 ul**
	Shear Modulus	**10766.3 ksi**
Part Name (s)	**weld assembly_rev1.iam CF275_ESL_Connector_To_Chamber_with_tube_final_weld_piece_horizontal2023.ipt CF275_ESL_Connector_To_Chamber_with_tube_final_weld_piece_2023_MIR.ipt CF275_ESL_Connector_To_Chamber_with_tube_final_2023.ipt**	

Operating conditions

Force:1

Load Type	**Force**
Magnitude	**50.000 lbforce**
Vector X	**0.000 lbforce**
Vector Y	**50.000 lbforce**
Vector Z	**0.000 lbforce**

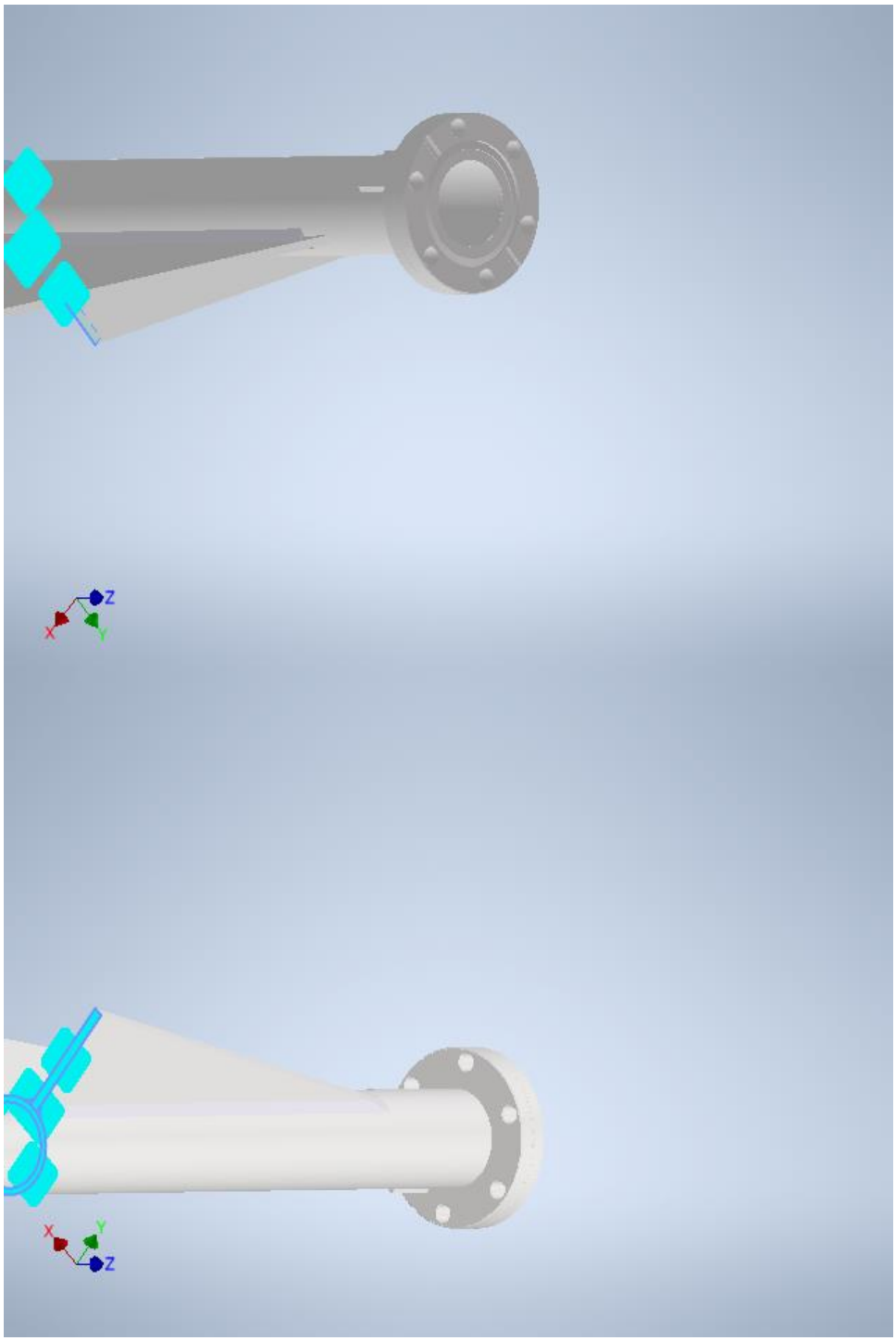
Selected Face(s)



Fixed Constraint:1

Constraint Type	Fixed Constraint

Selected Face(s)



Contacts (Bonded)

Name	Part Name(s)
Bonded:1	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_horizontal2023:1

Bonded:2	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1
Bonded:3	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_horizontal2023:1
Bonded:4	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1
Bonded:5	CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1 CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_horizontal2023:1
Bonded:6	CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1 CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1
Bonded:7	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1
Bonded:8	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1
Bonded:9	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_weld_peice_2023_MIR:1
Bonded:10	Welds CF275_ESL_Connector_To_Chamber_with_tube_final_2023:1

Results

Frequency Value(s)

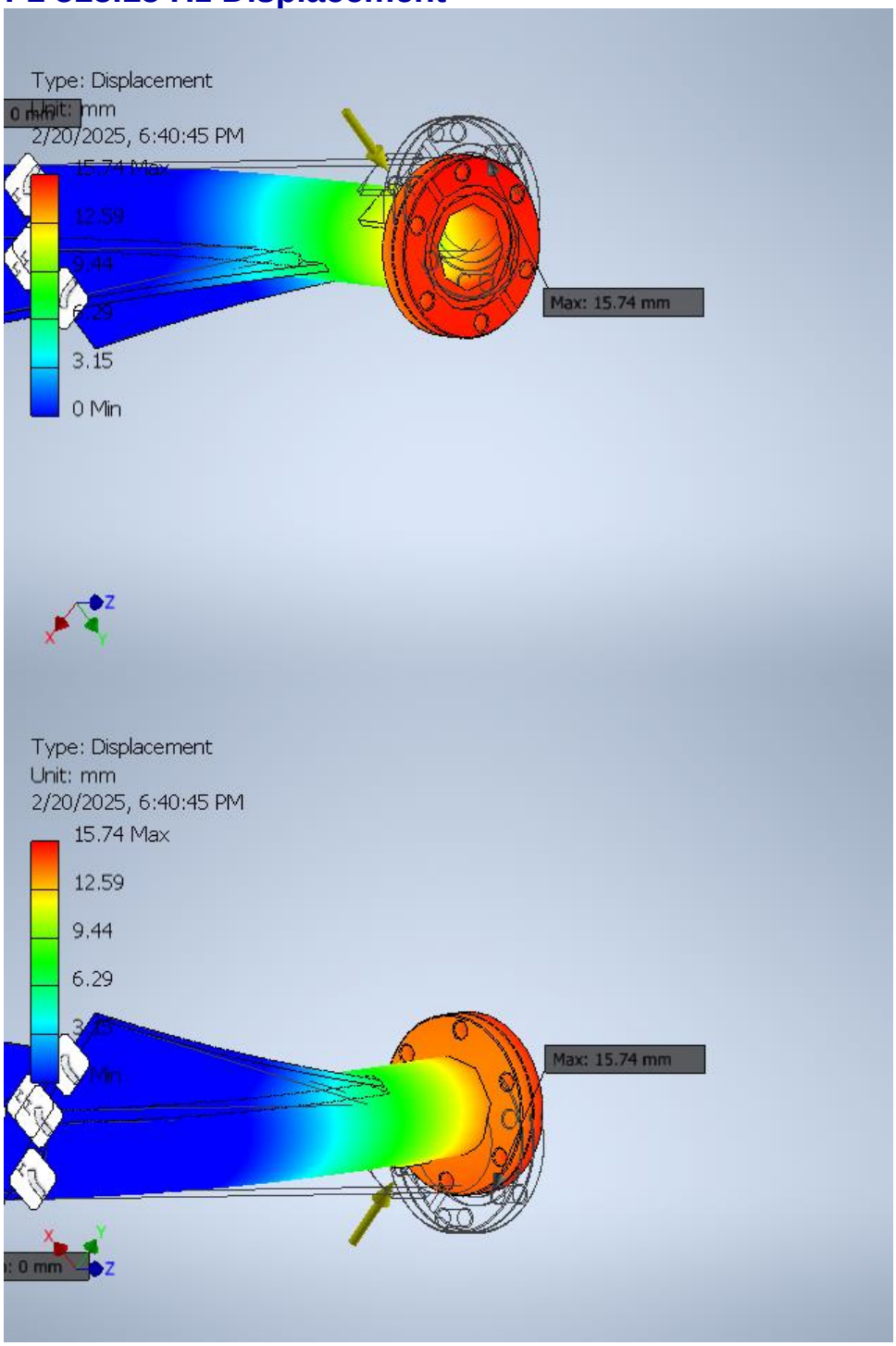
F1	515.15 Hz
F2	591.67 Hz
F3	1666.07 Hz
F4	2378.91 Hz
F5	2460.78 Hz
F6	3244.25 Hz
F7	3388.78 Hz
F8	4149.03 Hz

Result Summary

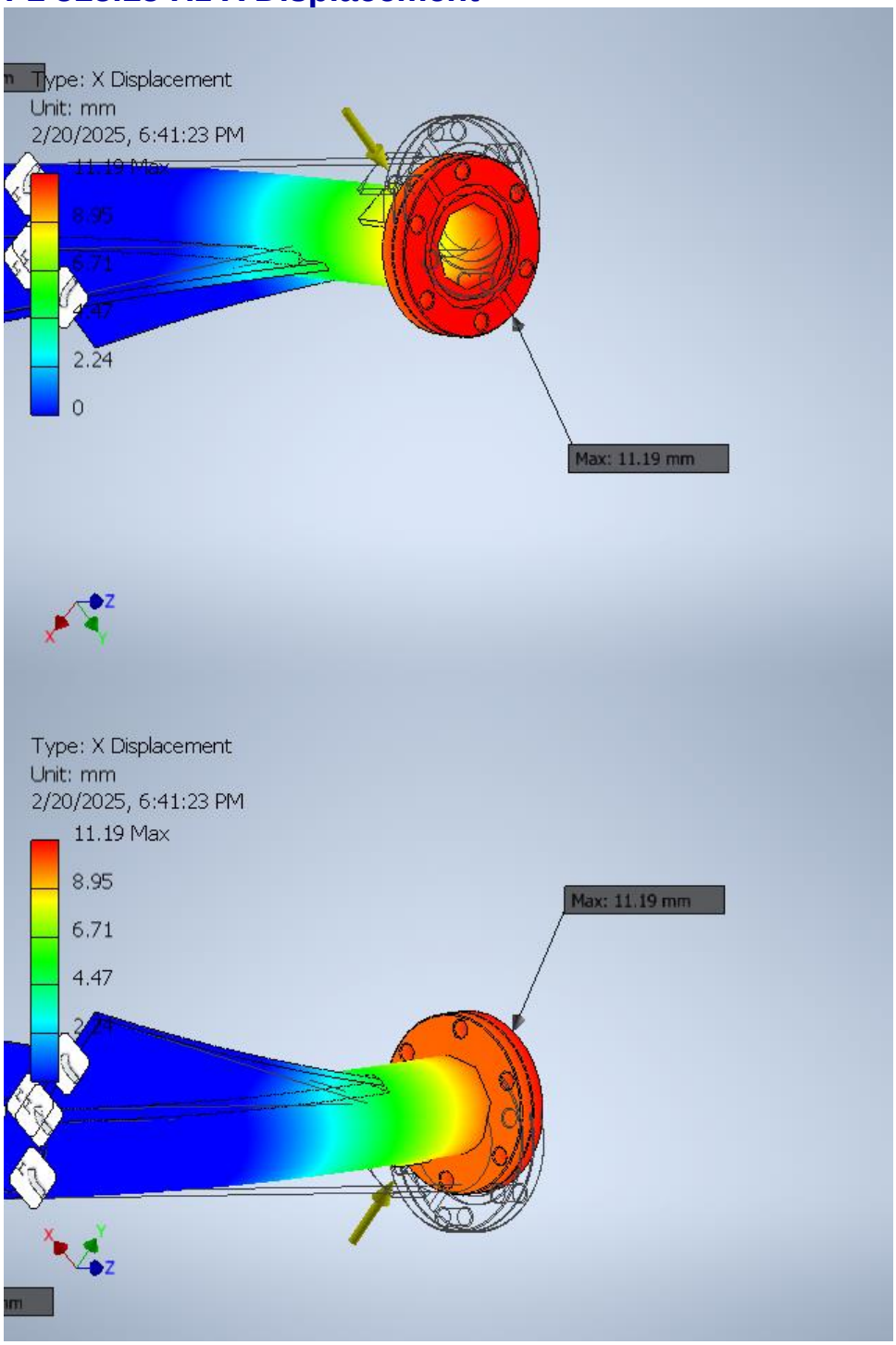
Name	Result Value
Volume	149118 mm^3
Mass	2.62999 lbmass

