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Monte Carlo Analysis of Filter Cavity Tube (FCT) Alignment Strategies

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Table of Contents

1 Introduction

The A+ Project[1] scope includes the addition of an optical Filter Cavity (FC). The vacuum system layout for the 300 m long FC includes a long Filter Cavity Tube (FCT), which extends from vacuum chamber HAM7 to vacuum chamber BSC3, in the corner station LVEA, and then to vacuum chamber HAM8, which is housed in the Filter Cavity End Station (FCES) building. Most of the length of the FCT is housed in the Filter Cavity Tube Enclosure (FCTE) which spans between the corner station and the FCES.

The purpose of this document is to explore the accuracy of various alignment strategies of the FCT, taking into account the FCT dimensional tolerances and the capabilities of the FCT Supports, using a Monte Carlo analysis approach. These results are intended to inform/guide the FCT installation and alignment procedure[2]. In particular whether specific serial numbers of FCT component tubes need to be matched based on their measured geometrical deviations.

2 Alignment requirements

Optical baffles are placed inside of the FCT to mitigate specular reflections and optical scattering from the FCT. All FCT baffles are to be installed within 20” of the end of a tube[3] section.

In the conceptual design document the lateral (de-centering) tolerance of the FCT, to be accommodated by the bellows was estimated[4] to be ± 0.831” as a pessimistic (though not worst) case. Based on this FCT de-centering tolerance at the bellows, Lee McCuller suggested[5] that the baffle inner diameter be ≥ 5.5”. The FCT baffle cone[6] aperture is 5.92” (corresponding to 6.00” outer diameter). This additional 0.2” radial opening (5.92-5.5)/2 together with the ± 0.831” de-centering estimate means that we can tolerate ± 1.0” baffle decentering, which is consistent with the overall FCT straightness requirement of ± 1.0” cited in the final design document[7], or 0.7” (18 mm) radial.

3 Support Types

There are two FCT Support Types: Fixed and Guided[8].

[1] LIGO-M1800264, A+ Project Execution Plan

[2] LIGO-E2100080, A+ Project, Filter Cavity, Tube Supports Installation & Alignment Procedure

[3] LIGO-E2000177-v2, A+ Baffles for O4 CDR, pg. 22 of google doc

[4] section 4.1.3 of LIGO-T2000002-v2, A+ Filter Cavity Tube, Expansion Joints and Tube Supports: Conceptual Design and Requirements: This was an early estimate of the FCT lateral deviation due to tolerances which was incorrectly assumed to be entirely taken up by bellows shear deflection. In this scenario (since the guided supports should not apply a lateral load to balance against the bellows load), the bellows force would be counteracted by bending of the FCTs between the bellows and the fixed support.

[5] 14-July-2020 email thread “ID of FC baffles can be decreased”

[6] LIGO-D2000332, A+, SLiC, FC TUBE BAFFLE, CONE

[7] Section 5 of LIGO-T2000475-v1, A+ Filter Cavity Tube, Expansion Joints and Tube Supports: Final Design and Requirements

[8] LIGO-T2000475, A+ Filter Cavity Tube, Expansion Joints and Tube Supports: Final Design and Requirements

The purpose of the Fixed (F) Supports is to firmly hold the FCT in the proper position while resisting forces due to thermal expansion and atmospheric pressure (when a FCT section is under vacuum and an adjacent section is at atmospheric pressure).

The purpose of the Guided (G) Supports is to hold the FCT up while allowing the FCT to slide in axial direction due to thermal expansion/contraction. The Guided Supports also have restraints in the lateral direction so that in an earthquake the FCT is prevented from falling off of the supports. These restraints allow approximately ± ~1/4” (± ~6 mm) lateral motion and + ~1/4” (+ ~6 mm) vertical motion; These are not well controlled/dimensioned features on the drawing from the manufacturer so they may vary somewhat.

4 FCT Dimensional Tolerances

The FCTs have three controlled geometric tolerances[9] which are relevant to the accuracy of the alignment of the tube assembly:

- Tube straightness of .025”/ft per ASTM A778 (or 0.5” for the 20 ft long FCTs, D1900443-v9, type 01)
- Conflat flange-to-flange parallelism of .01” over 10”, or 1 mrad
- Conflat flange de-centering relative to the tube centerline axis of ± 1/16”

The perpendicularity of each of the two flanges relative to the tube centerline also affect assembly alignment accuracy, but this was not specified in the FCT drawing.

The manufacturer has reported quality assurance measurements[10] of Conflat flange-to-flange parallelism for the first 49 tubes delivered. The histogram of these measurements (expressed in mrad) appears to be roughly Gaussian (normally distribution) centered at 0.9 mrad with a standard deviation of ~0.1 mrad, but essentially clipped at the limit of 1 mrad, with only 3 tubes with slightly larger than 1 mrad parallelism, as shown in Figure 1.

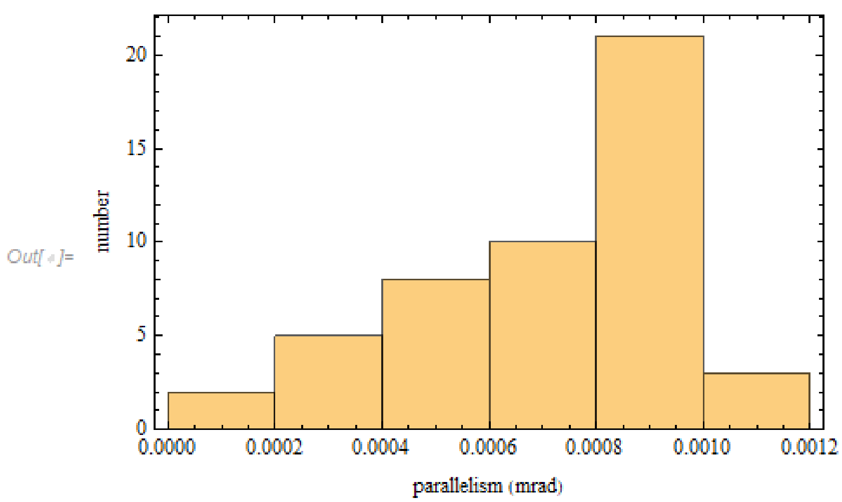


Figure 1 Histogram of FCT, Conflat Flange-to-Flange parallelism measurements

[9] LIGO-D1900443, A+ VE, FC Tube, 10in OD

[10] LIGO-Q2100001, QA Reports: A+ filter cavity beamline

A histogram of the parallelism (in radians) of the first seventeen 6-way Crosses delivered appears to be approximately Gaussian (normally distribution) centered at 0.8 mrad with a standard deviation of ~0.1 mrad, but clipped at the limit of 1 mrad, as shown in Figure 2.