Figures

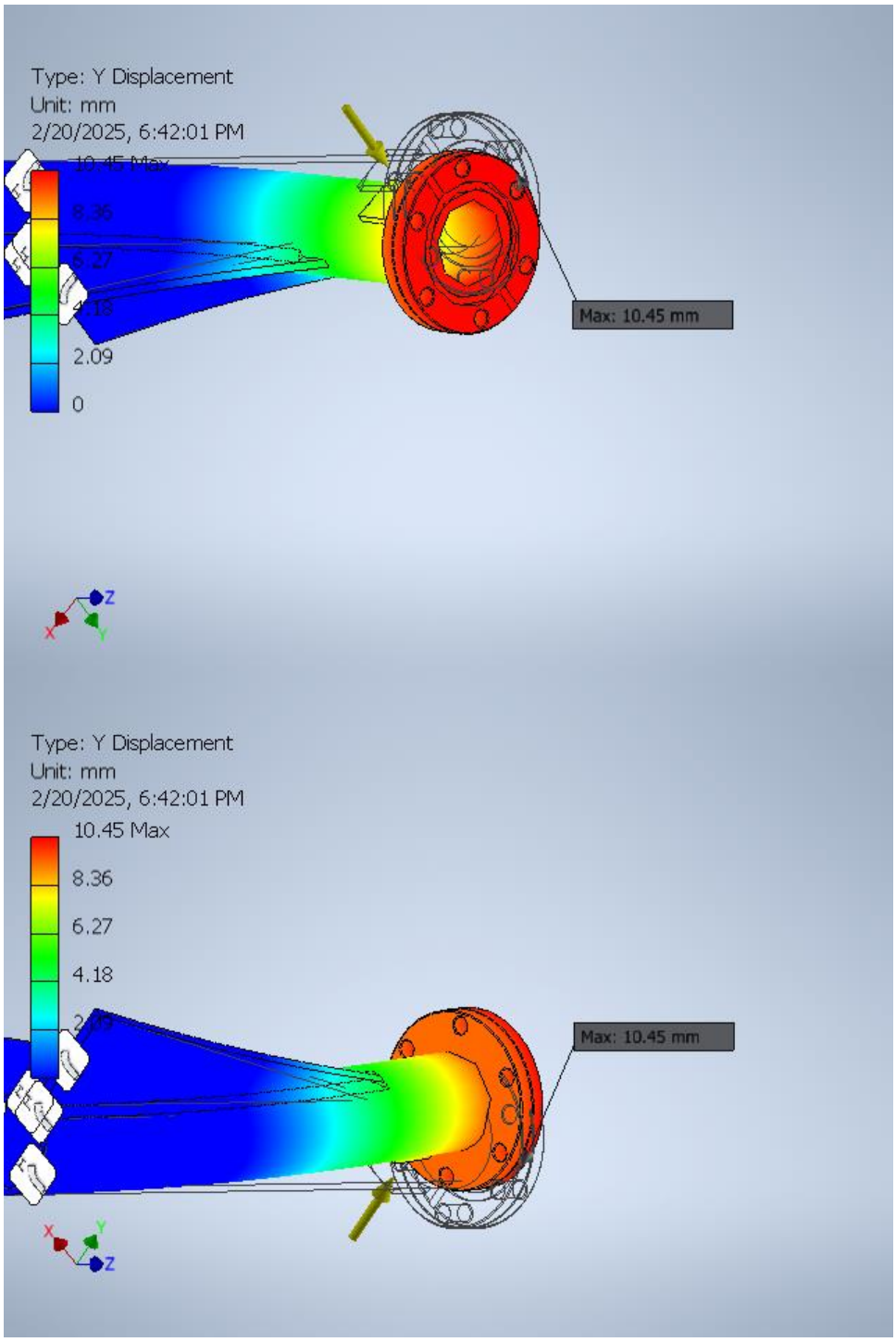
F1 515.15 Hz Displacement



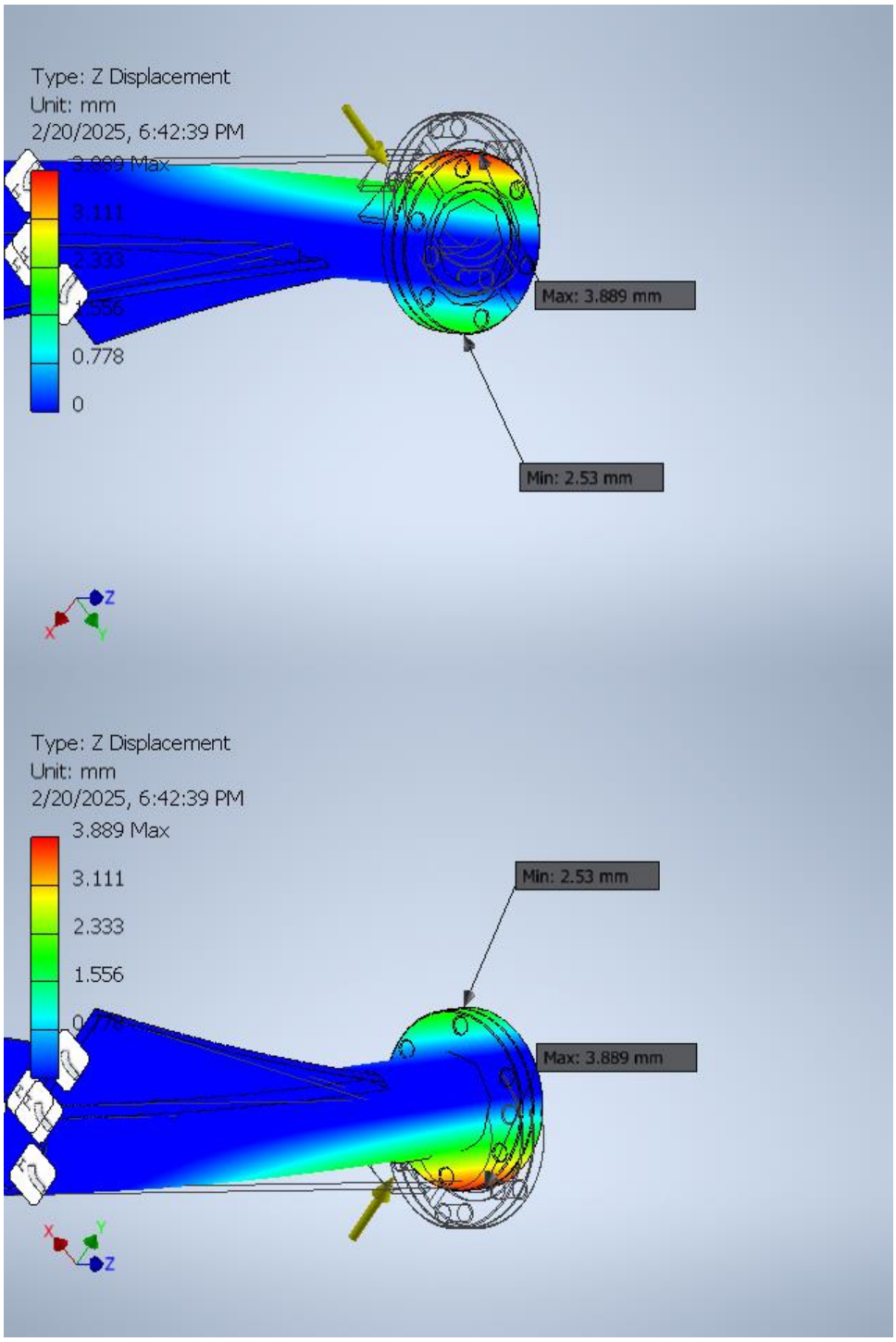
F1 515.15 Hz X Displacement



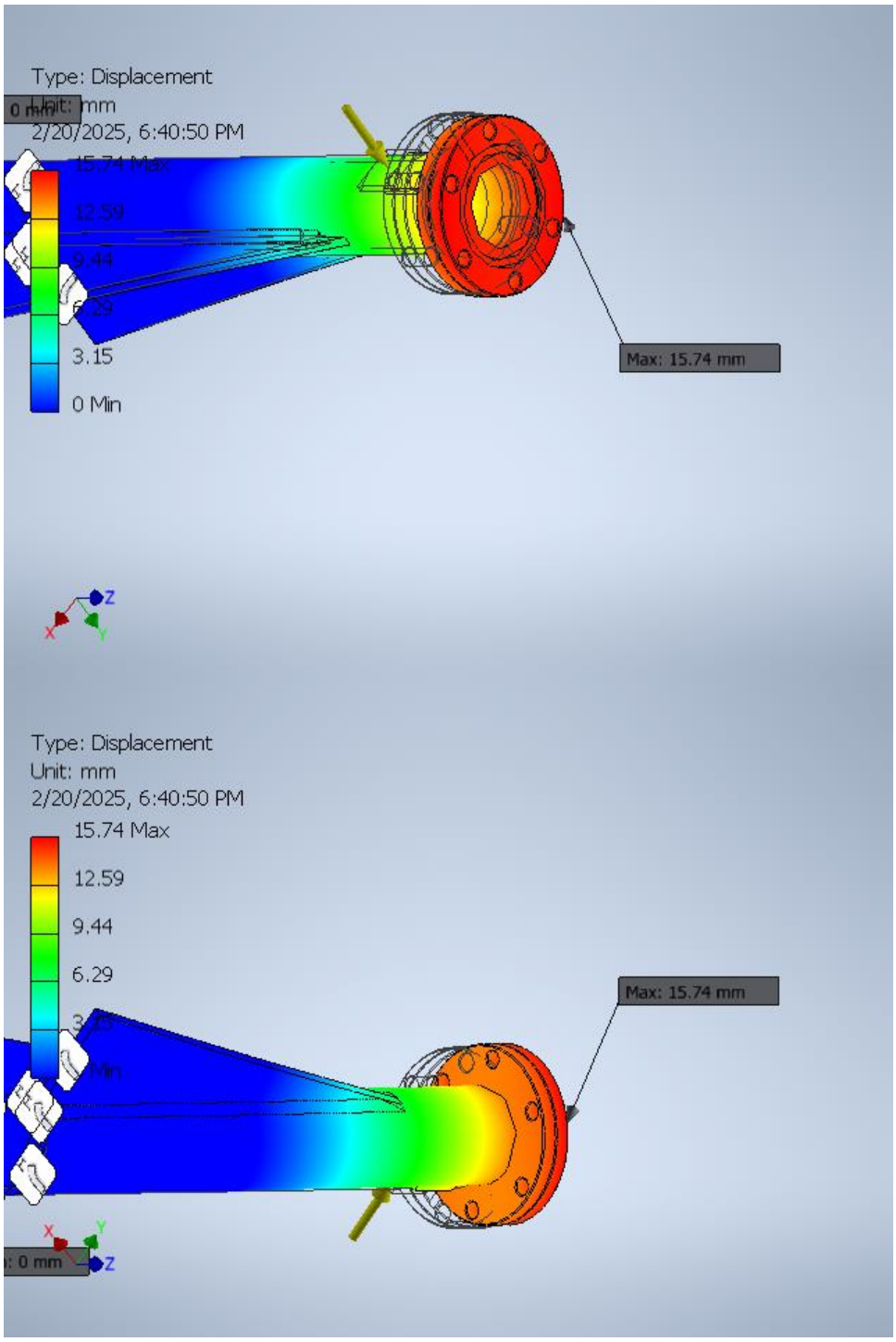
F1 515.15 Hz Y Displacement



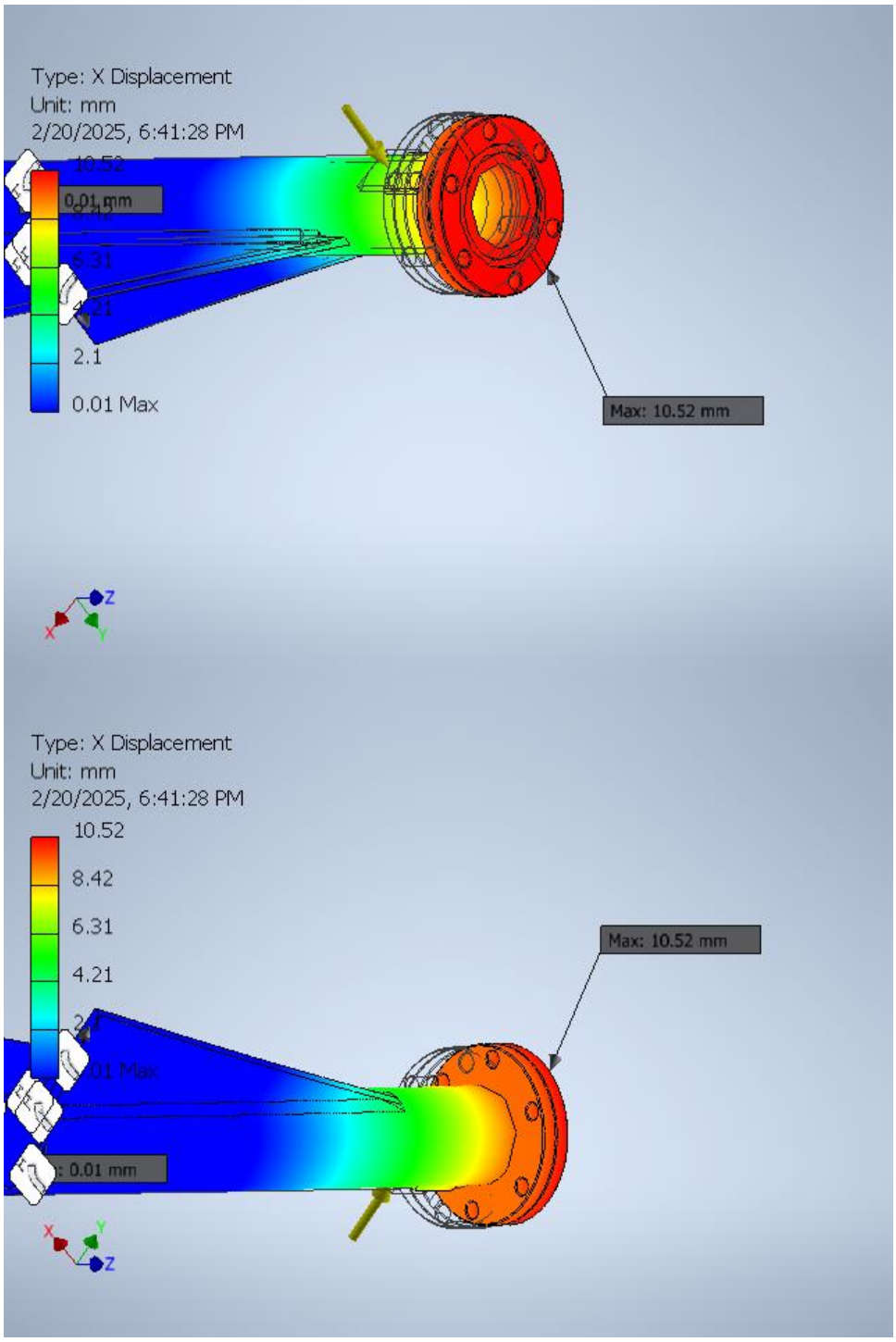
F1 515.15 Hz Z Displacement



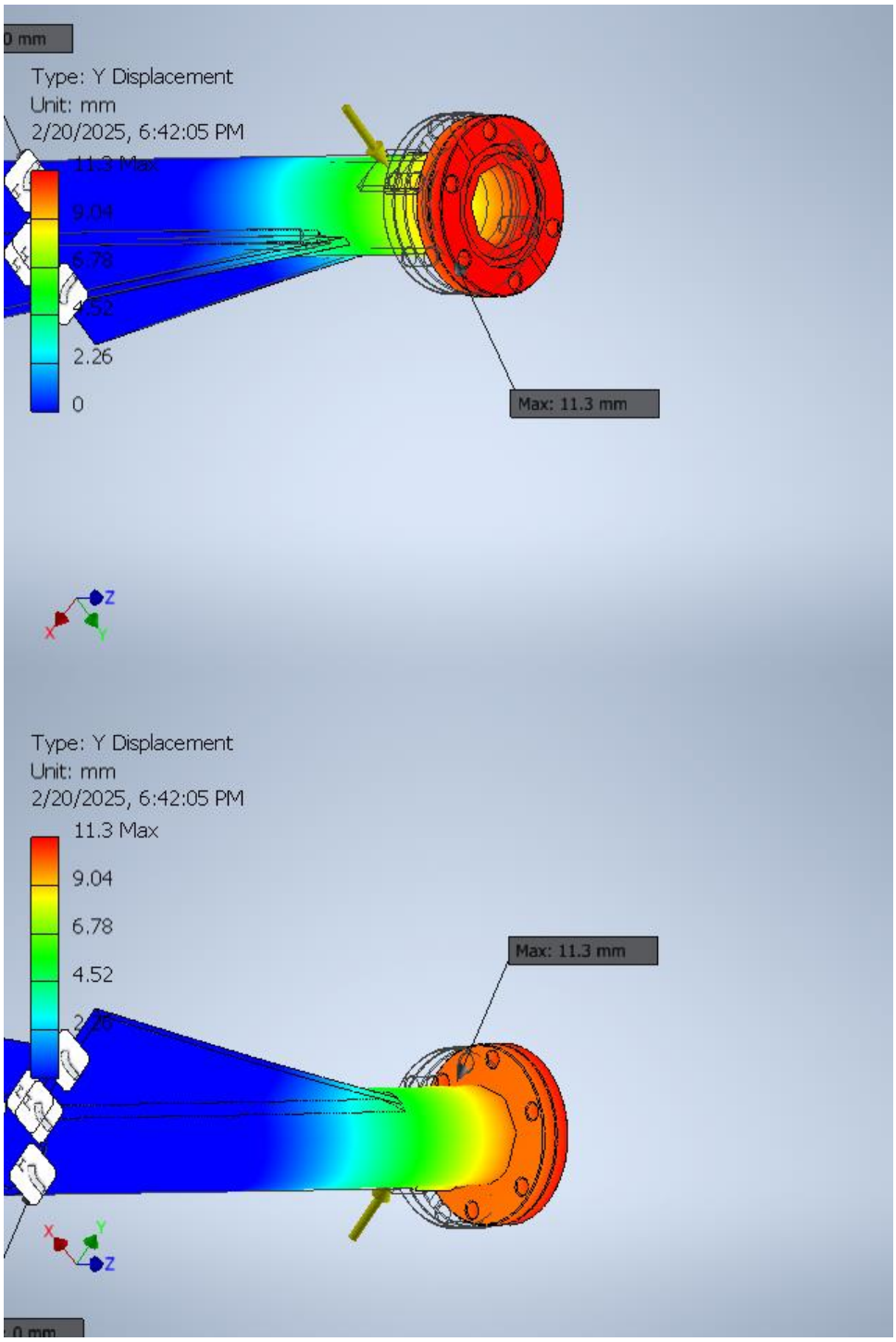
F2 591.67 Hz Displacement



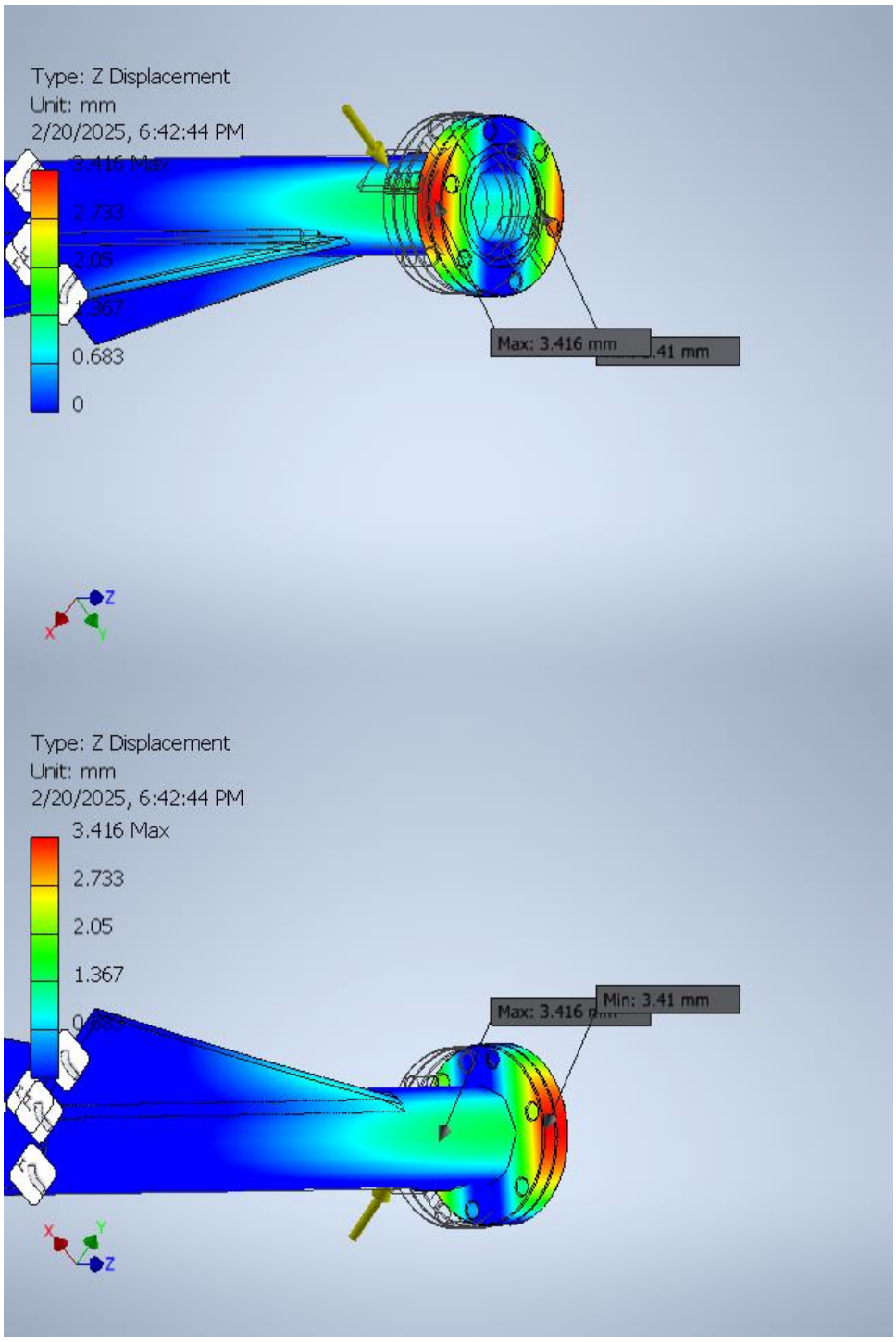
F2 591.67 Hz X Displacement



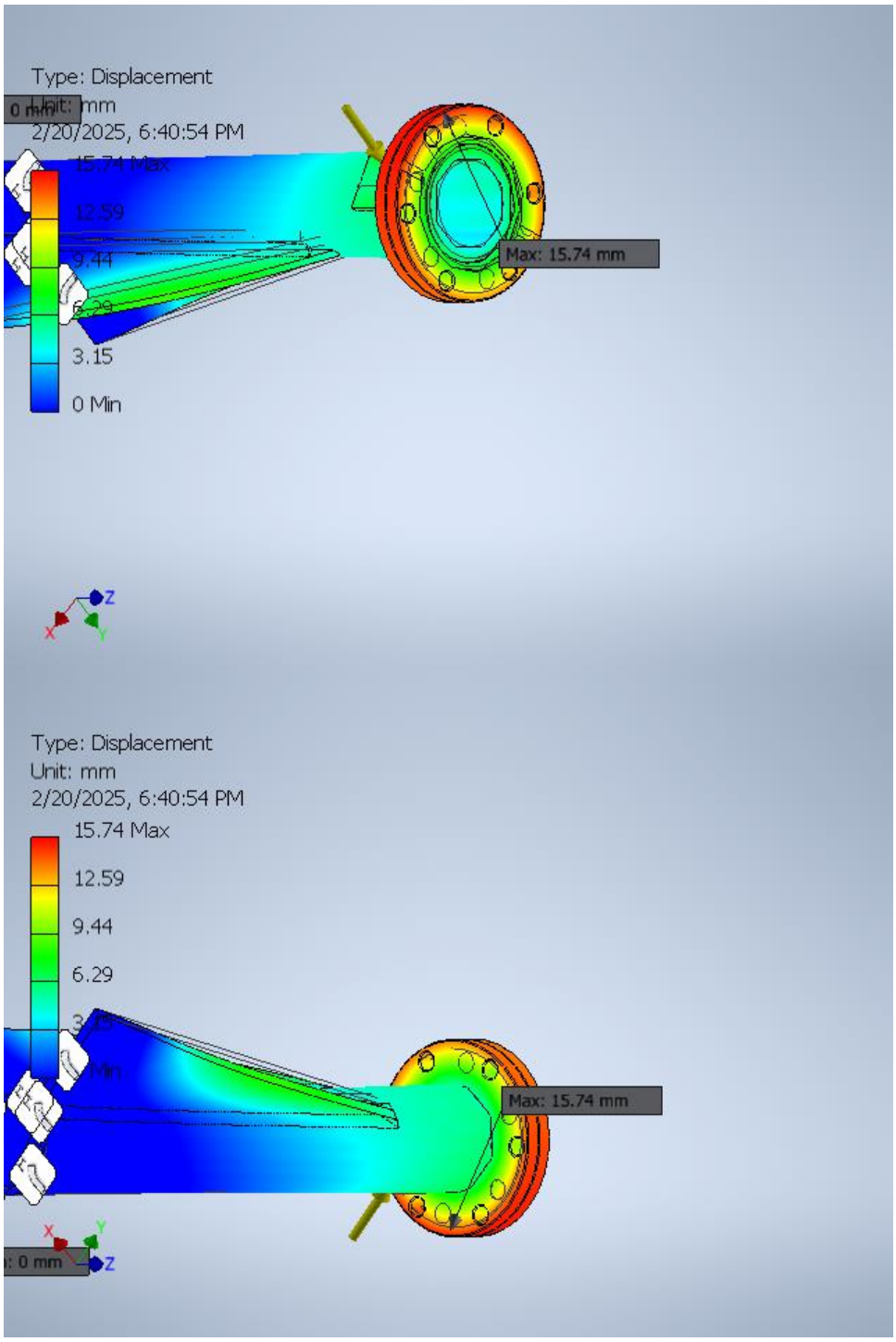
F2 591.67 Hz Y Displacement



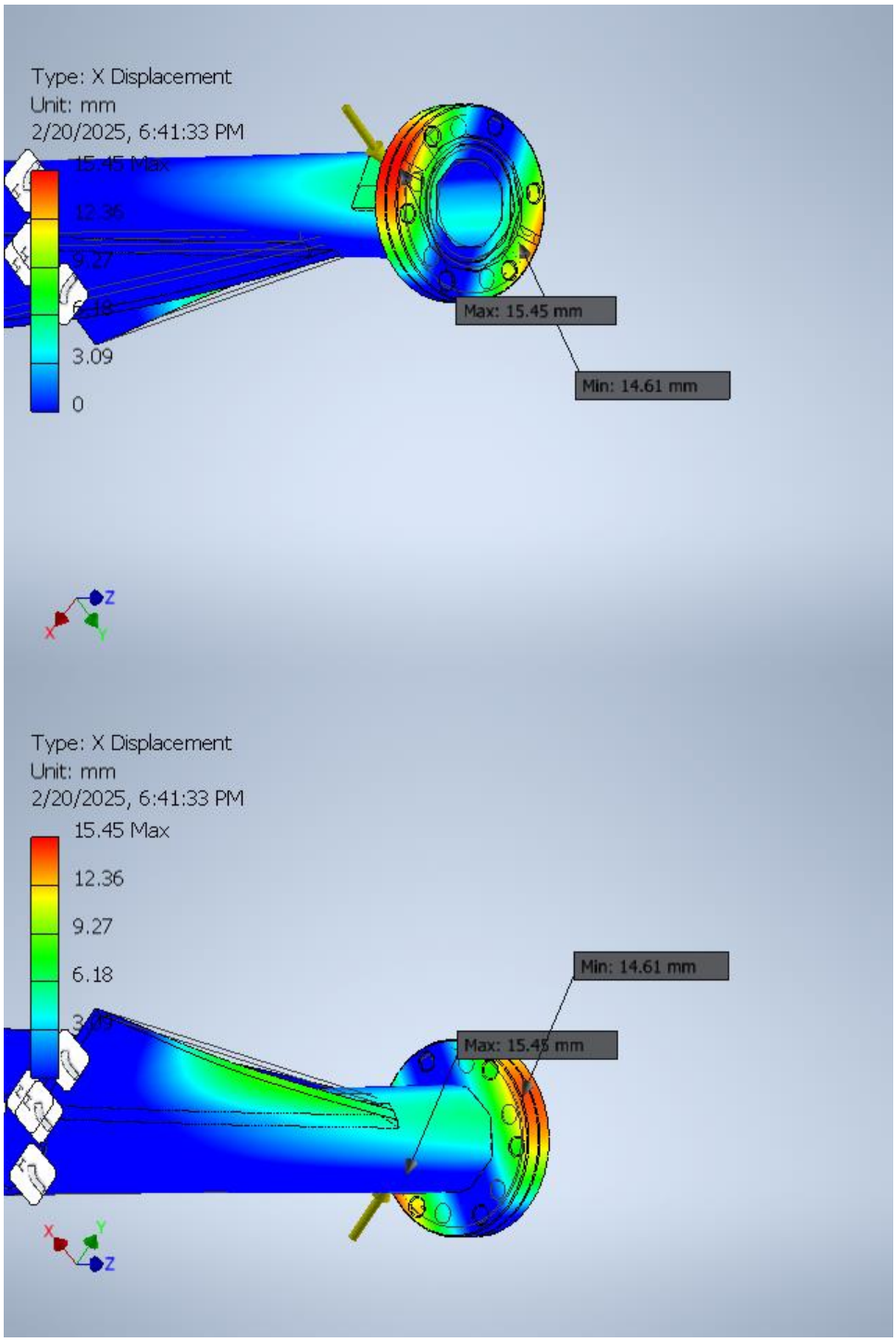
F2 591.67 Hz Z Displacement



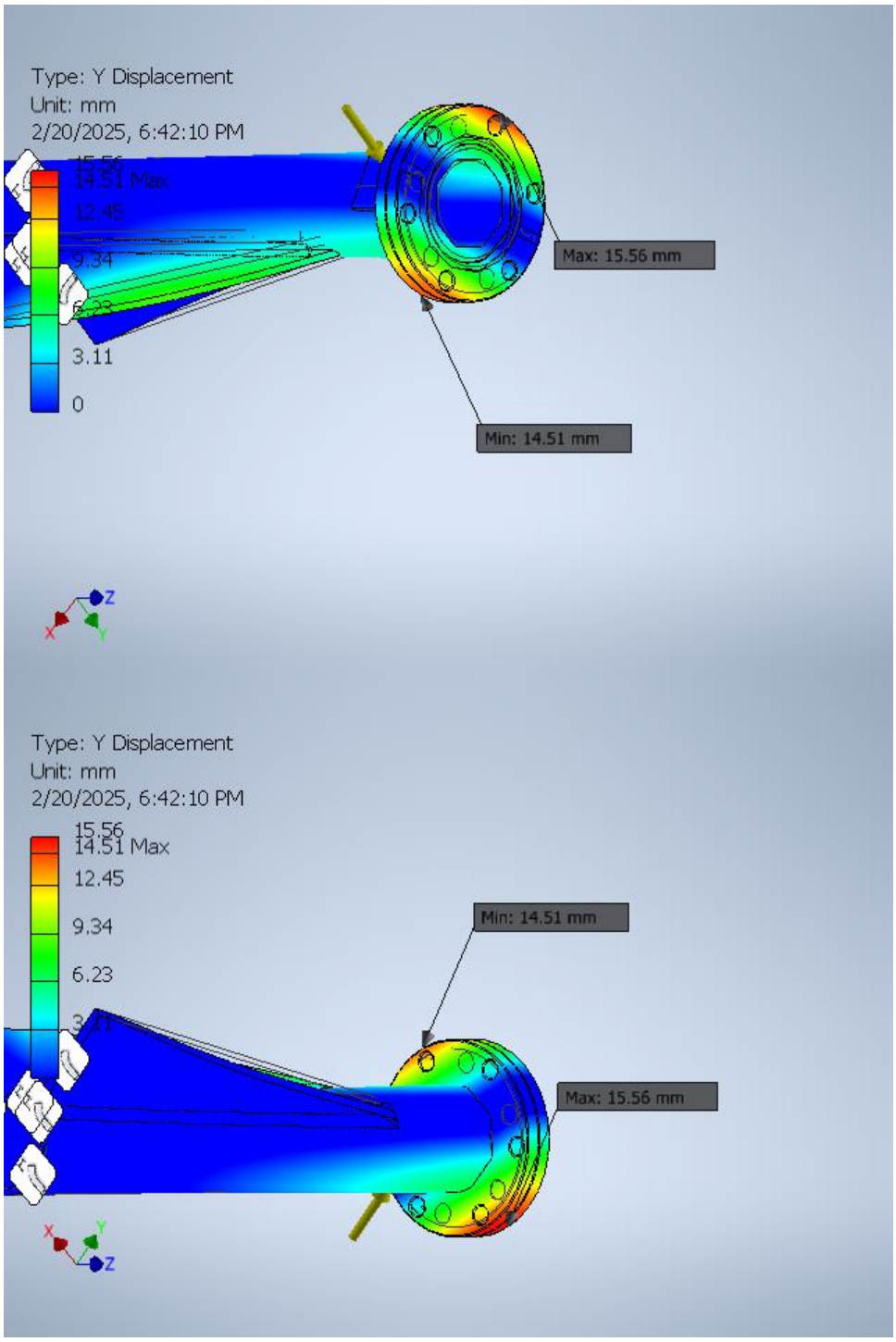