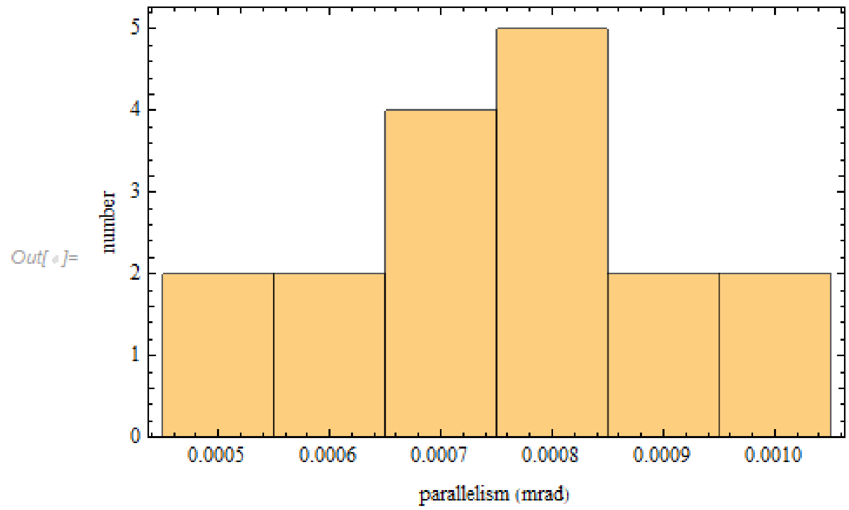


Figure 2 Histogram of 6-Way Cross, Conflat Flange-to-Flange parallelism measurements

5 Example FCT Structural Group

FCT Structural Groups are defined here as the FCT, and its supports, which span between Fixed Supports or Chambers (aka anchors). These anchors, to first order, isolate each group from one another structurally. Every Bellows or Gate Valve/Bellows pair is adjacent to an anchor. There are 8 different structural groups as depicted in LIGO-D1900456. The most prevalent, and longest, group is designated 3B in LIGO-T2000580, and is depicted in Figure 3. Structural Group 3B is used exclusively in this analysis to get estimates of the accuracy of various alignment strategies since it is the longest structural group type. This group consists of three, 20 ft long tubes, one 6-way cross, one fixed support, three guided supports and one bellows.

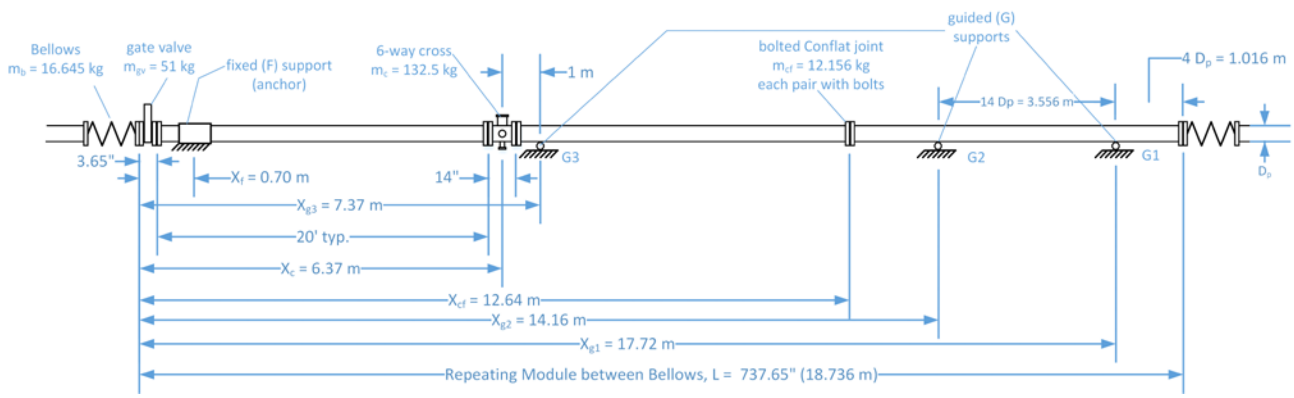


Figure 3 FCT Structural Group 3B

6 Random distributions of tolerances

6.1 Conflat flange parallelism and perpendicularity

The parallelism of the Conflat flanges is modeled as a normal distribution with a mean of 1 mrad, standard deviation of 0.3 mrad but truncated at 1 mrad, resulting in the histograms in Figure 3.

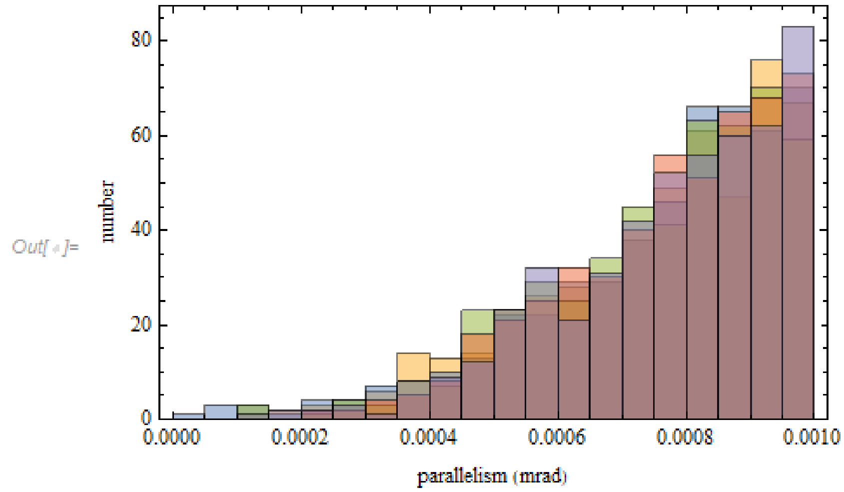


Figure 4 FCT Parallelism histogram used in the simulation

Five realizations depicted for the 5 components in the simulation: 1st tube, 6-way cross, 2nd tube, 3rd tube and 1st tube of the next structural group.

In order to account for the Conflat flanges not being perpendicular to the tube axis, the first flange angle is set to be uniformly sampled fraction from -1 to 1 of the parallelism instance and the angle of the second flange is set equal to the balance, i.e.

θ = RandomVariate[TruncatedDistribution[{θmin, θmax},NormalDistribution[θm, σ]], nTrials]

θ1 = Theta RandomVariate[UniformDistribution[{-1, 1}], nTrials]

θ2 = θ – θ1

where

θ = conflat flange parallelism (rad)

θmin = 0 rad

θmax = 0.001 rad

θm = 0.001 rad

σ = 0.0003 rad

nTrials = 100 (typically)

θ1 = perpendicularity of the 1st flange of a tube (rad)

θ2 = perpendicularity of the 2nd flange of a tube (rad)

The resulting histograms for θ1 and θ 2 is shown in Figure X. Note that since the individual flange perpendicularity is assumed to have the same ± range as the flange parallelism, the overall range is up to .002 mrad.

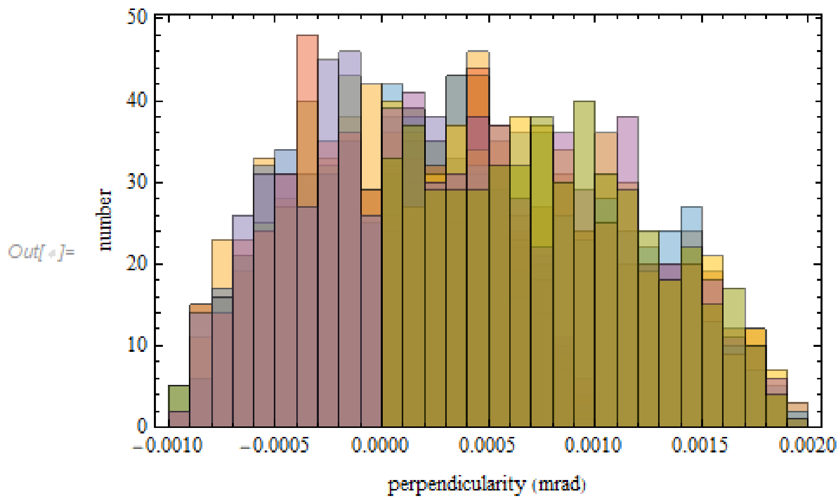
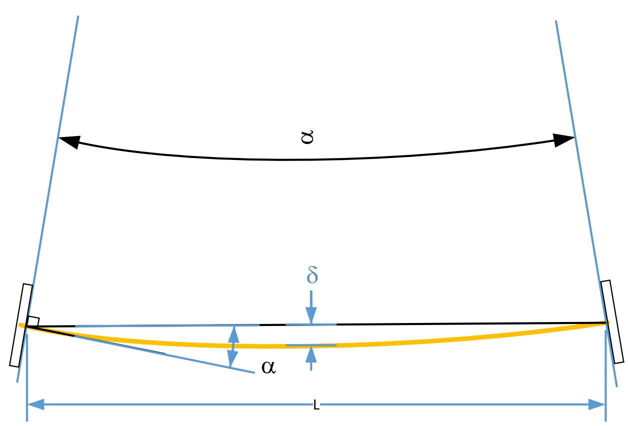


Figure 5 FCT Perpendicularity histogram used in the simulation
Five realizations depicted for the 5 components in the simulation: 1st tube, 6-way cross, 2nd tube, 3rd tube and 1st tube of the next structural group.