F3 1666.07 Hz Displacement



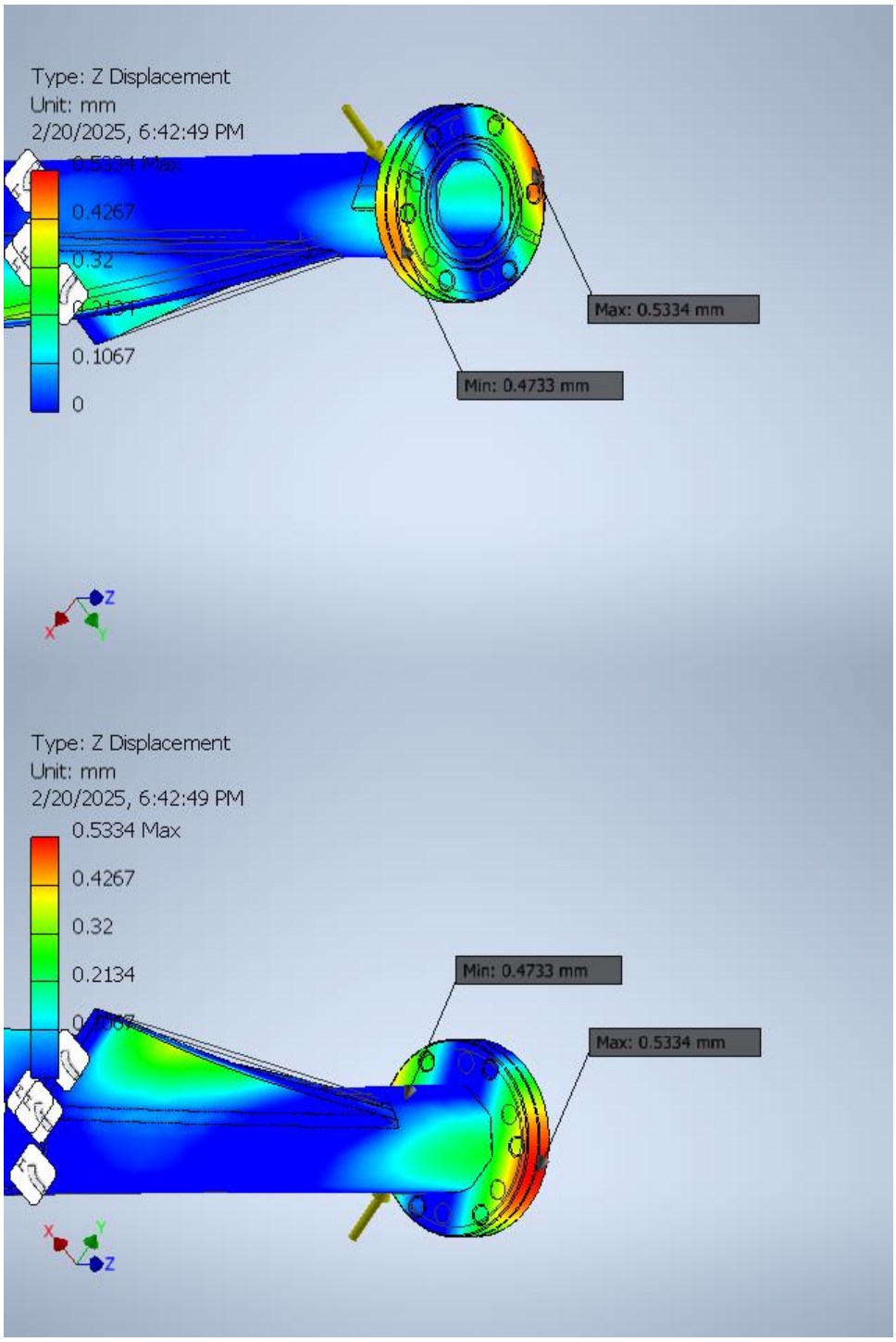
F3 1666.07 Hz X Displacement



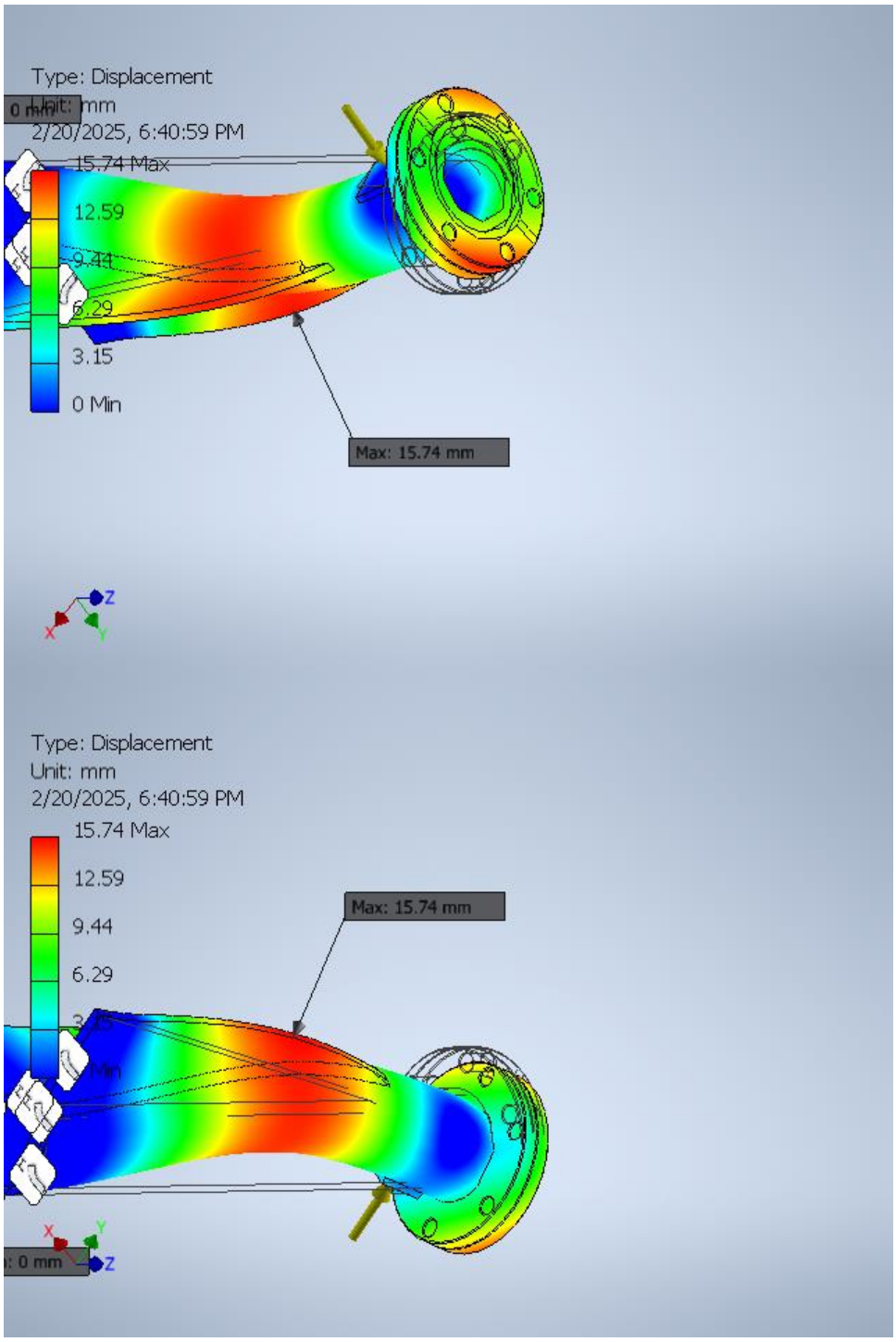
F3 1666.07 Hz Y Displacement



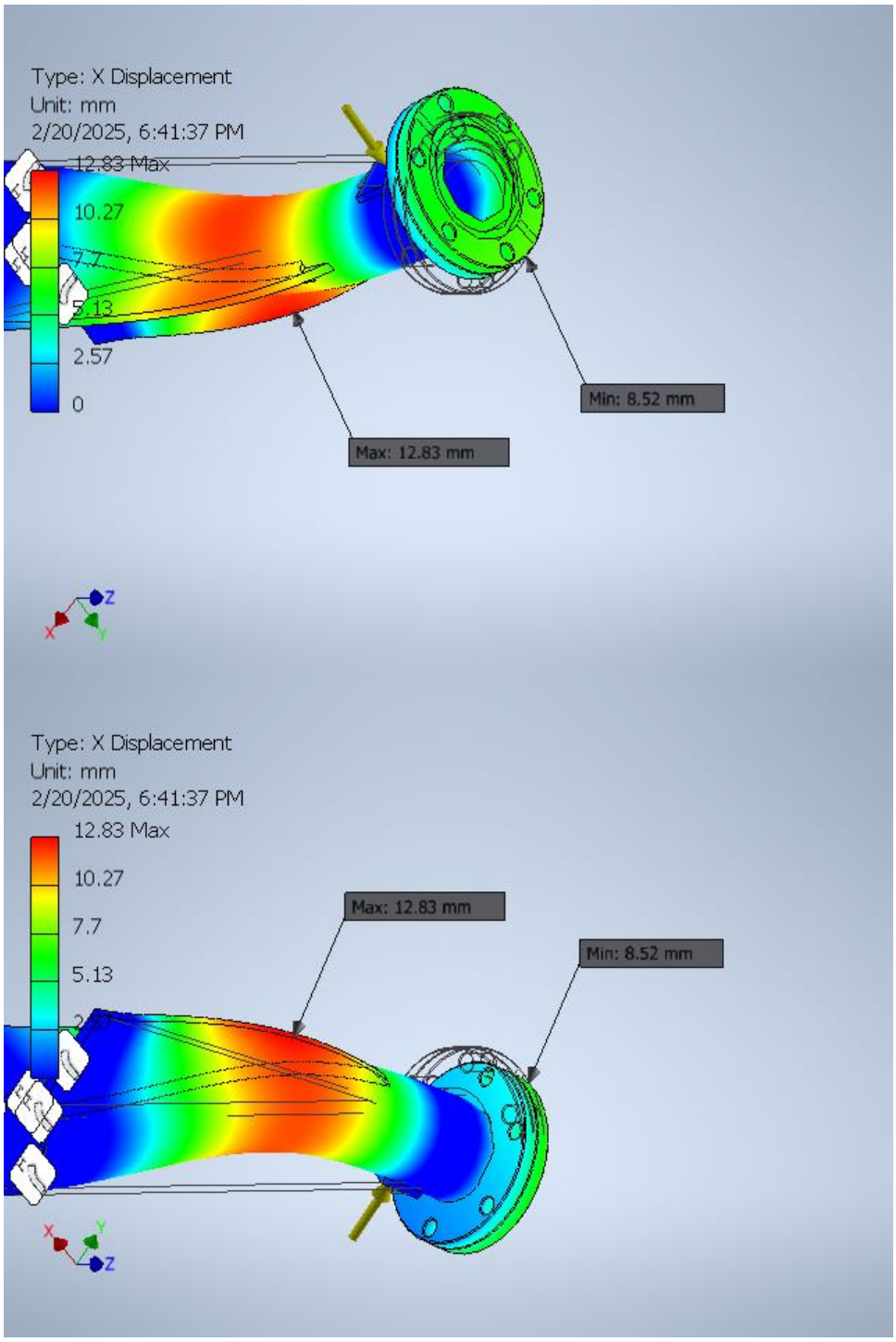
F3 1666.07 Hz Z Displacement



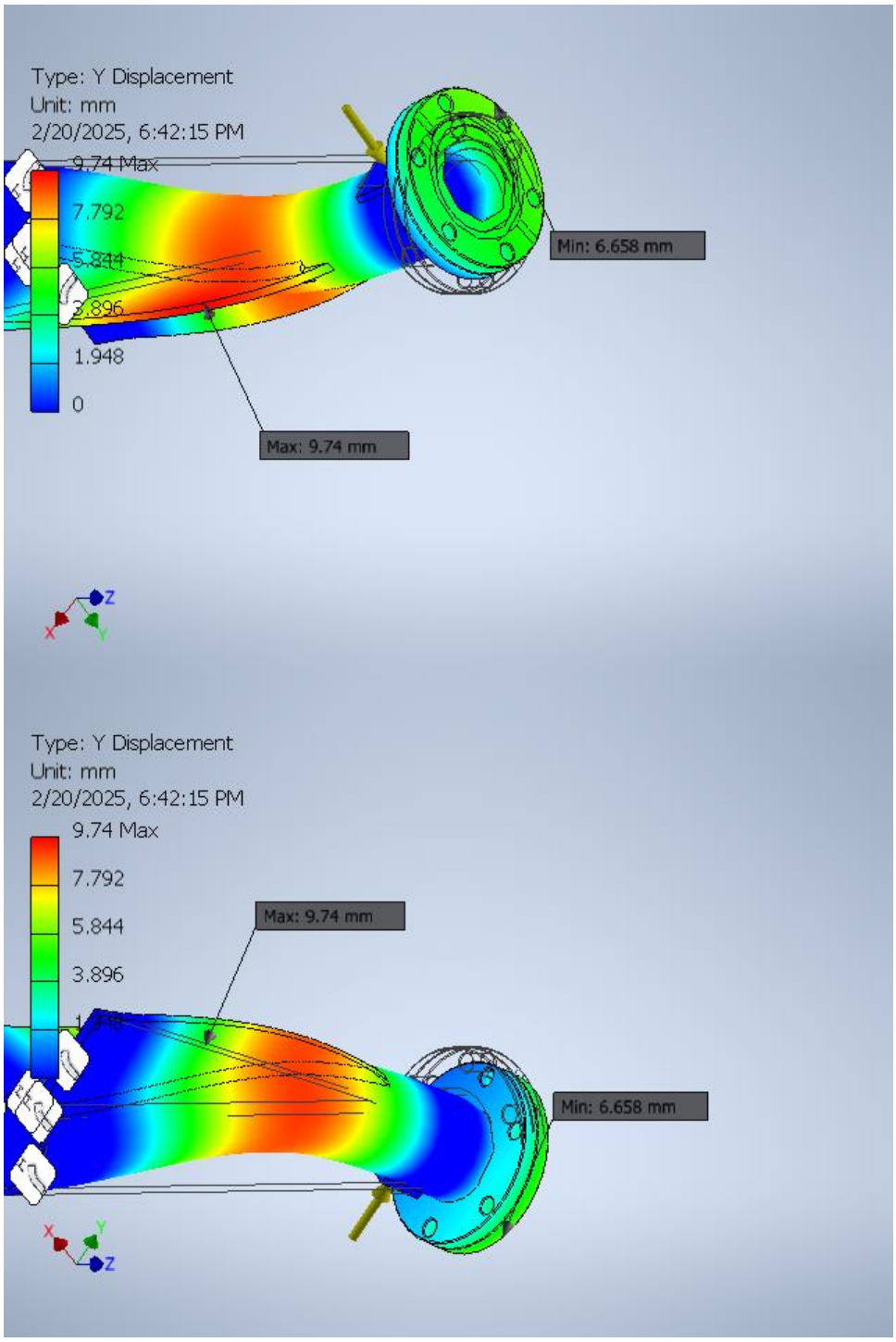
F4 2378.91 Hz Displacement



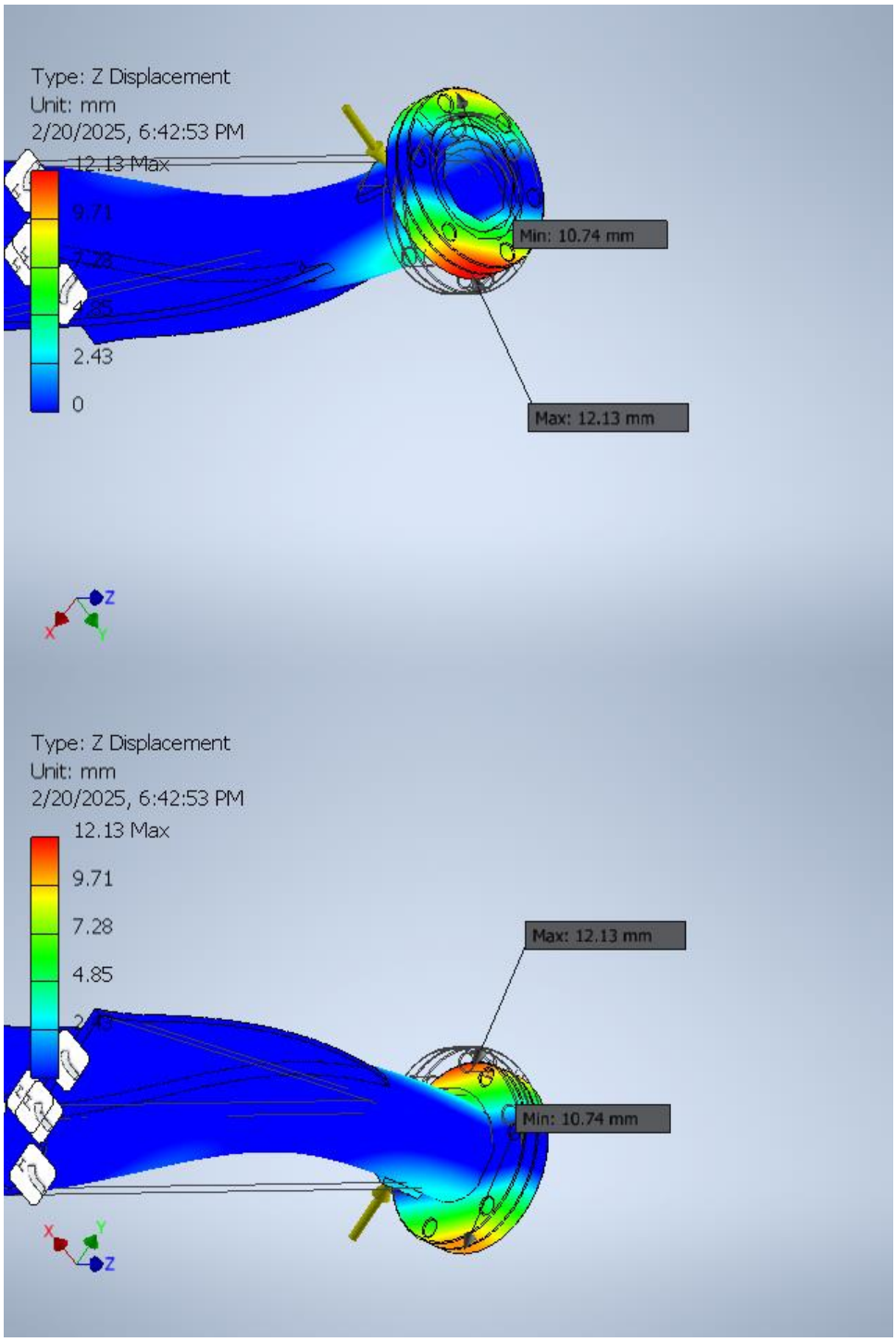
F4 2378.91 Hz X Displacement



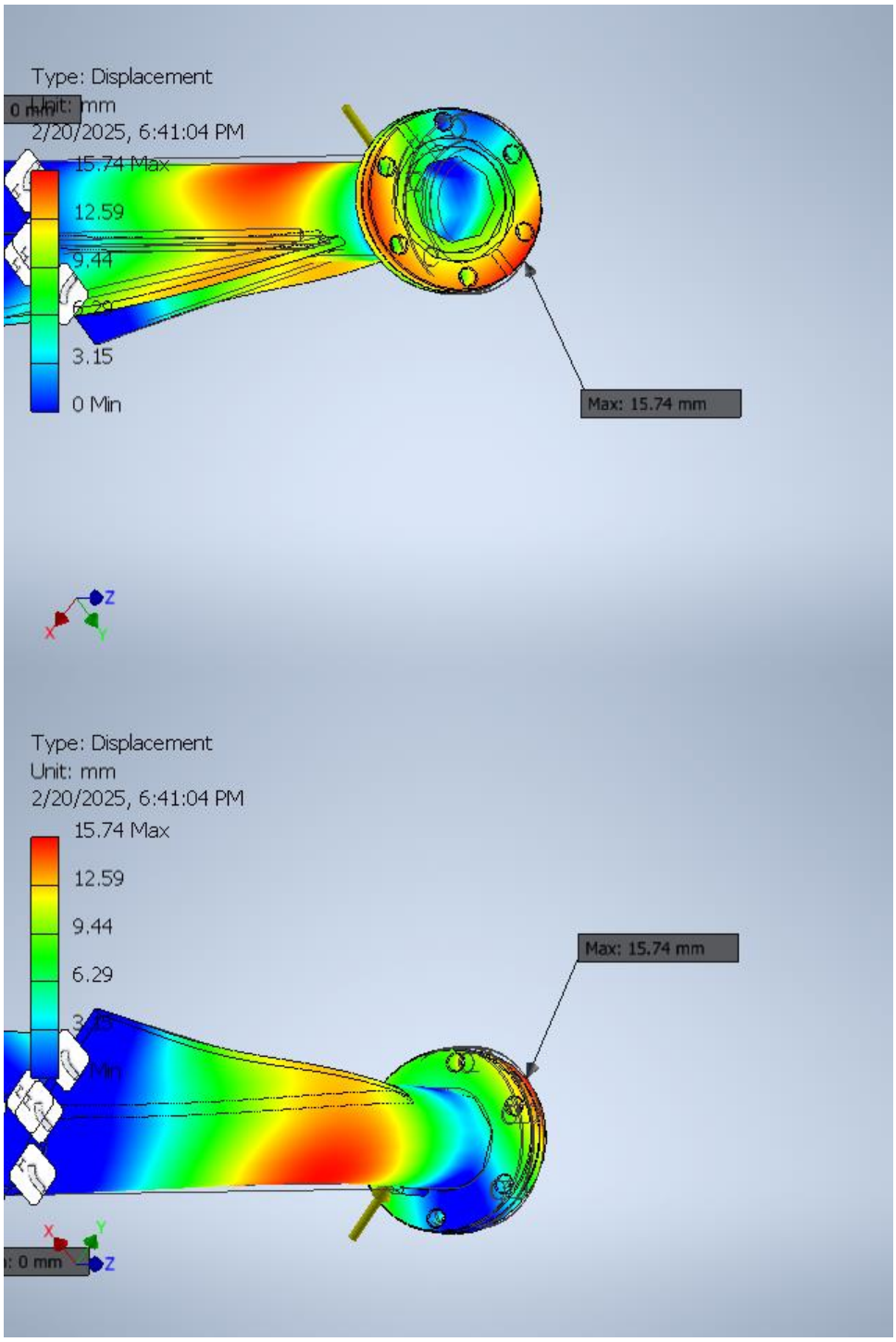
F4 2378.91 Hz Y Displacement



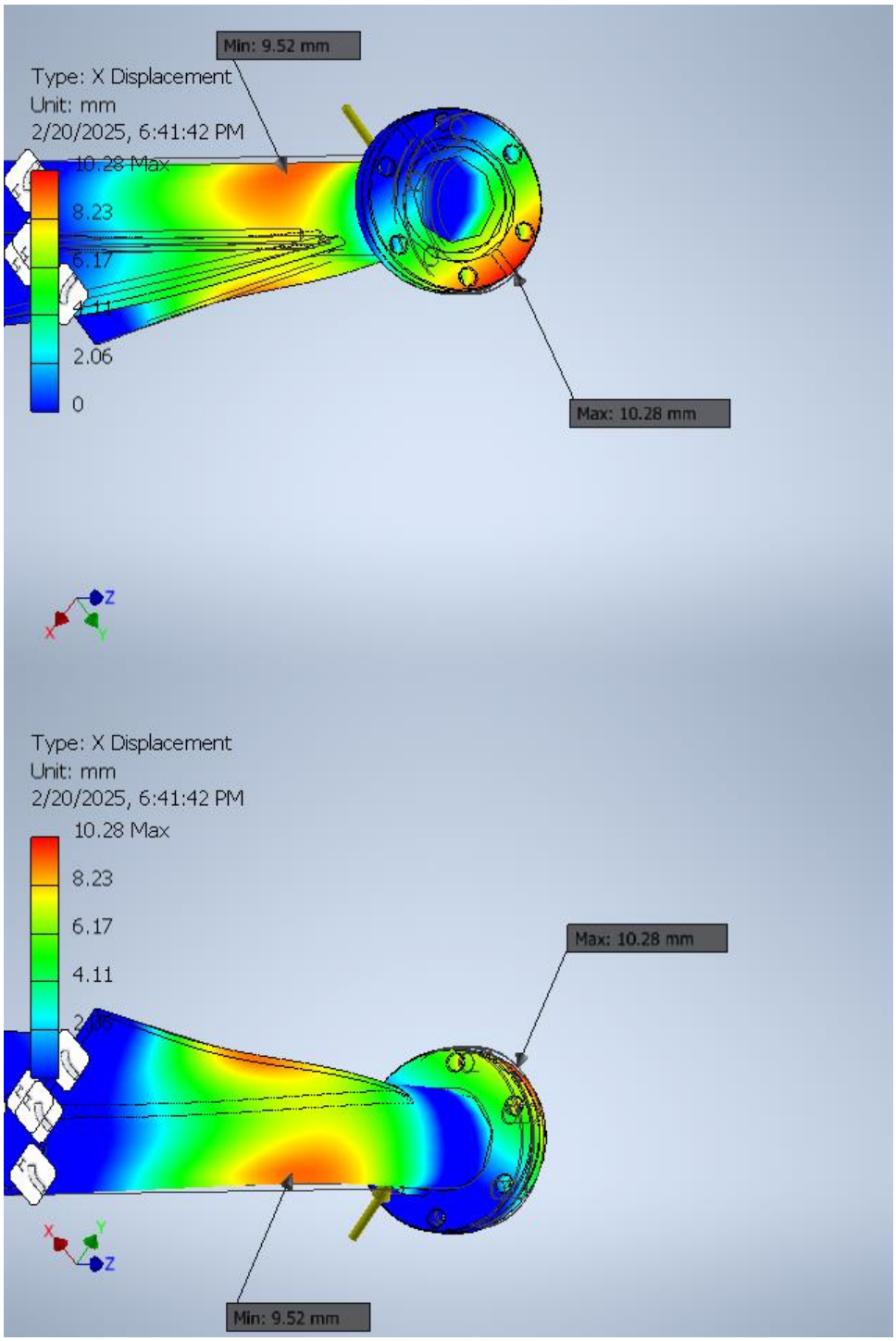
F4 2378.91 Hz Z Displacement



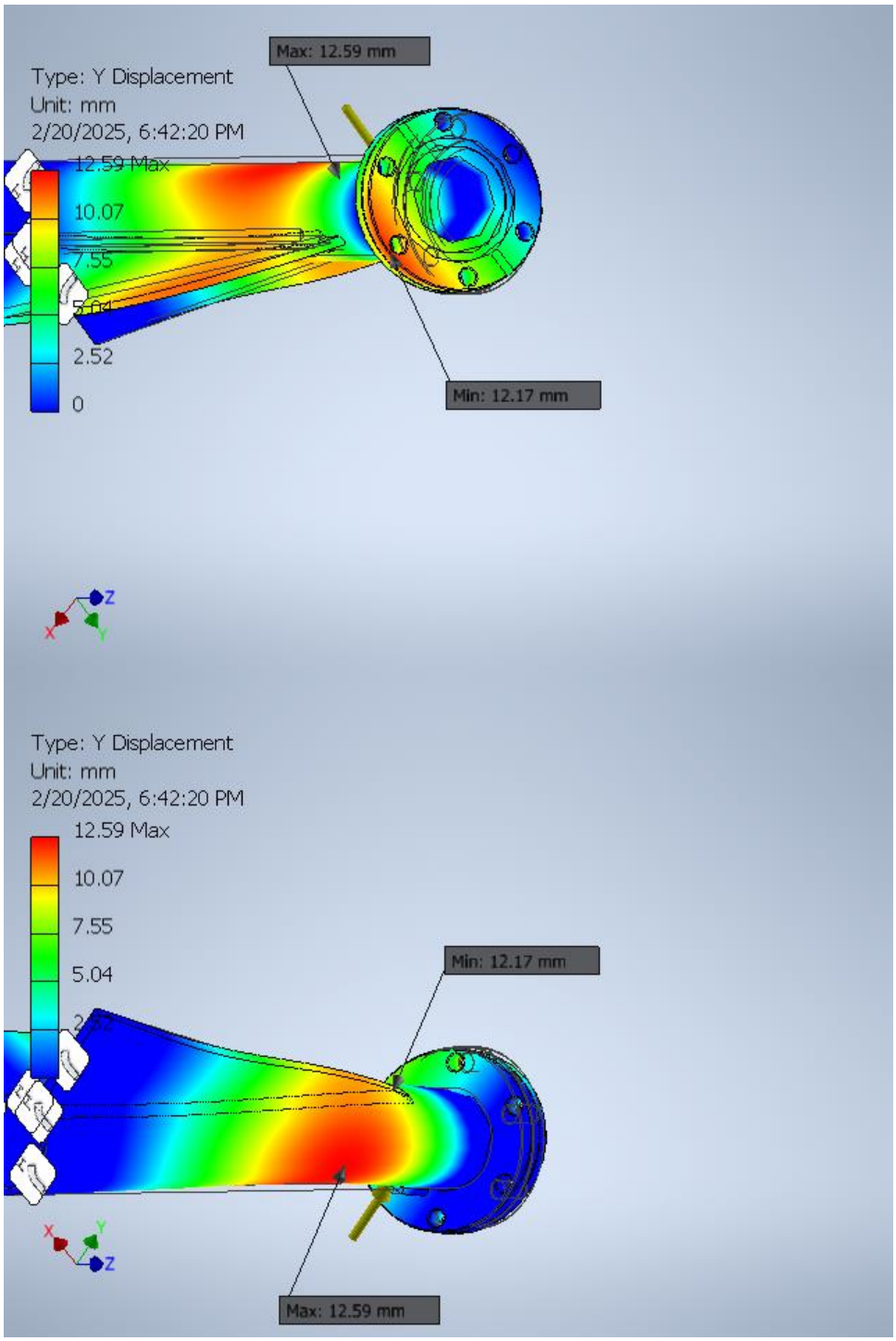
F5 2460.78 Hz Displacement