However note that since the perpendicularity of each flange relative to the tube centerline was not specified, we may have considerably larger perpendicularity deviations than this model predicts. In particular, if a conflat flange at one end of each tube were set to be locally perpendicular to the tube centerline at that end, and the conflat flange at the other end of the tube was set to be parallel to the first flange, then each flange could deviate from perpendicularity to the tube centerline by as much as 4 mrad, as shown in Figure X. This deviation is based on the allowable tube straightness, discussed in the next section.



Suppose the CF Flanges are perfectly square to the axis local to each end of the non-straight tube.
For h = 0.5", L = 240", α = 8.3 mrad ≈ angle due to the non-parallelism specification of the CF flanges relative to each other.

Figure 6 Relationship between flange parallelism, flange perpendicularity to the tube axis and tube non-straightness (curvature)

6.2 Tube straightness

The simplest, and most likely, form of non-straightness of a tube is a circular arc resulting in the specified maximum deviation from straightness (0.025" per ft, or 0.5" over a 20 ft tube length). This Monte Carlo analysis is based on a uniform distribution of non-straightness values from 0 to 0.5" (12.7 mm).

6.3 Clocking angles

The orientation of the geometric deviations azimuthally about the tube axis is represented by a rotation or clocking angle, as depicted in Figure 7. However note that the conflat flange de-centering tolerance was not included in this analysis since it is relatively small (± 1/16" per LIGO-D1900443).

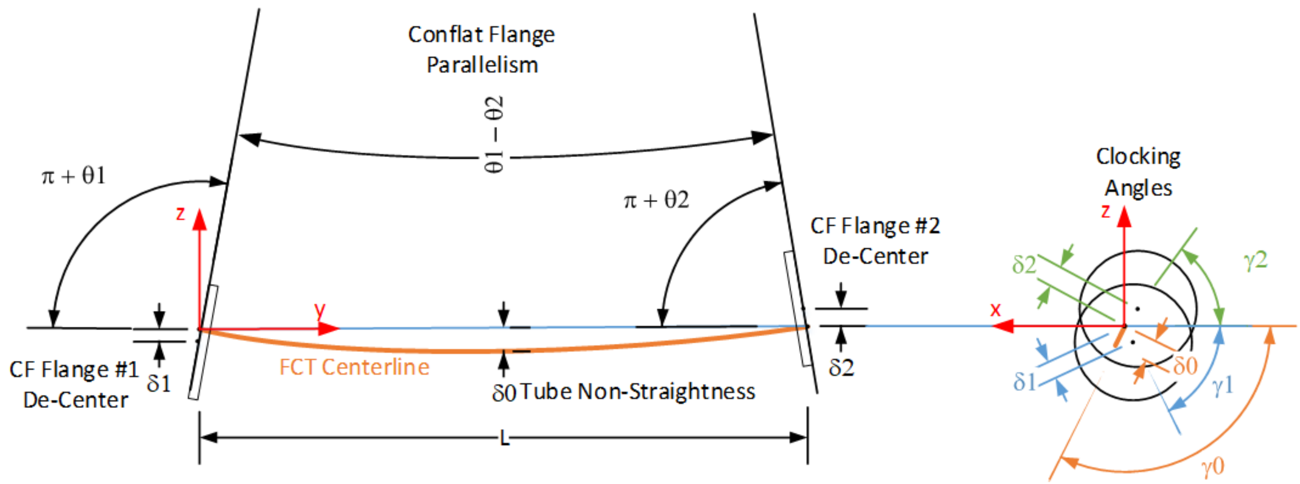


Figure 7 Clocking angles

7 Elastic deflections

In the alignment scenarios considered in the following section, only the tolerances mentioned in section 6 are included. The gravity induced elastic deflection[11] (with a fully loaded cross) for structural group 3B is less than 1 mm.

8 Alignment scenarios

In all of the following figures showing 3D curves of the tube centerlines, the axis parallel to the tube centerline is scaled by 1/100 in order to emphasize the transverse (horizontal and vertical) deviations from the ideal FC centerline.

[11] LIGO-T2000580, Conflat Flange Bolt Stress in the Filter Cavity Tube (FCT) as a function of Guided Support number and locations

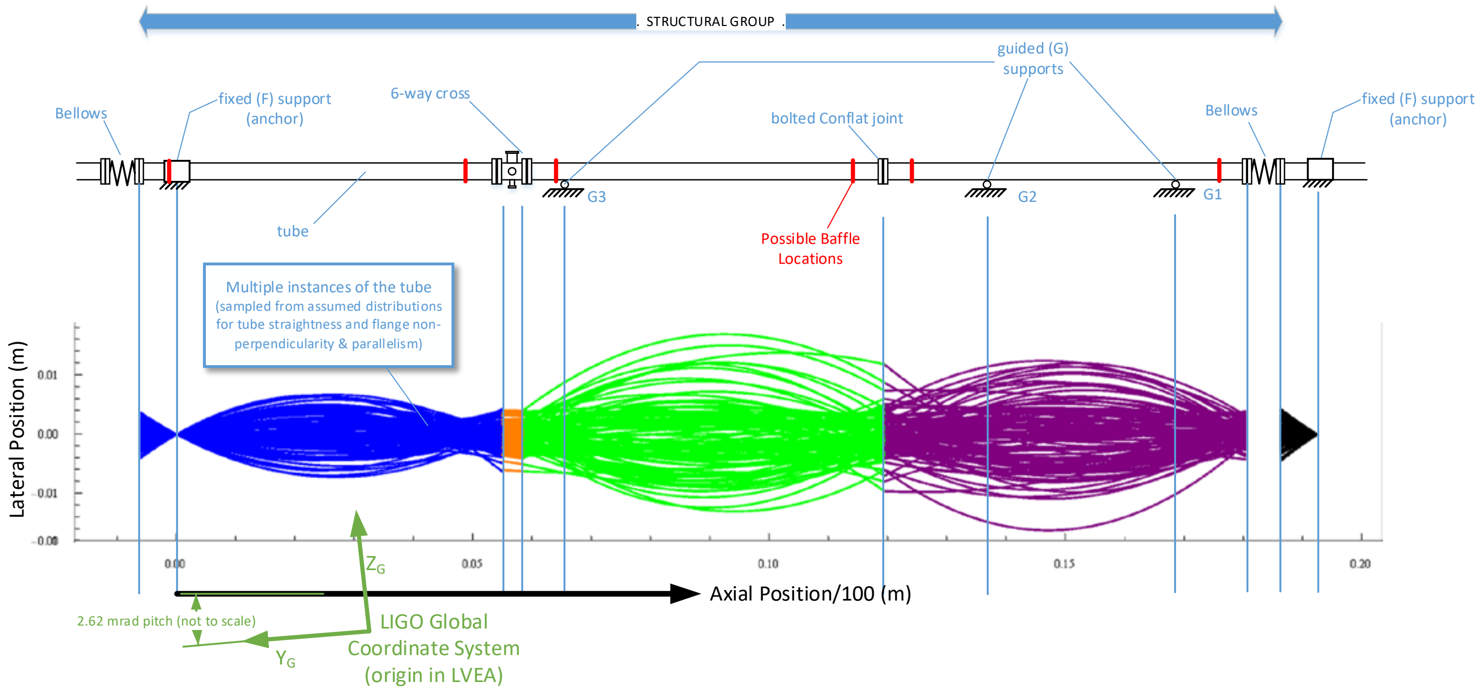


Figure 8 Three-Dimensional (3D) curve representation of random realizations of the FCT structural group 3B

8.1 Case 0: Straight tubes with maximum flange parallelism/perpendicularity clocked to point down

This is an unrealistic worst case scenario (with regard to flange parallelism) shown just for illustration, where all conflat flanges on the tubes and crosses are at the maximum allowed and are clocked (aligned rotationally) so that they all point in the same direction (down in this case). The tube deviation (positional error) at the right bellows is -62 mm.