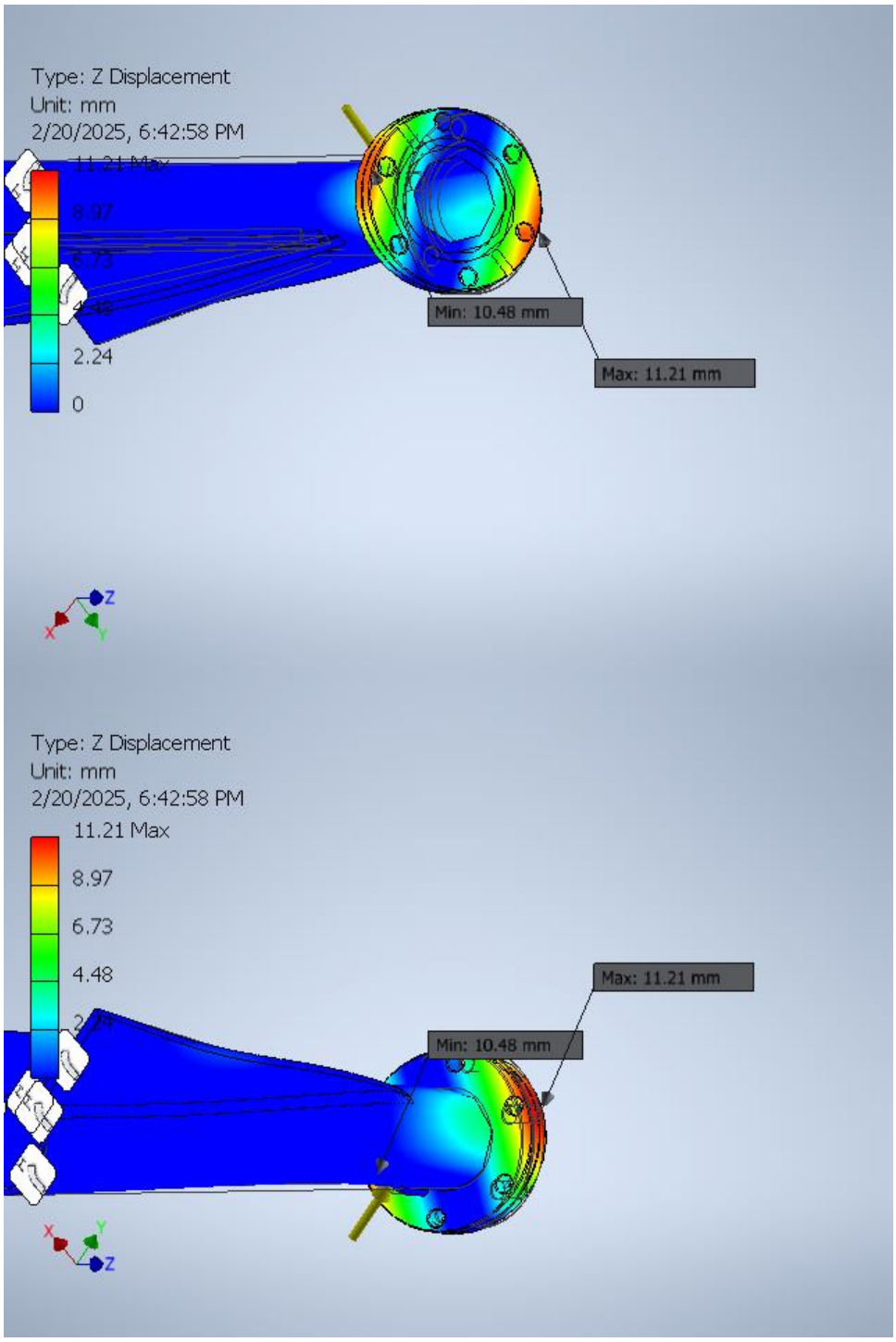
F5 2460.78 Hz X Displacement



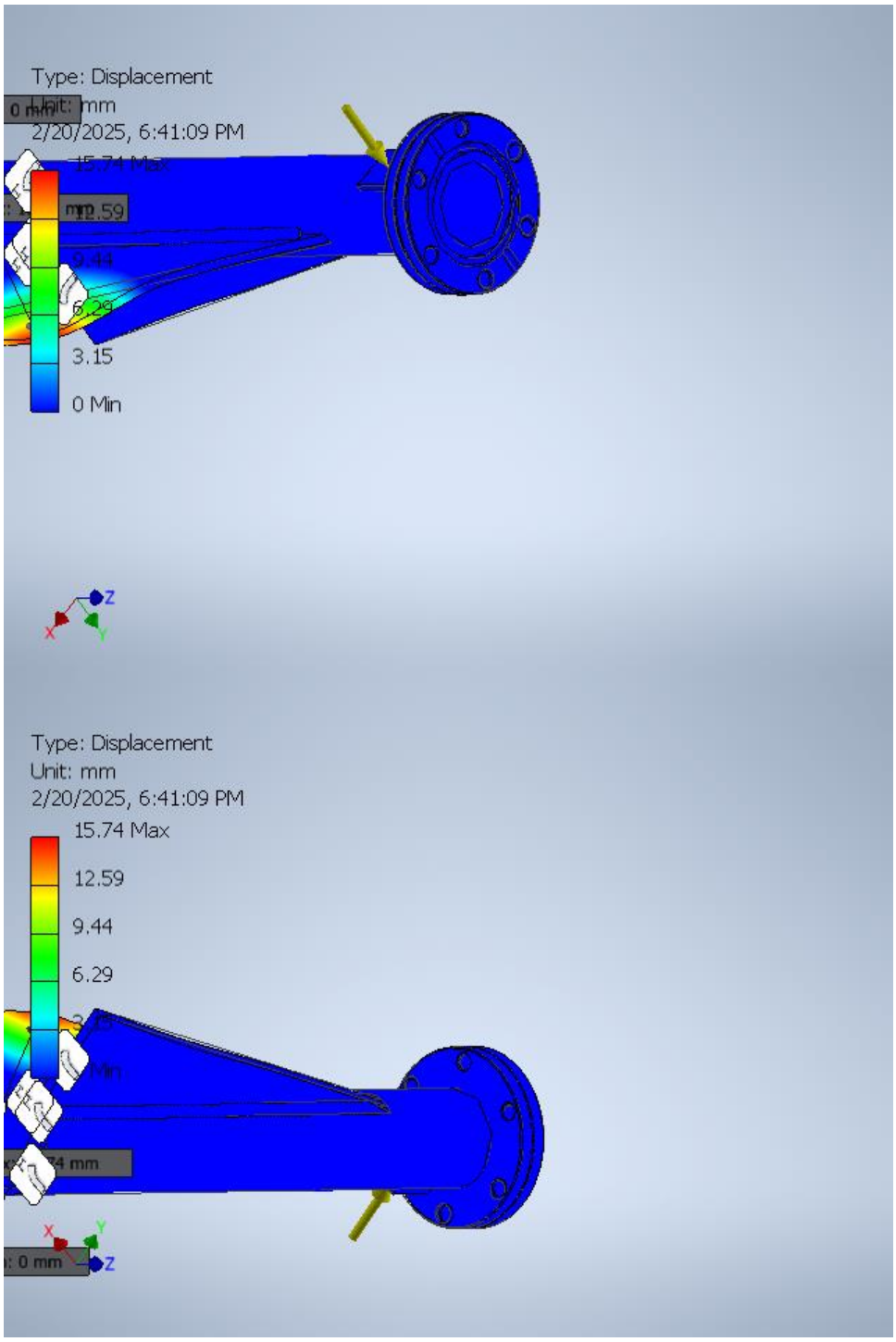
F5 2460.78 Hz Y Displacement



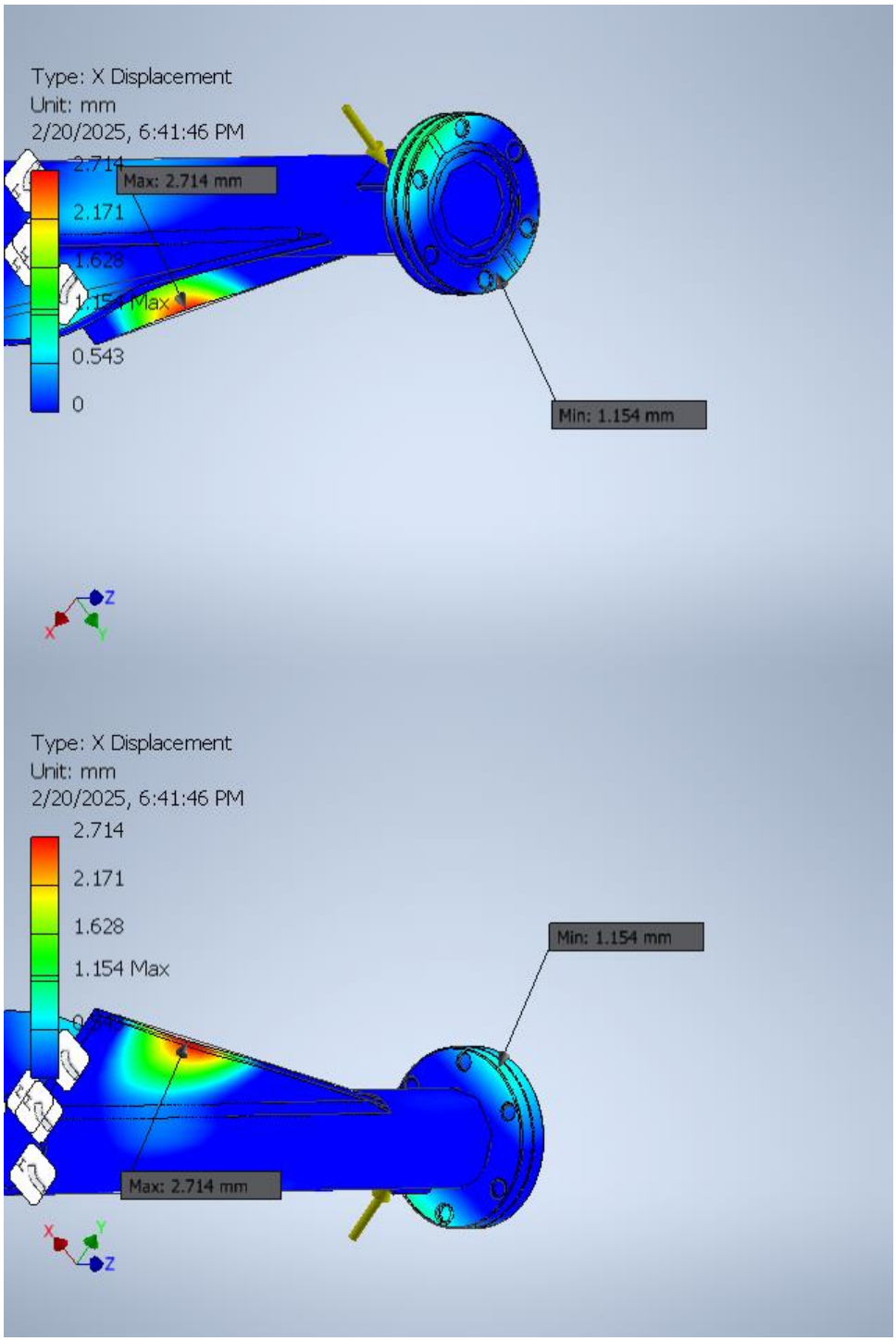
F5 2460.78 Hz Z Displacement



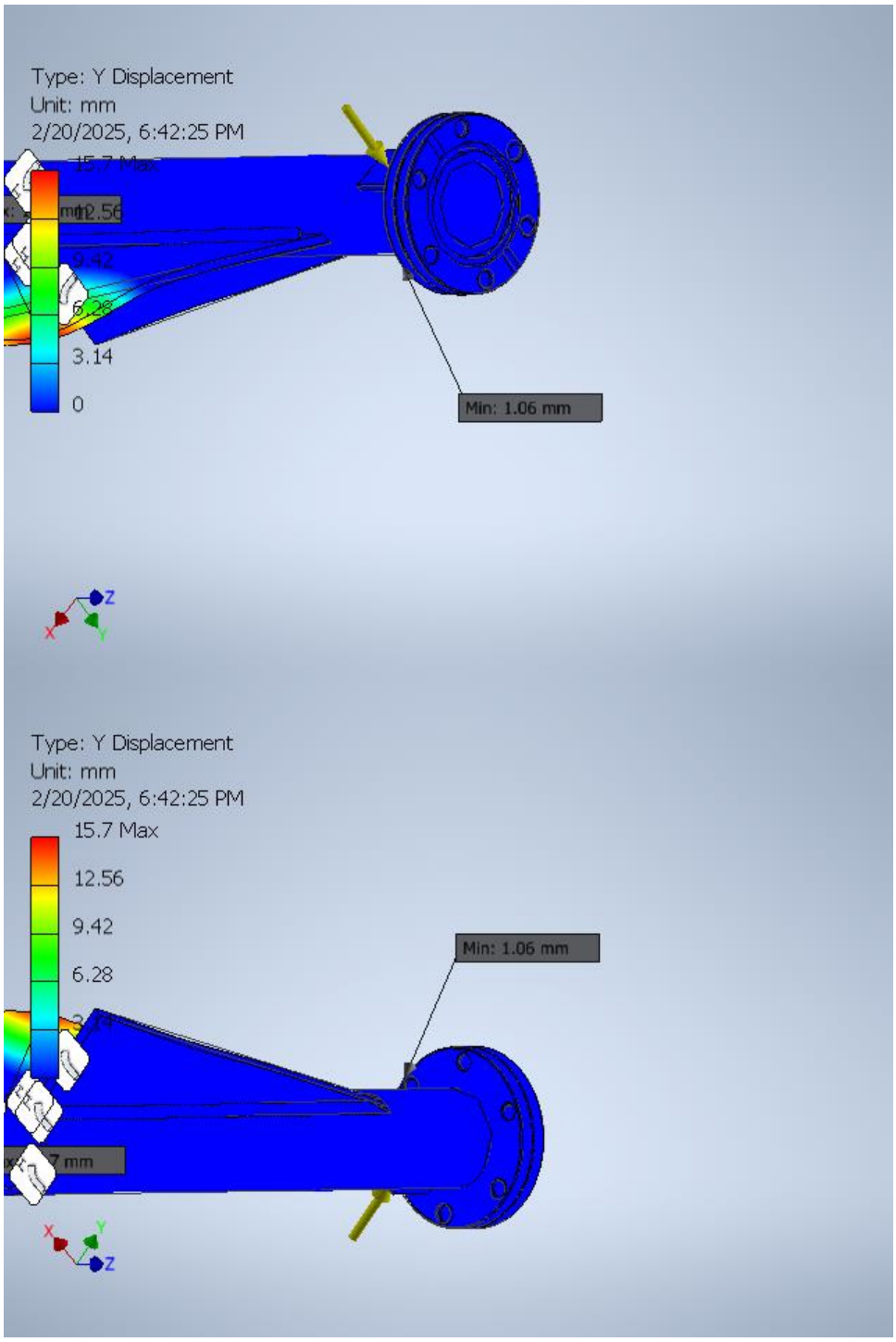
F6 3244.25 Hz Displacement



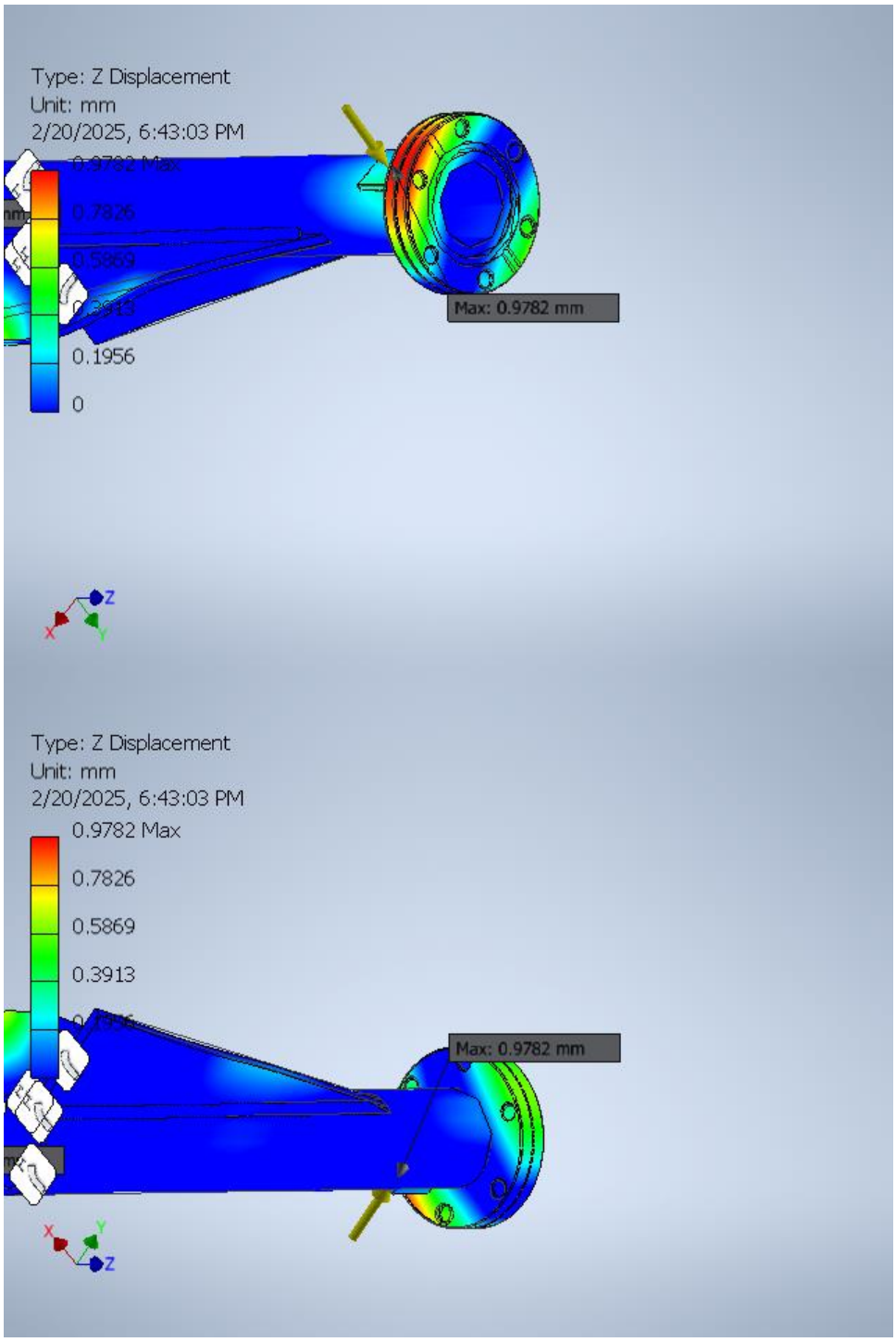
F6 3244.25 Hz X Displacement



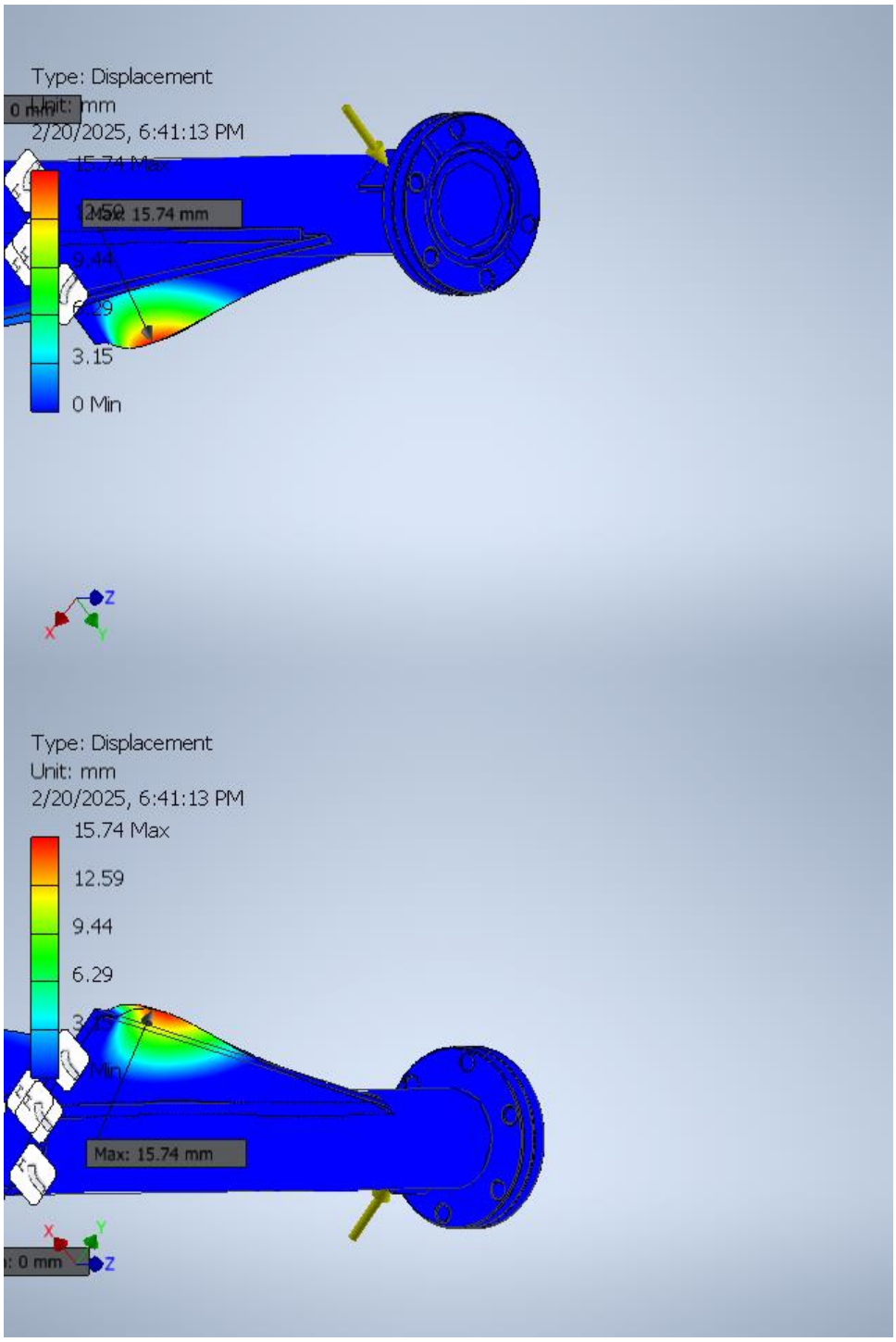
F6 3244.25 Hz Y Displacement



F6 3244.25 Hz Z Displacement



F7 3388.78 Hz Displacement



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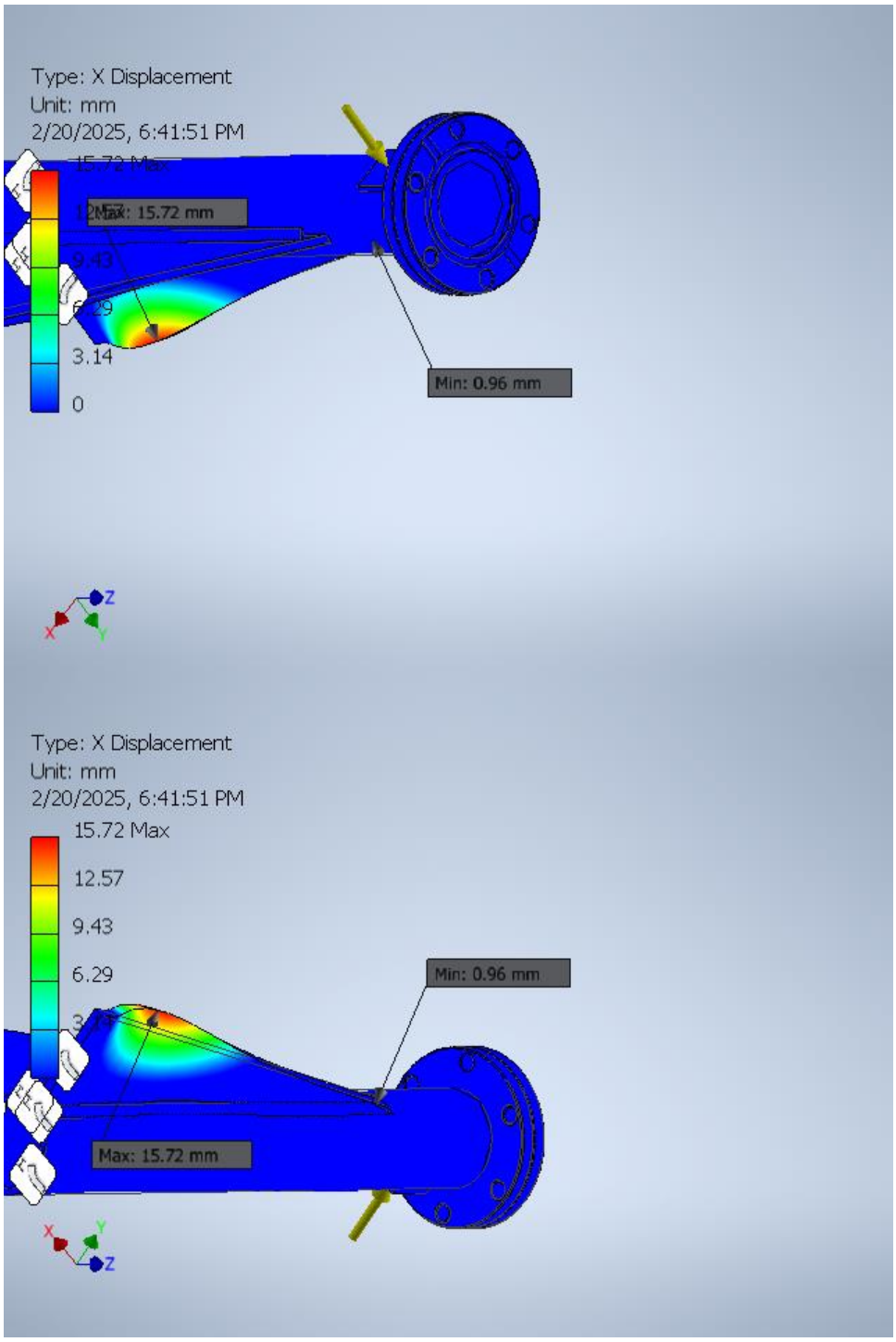
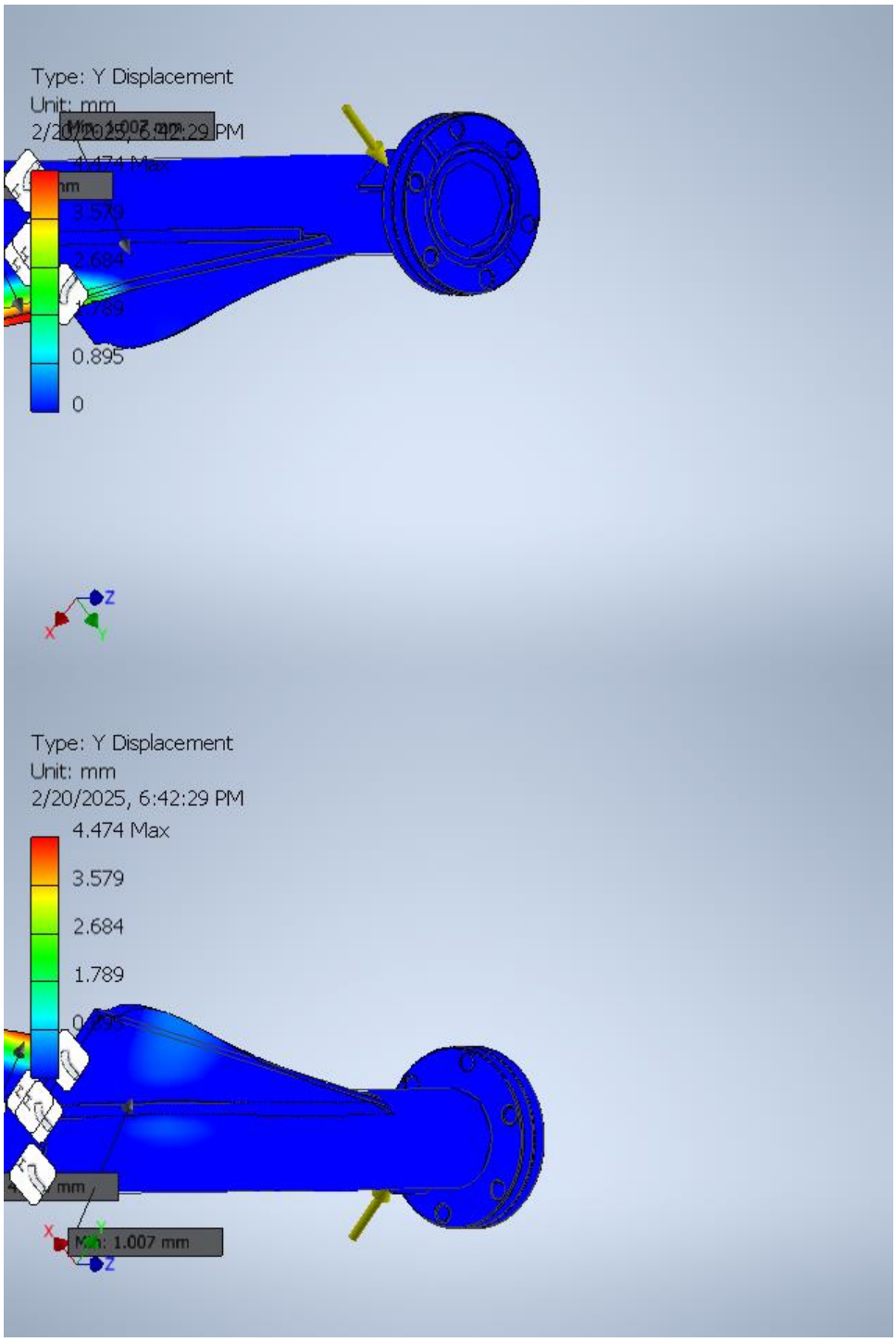