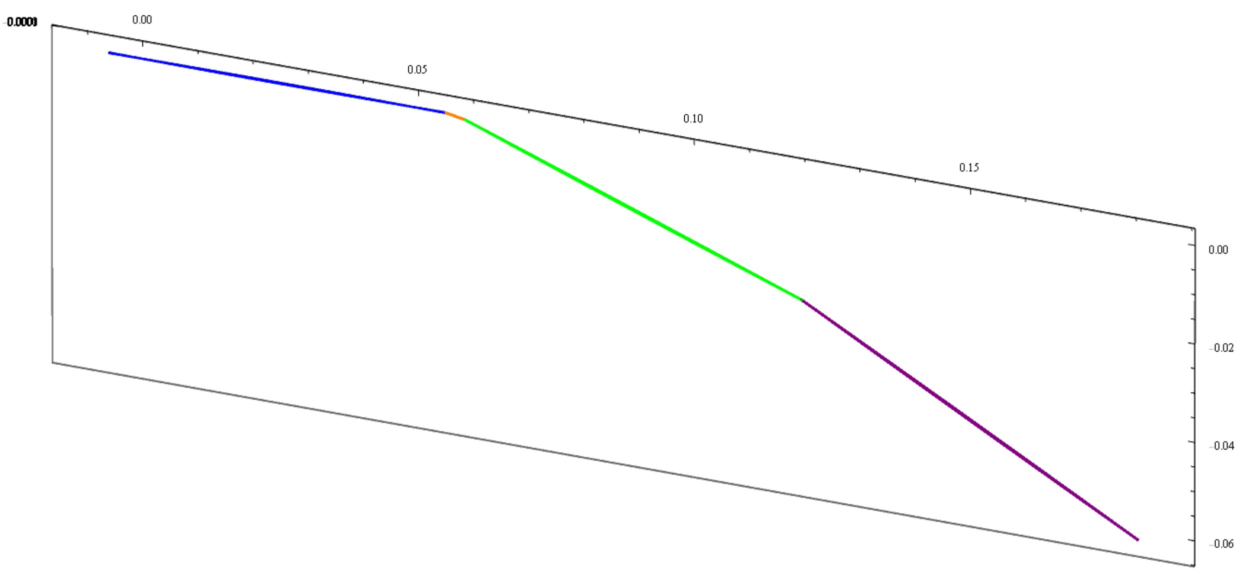


Figure 9 Case 0: Straight tubes with maximum flange parallelism/perpendicularity clocked to point down

8.2 Case 1: Straight tubes with flange parallelism/perpendicularity randomly clocked

Another scenario for illustration only. Based on 100 trials, pointing the 1st tube along the desired FCT centerline and randomly clocking subsequent components (6-way cross, 2nd tube, 3rd tube) would result in ± 27 mm lateral and vertical (28 mm radial) errors at the end of the 3rd tube (at its connection with a bellows) if the guided supports (G3, G2 and G1) apply no constraints, i.e. if the structural group floats free in space. Note that these errors in fact exceed the lateral and vertical gap sizes ('play') in the guided support shoes.

The lateral shear stiffness of the bellows is estimated[12] to be 587 lbf/in (103 kN/m). Consequently the lateral bellows force for this case would be up to 647 lbf (2.9 kN). This force would far exceed the frictional force on G1 and cause the difference in horizontal component (x) of the two ends of the bellows to approach zero.

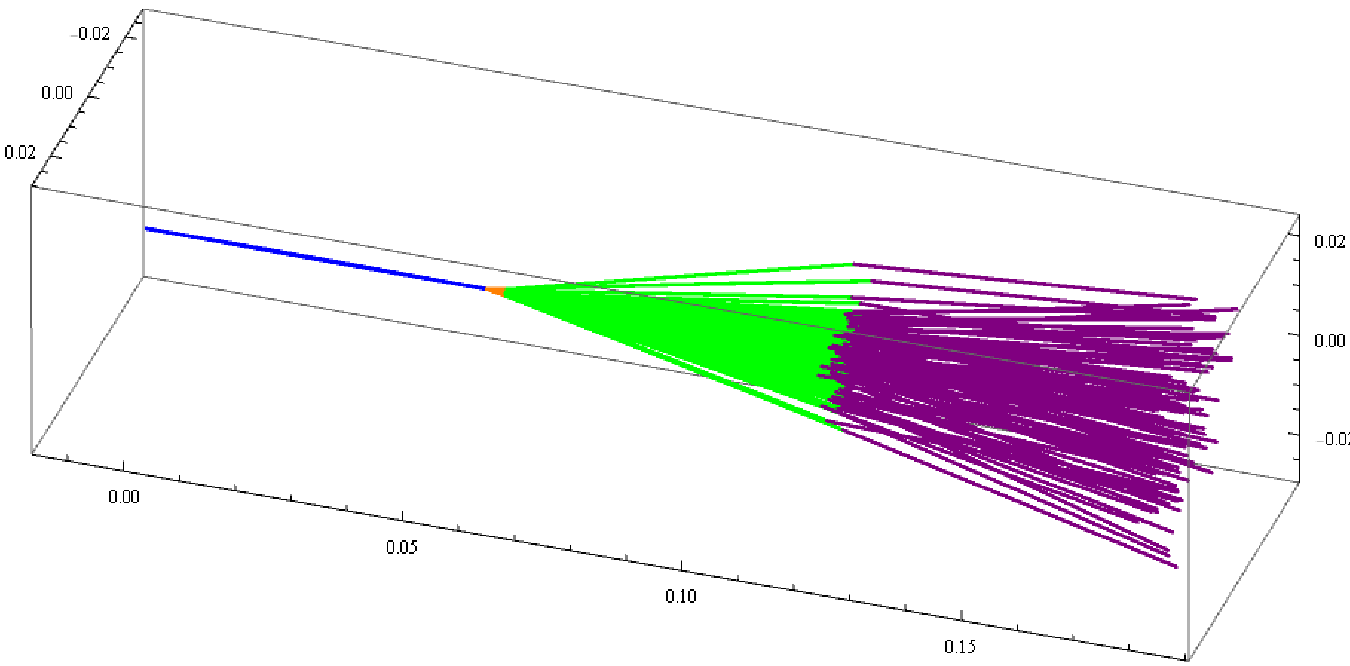


Figure 10 Case 1: Straight tubes with flange parallelism/perpendicularity randomly clocked

8.3 Case 2: Straight tubes with flange parallelism/perpendicularity randomly clocked, rotated to correct position at G1

Same as Case 1, but then rotate (pitch and yaw) the entire Structural Group about the Fixed Support position (F) in order to correct the deviation from the correct position at Guided Support G1. The maximum rigid body rotation in pitch and yaw is ~1.5 mrad.

Since F and G1 are close to the bellows the resulting apparent bellows shear is < 2.4 mm. The lateral bellows force would be < ~55 lbf (245 N). This force would likely exceed the frictional force on

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12 LIGO-T2000475-v1, section 6.2, A+ Filter Cavity Tube, Expansion Joints and Tube Supports: Final Design and Requirements

Guided Support 1 and cause the difference in horizontal component (x) of the two ends of the bellows to approach zero. This difference is less than the lateral play in the G1 guided support shoe.

The lateral position errors at G3 and G2 for these rotated assemblies are < 6 mm. These positional errors may exceed the size of the shoe lateral gaps. If so, G2 and G3 would need to be repositioned (up and/or left or right), i.e. let the guided support shoe follow the tube assembly.

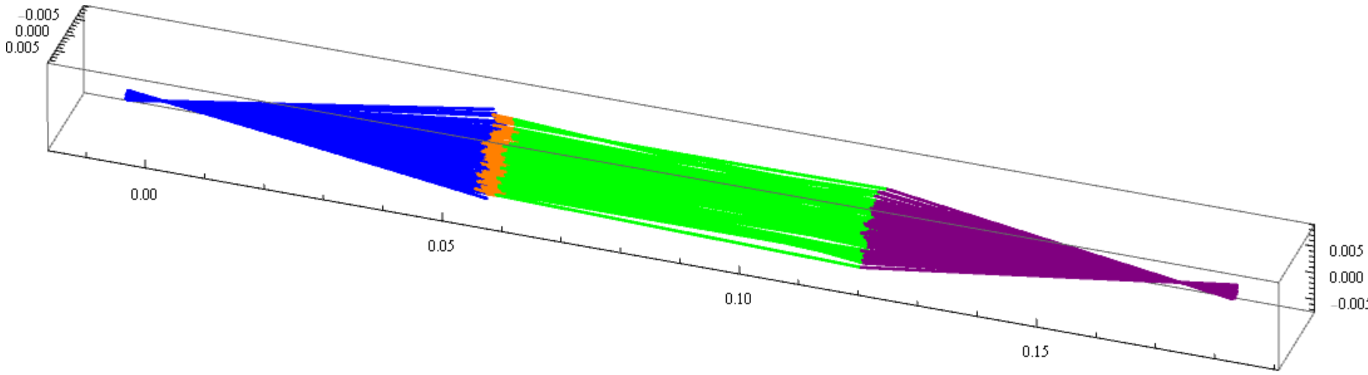


Figure 11 Case 2: Straight tubes with flange parallelism/perpendicularity randomly clocked, rotated to correct position at G1

8.4 Case 3: Non-Straight tubes with flange parallelism/perpendicularity and tube curvature randomly clocked

Same as Case 1, but with random sampling of tube curvature from the ASTM allowable non-straightness, and with the tube from the next structural group on the other side of the bellows represented as well. The maximum radial positioning error (for 100 random trials) of the structural group at the bellows is 29 mm, similar to Case 1 (as expected). The maximum radial positioning error of the other end of the bellows (from the next structural group) is 4.5 mm.

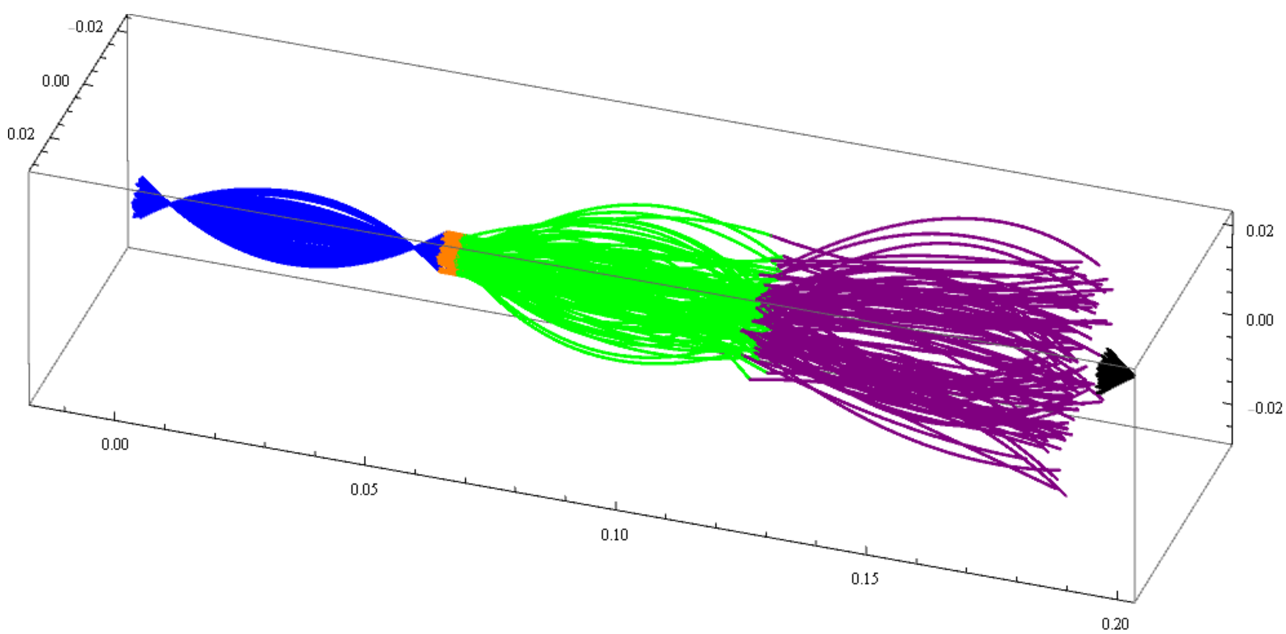
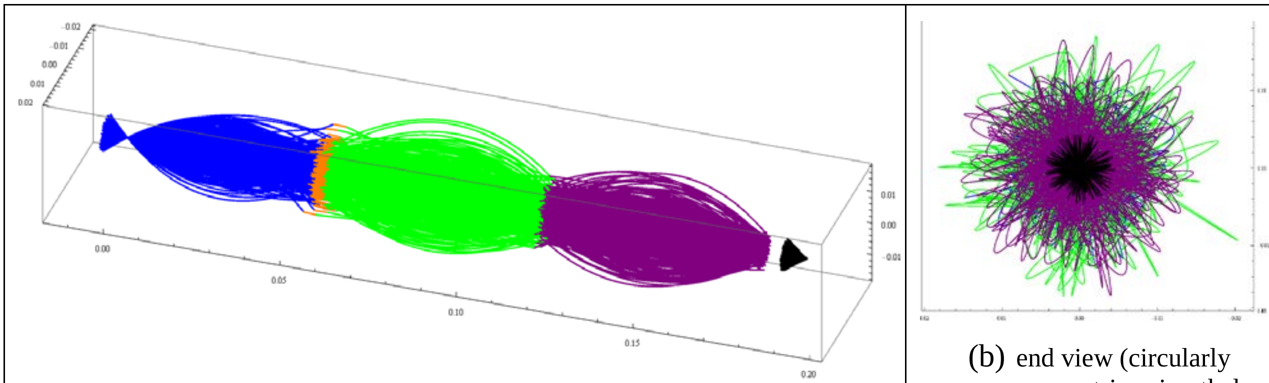


Figure 12 Case 3: Non-Straight tubes with flange parallelism/perpendicularity and tube curvature randomly clocked

8.5 Case 4: Non-Straight tubes with flange parallelism/perpendicularity and tube curvature randomly clocked, but rotated to zero bellows shear

Same as Case 3 but with the structural group rotated (as a rigid body) in pitch and yaw about the fixed support (F) in order to match the lateral position (horizontally and vertically) of the other end of the bellows (based on a random sampling of the first tube in the next structural group), i.e. to force the bellows shear to be zero[13].