F7 3388.78 Hz Y Displacement



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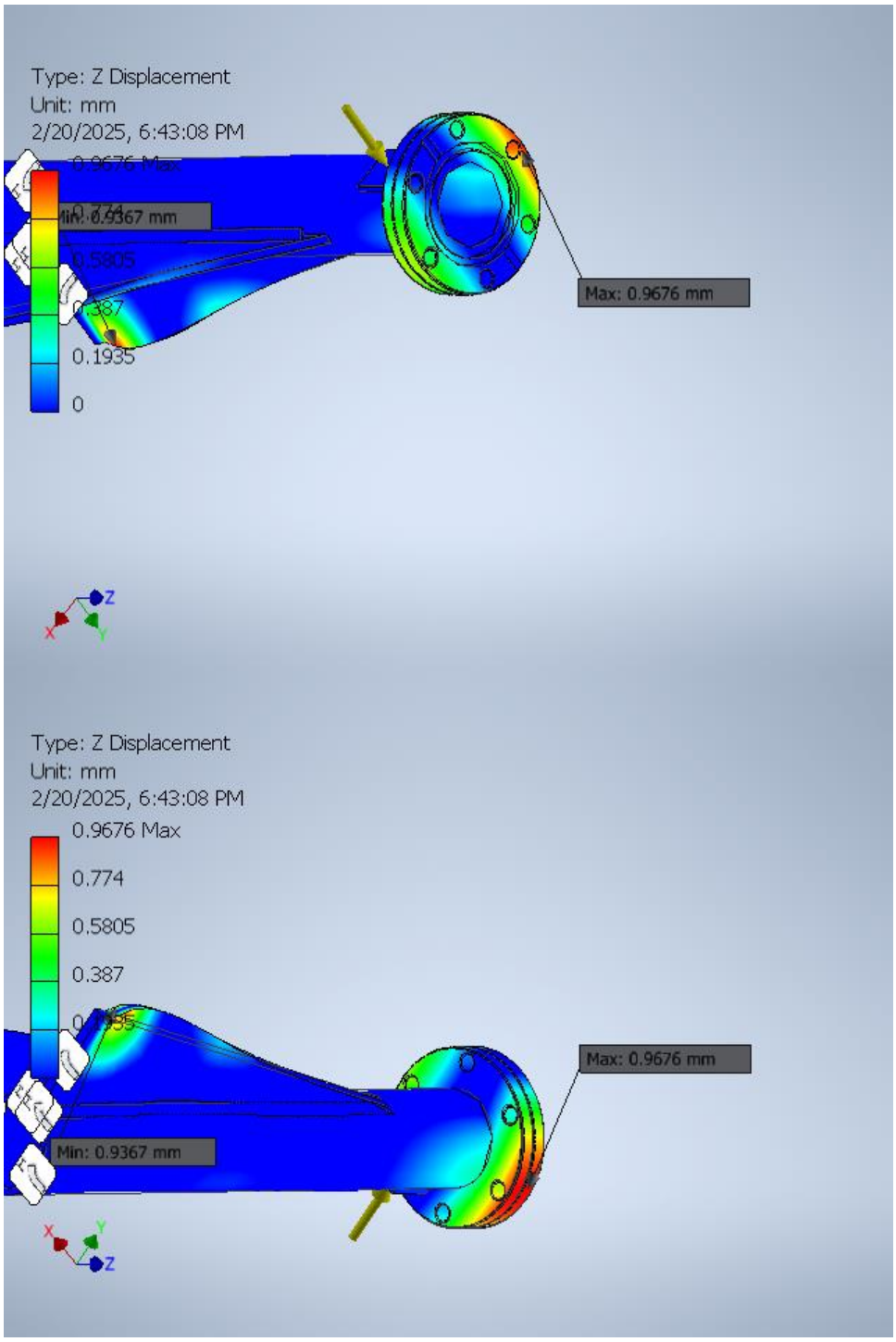
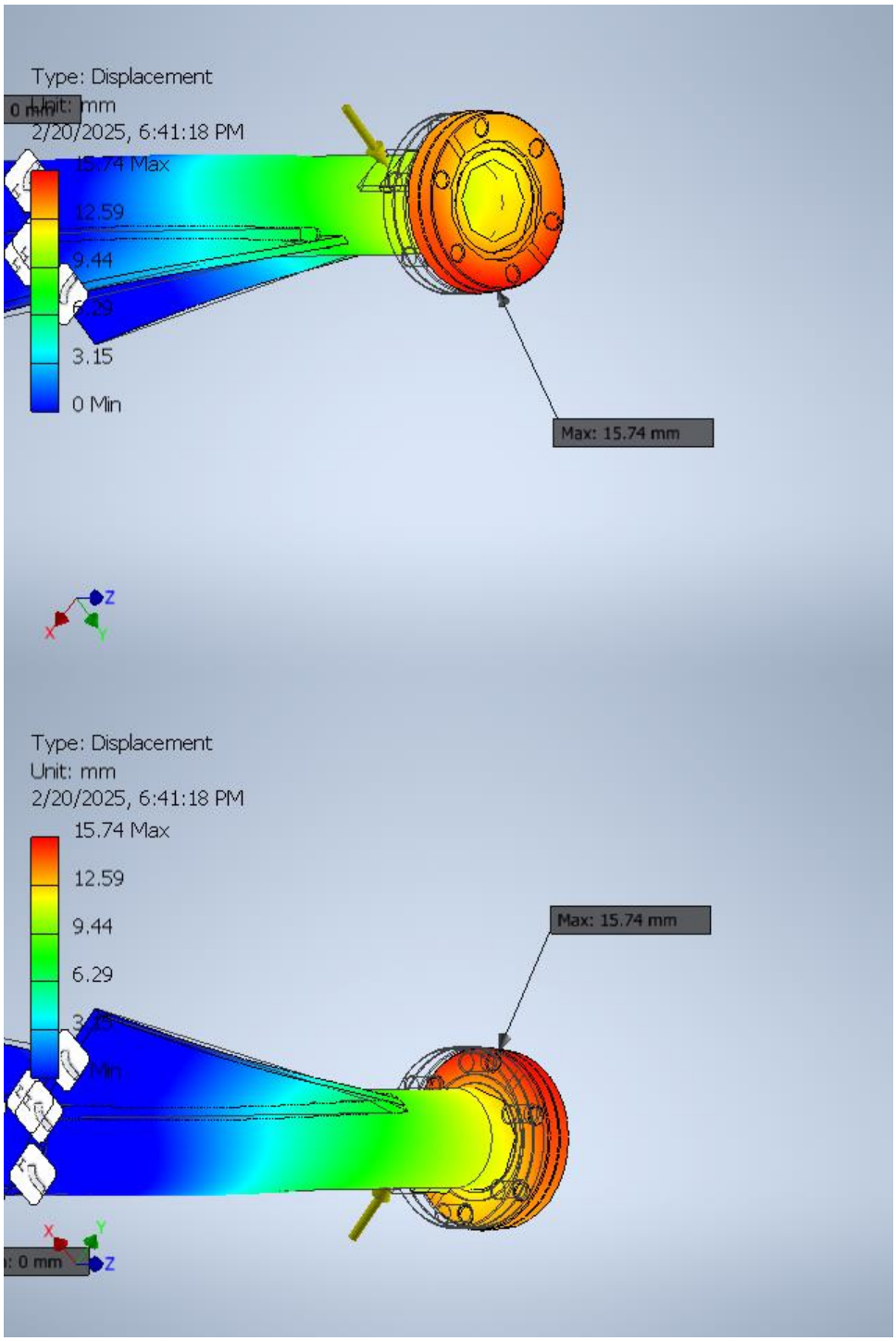


F8 4149.03 Hz Displacement



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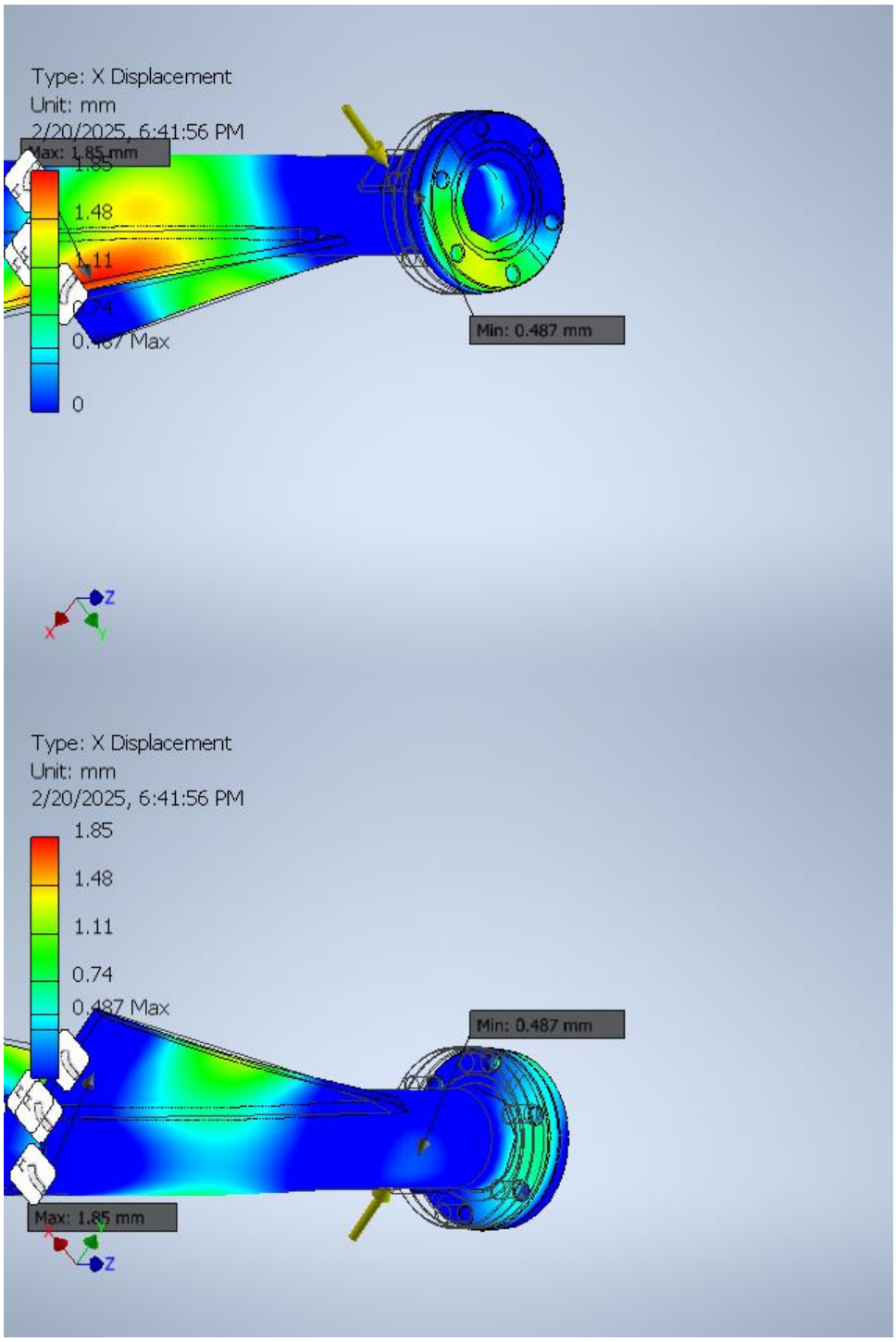

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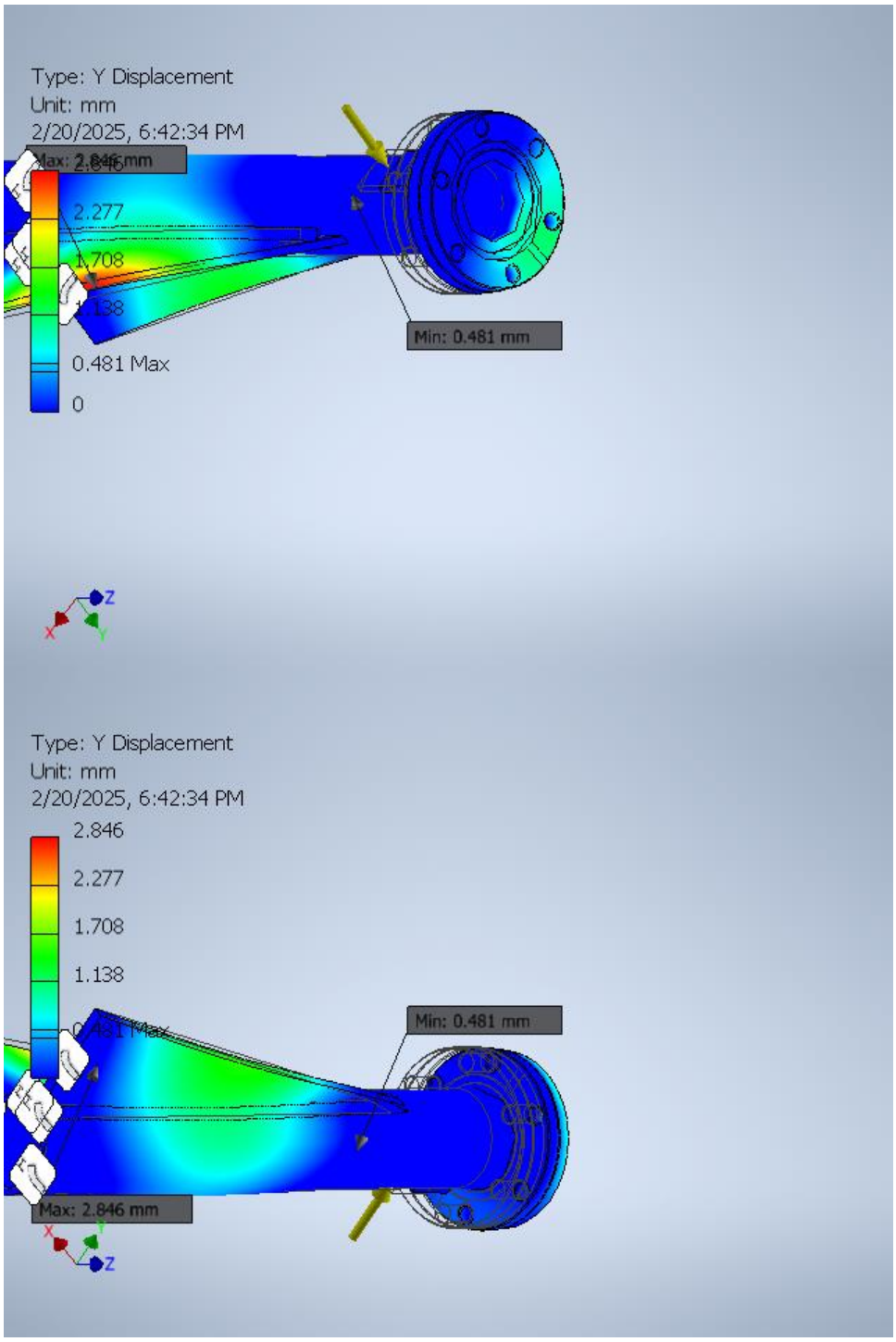

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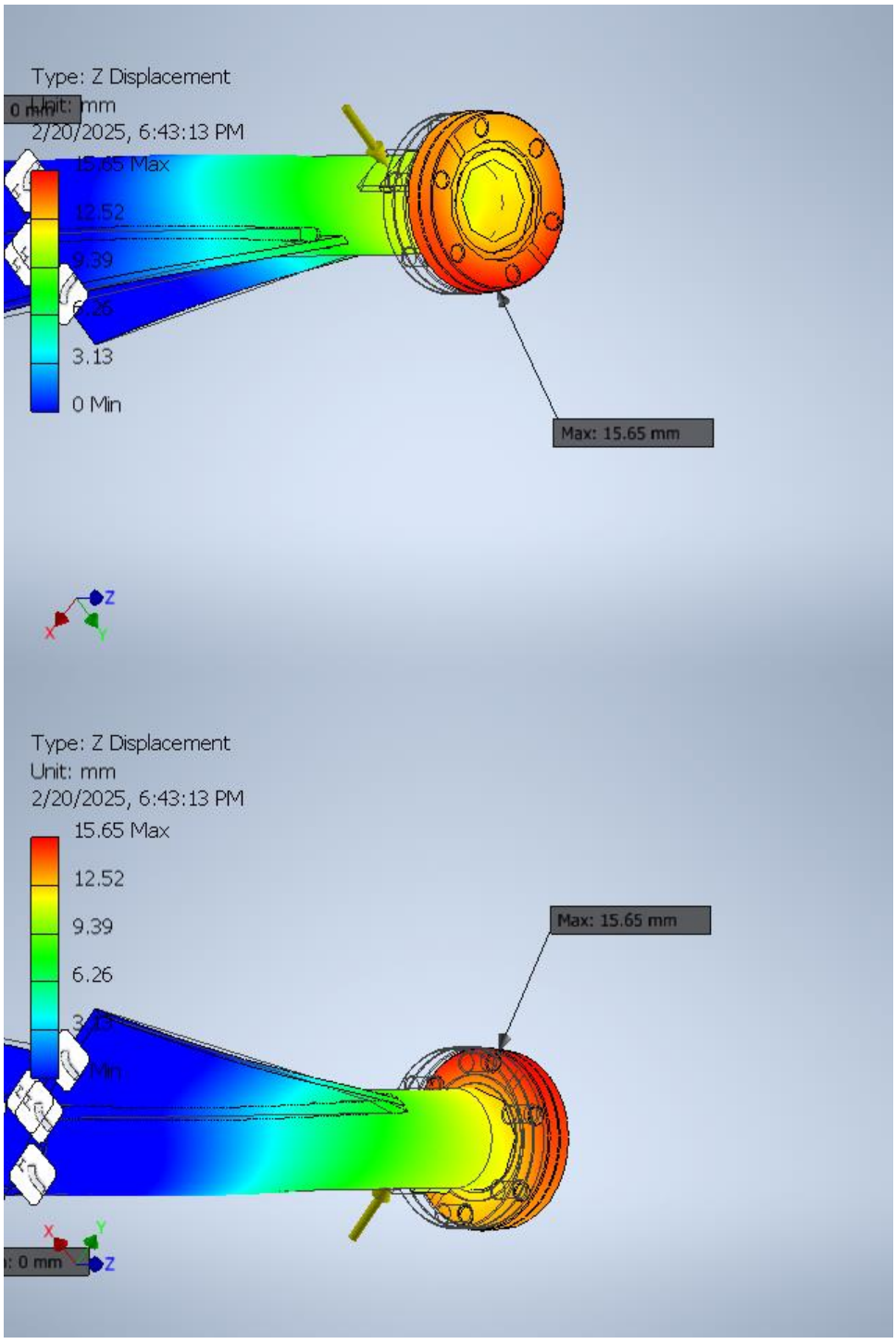
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15.65 Max
12.52
9.39
6.26
3.13
0 Min
Max: 15.65 mm
Z
X
Y
Type: Z Displacement
Unit: mm
2/20/2025, 6:43:13 PM
15.65 Max
12.52
9.39
6.26
Max: 15.65 mm
Z