(a) perspective view: The black lines on the far right represent the centerlines of the first FCT in the next structural group from the bellows to a fixed support. The gap between the purple lines and the black lines represent the bellows. Each of the 500 random instances of the structural group are rotated about the fixed support position to zero the bellows shear (i.e. match the X and Z coordinates of its mating bellows end from the next structural group)

(b) end view (circularly symmetric azimuthal errors)

Figure 13 Case 4: Non-Straight tubes with flange parallelism/perpendicularity and tube curvature randomly clocked, but rotated to zero bellows shear

The deviation (positional error) from the theoretical FC axis for the centerlines of the first tube of the next structural section (due solely to random sampling of the non-straightness of the tubes) is represented by the black centerlines in Figure 13. The maximum deviation is 4 mm (based on 500 random samples), as indicated in the histograms in Figure 14.

[13] *The bellows shear in the simulation is actually not zero, but the magnitude is < 1 mm. The reason has to do with performing the rotation transformation of each of the 3D space curves (which represent the tube centerlines) around the origin (left end of the first tube) and then translating to a common point representing the fixed support (F) position – rather than rotating about the fixed support (F) position. Attempts to properly rotate about the F position have so far resulting in separation of the ends of the pipes in sequence. The error is small since the origin and the location of F are close, so I've not pursued a correction further.*

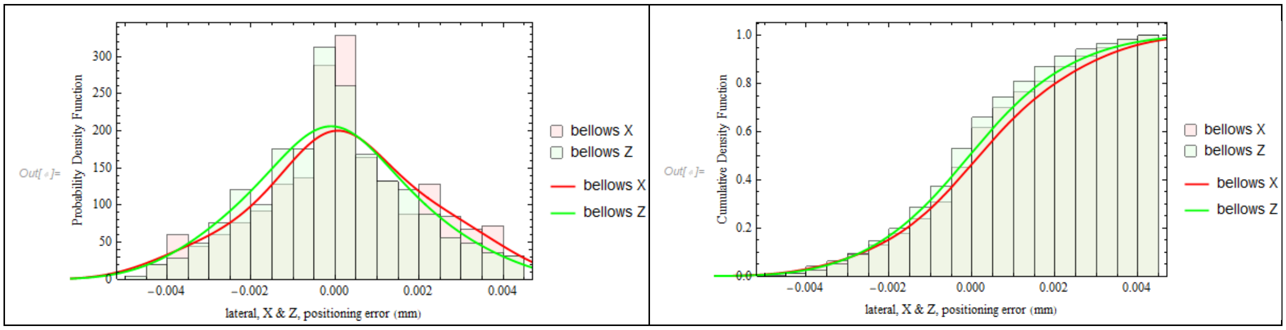


Figure 14 PDF and CDF histogram plots for the positional errors of the bellows end

The maximum magnitude of the pitch and yaw (of the structural group relative to the theoretical FCT axis) required to zero the bellows shear (based on the model described in section 6.1) is 2.2 mrad (based on 500 random samples), which is less than, but comparable to, the pitch (0.150 deg = 2.62 mrad) and yaw (0.1885 deg = 3.29 mrad) of the theoretical/ideal filter cavity axis (relative to the LIGO Global coordinate frame[14]). The histogram indicates that 80% of the time the pitch and yaw (relative to the theoretical FC axis) is 1 mrad or less.

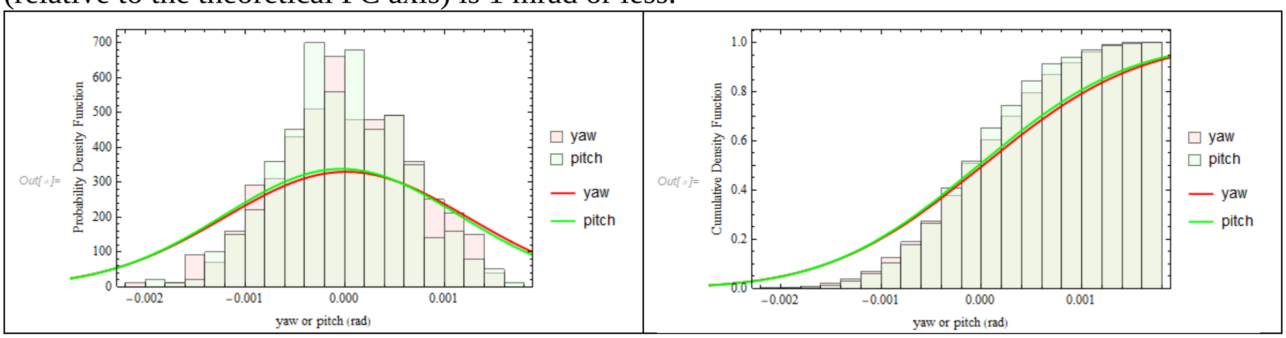


Figure 15 The Probability Density Function (PDF) and Cumulative Distribution Function (CDF) plots of the pitch and yaw angles (relative to the theoretical FC axis), based on 500 random samples

Of course what really matters at each support location is the local pitch and yaw slope which also depends upon the curvature of the tube due to non-straightness. The histograms of the local slope (pitch and yaw) relative to the theoretical FC centerline (including the overall corrective pitch and yaw imposed on the structural group to zero the bellows shear) are shown in Figure 16. In all cases the pitch and yaw are less than ~ 7 mrad (relative to the theoretical FC centerline), so the pitch and yaw relative to the LIGO global axes is less than ~10 mrad. In most cases (~80%) the total pitch and yaw at each support relative to the LIGO global axes is < ~7 mrad.

[14] LIGO-T980044, Determination of Global and Local Coordinate Axes for the LIGO Sites

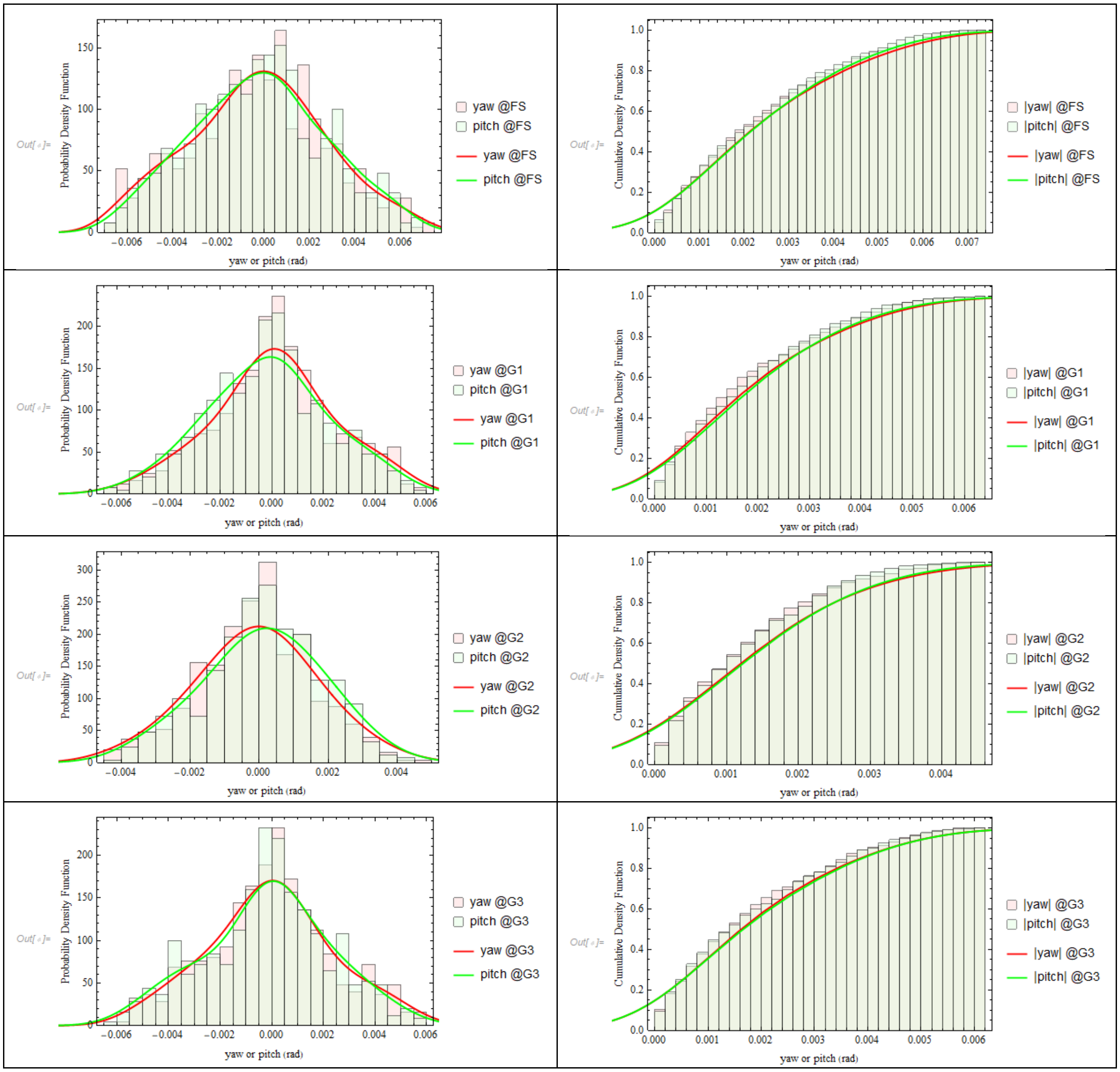


Figure 16 PDF and CDF plots of the local pitch and yaw at each support location (relative to the theoretical FC axis), based on 500 random samples

For perspective, note that the nominal pitch of the FC axis relative to local horizontal, 2.62 mrad, corresponds to just 0.03” over the 12” axial span of a support shoe (which is likely comparable to, or less than, the repeatability or dimensional tolerances of the piping support shoes).

If the supports do not impose any correction (force) to the FCT, then (based on 500 random trials), the maximum radial positioning errors at each of the three guided supports is 16 mm. The histogram of the lateral positioning errors at each of the three guided supports indicates that for 90% of the instances the lateral (horizontal or vertical) positioning error is < 7 mm, which is approximately equal to the gap size for the guided shoes. Consequently we can expect that ~90% of the time no correction to the guided pipe shoe position will be required.

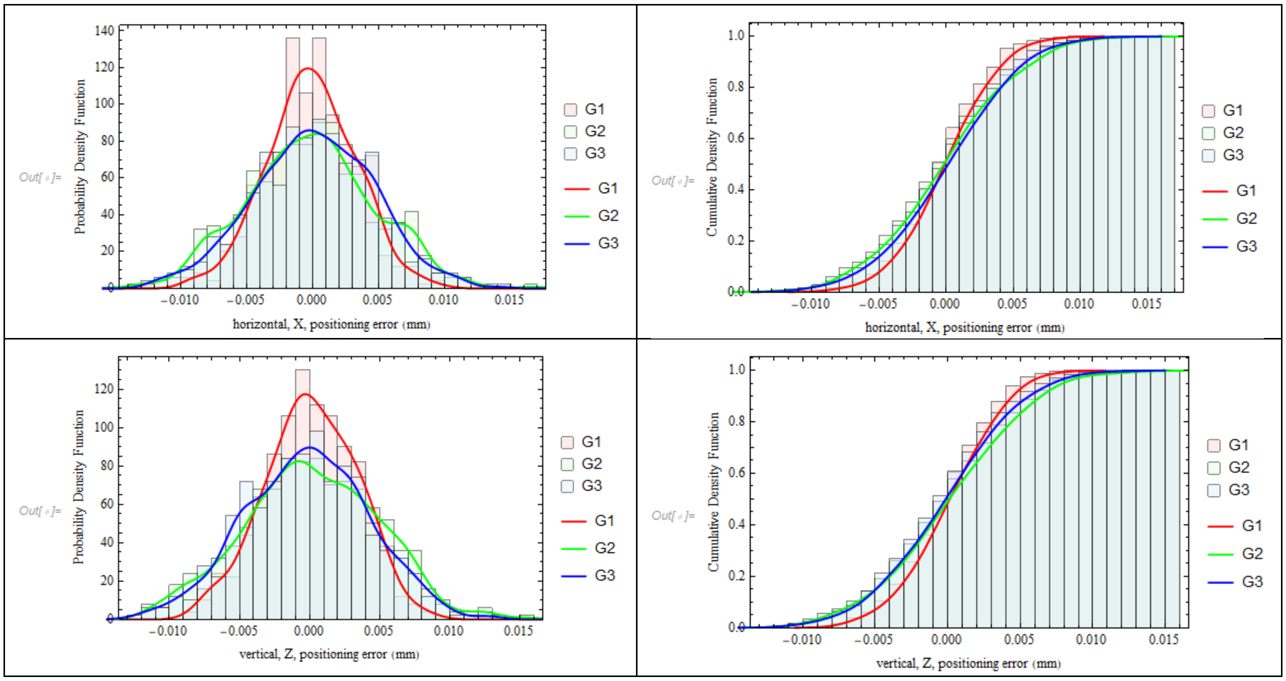


Figure 17 Case 4: PDF and CDF plots of the horizontal and vertical positioning errors at the locations of the Guided Supports (G1, G2 and G3), based on 500 random samples

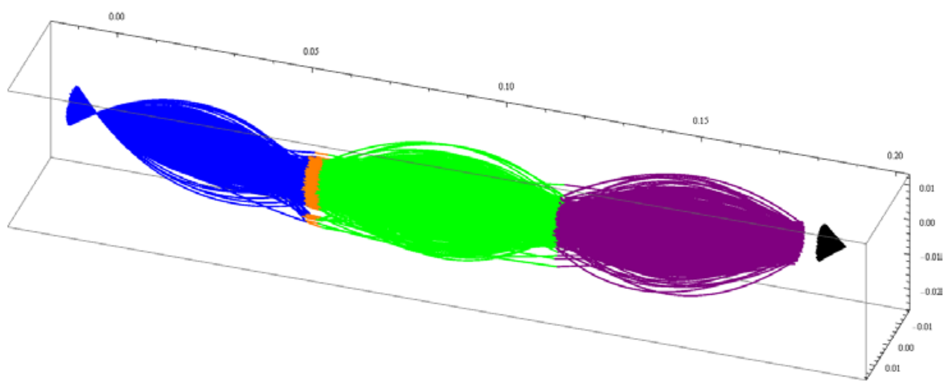
8.6 Case 5: Non-Straight tubes with tube curvature randomly clocked, flange parallelism/perpendicularity clocked to reduce yaw error, and the structural group rotated to zero bellows shear

For the previous case (case 4), the lateral deviations (horizontal and vertical) from the filter cavity axis, along the length of the structural group, are azimuthally symmetric, as indicated in Figure 13.b. It would be better if we could "squeeze" these deviations into the –Z region where the guided supports can apply an upward force to correct or counter these deviations. The following algorithm is intended to "squeeze" horizontal deviations into the vertical plane and preferentially downward:

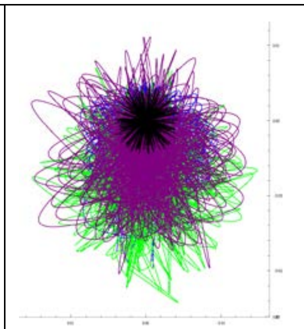
1) For the first tube (proceeding left to right in the -Y direction), compare the two flange perpendicularity angles. Place the flange with the largest non-perpendicularity at the right (-Y) end clocked to point up (zero yaw).
2) The second element in the structural group in the 6-way cross. The cross must be kept upright and cannot be clocked. Compare the two flange perpendicularity angles and place the flange with the largest non-perpendicularity at the right (-Y) end. The other flange perpendicularity (and parallelism) is randomly clocked.
3) Compare the two flange perpendicularity angles for the next tube (3rd element, proceeding left to right in the -Y direction). Place the larger one at the right (-Y) end (proceeding from the FS toward the bellows) clocked to point up. The other flange perpendicularity (and parallelism) is randomly clocked.
4) Compare the two flange perpendicularity angles for the next tube (4th element, proceeding left to right in the -Y direction). Place the larger one at the right (-Y) end (proceeding from the FS toward the bellows) clocked to point up. The other flange perpendicularity (and parallelism) is randomly clocked.

N.B.: We do not have perpendicularity measurements from the manufacturer, only parallelism measurements. This algorithm would require more information/measurements.

The result of this algorithm (for 500 random realizations) is shown in Figure 18. The horizontal deviations are somewhat less and the vertical deviations are biased downward.



(a) perspective view: The black lines on the far right represent the centerlines of the first FCT in the next structural group from the bellows to a fixed support. The gap between the purple lines and the black lines represent the bellows. Each of the 500 random instances of the structural group are rotated about the fixed support position to zero the bellows shear (i.e. match the X and Z coordinates of its mating bellows end from the next structural group)



(b) end view: deviations from FC axis are "squeezed" a little from yaw into pitch and biased downward (to be compensated by upward forces applied by the guided supports)

Figure 18 Case 5: Non-Straight tubes with tube curvature randomly clocked, flange parallelism/perpendicularity clocked to reduce yaw error, and the structural group rotated to zero bellows

Comparing the histograms of the lateral positioning errors at each of the three guided supports for this case against the previous case indicates a reduction of the horizontal deviation spread by only ± ~2 mm. The vertical positioning errors are clearly shifted to the negative region and would be corrected by the guided supports.

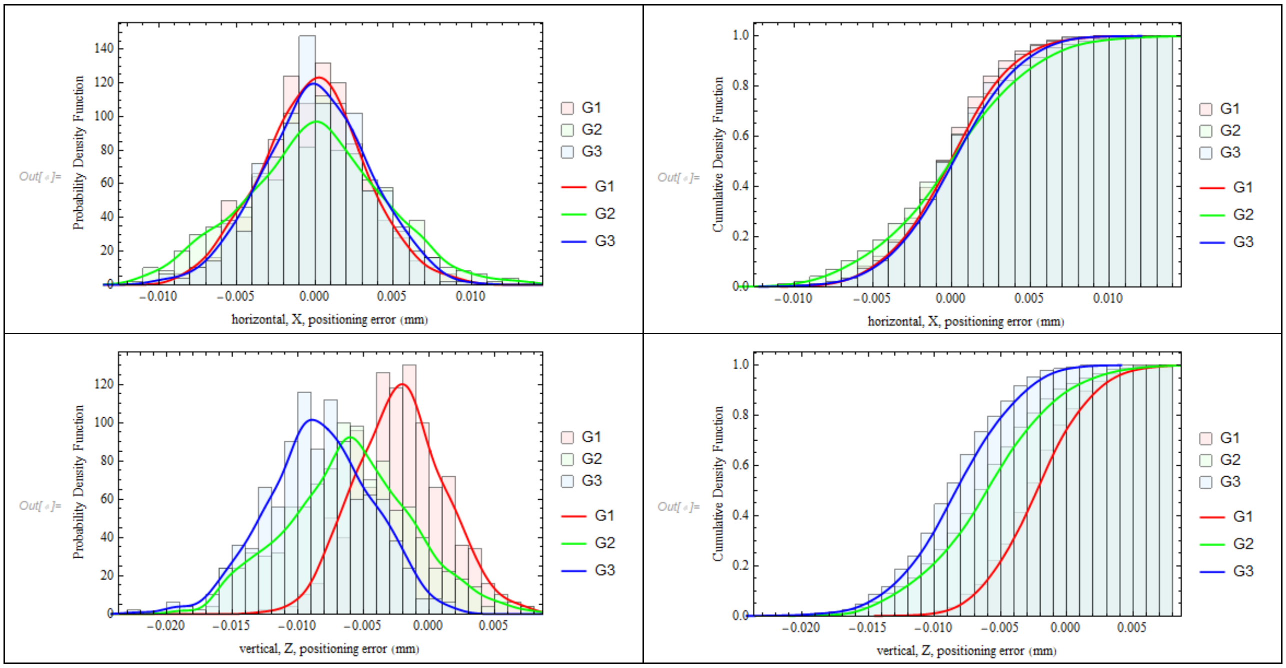
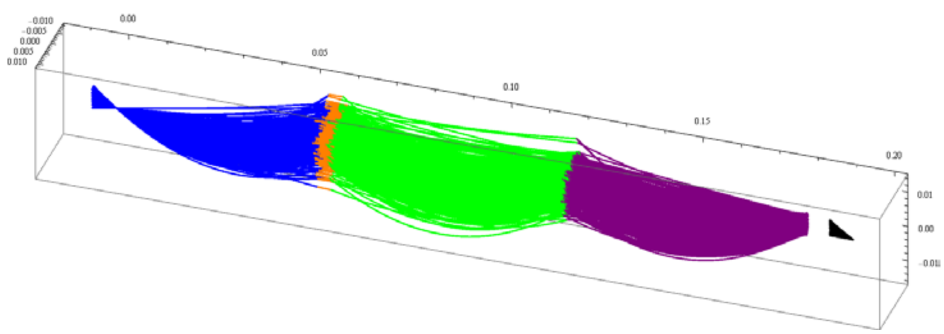


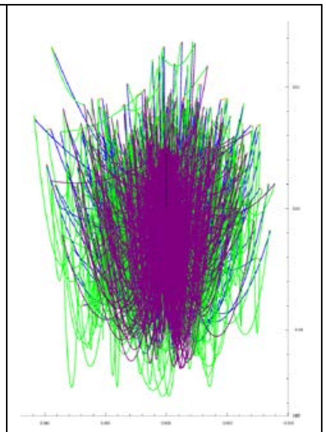
Figure 19 Case 5: PDF and CDF plots of the horizontal and vertical positioning errors at the locations of the Guided Supports (G1, G2 and G3), based on 500 random samples

8.7 Case 6: Non-Straight tubes with tube curvature clocked down, flange parallelism/perpendicularity randomly clocked, and the structural group rotated to zero bellows shear

This is another attempt to "squeeze" the horizontal deviations of the FCT centerline (from the FC axis) into the –Z region, where the guided supports can apply an upward force to correct or counter these deviations. The algorithm is simply to clock (rotate) the tube so that the non-straightness deviation is downward in the vertical plane. Note that the orientation of the tube's non-straightness is not a QA measure that is provided by the manufacturer. In order to accomplish this alignment approach the orientation of the non-straightness would need to be determined first. Determining the approximate orientation (clocking angle) of a ~0.5" non-straightness over a 20 ft. long pipe by eye shouldn't be too difficult. Determining the orientation of small non-straightness errors (less than say ~0.1") would be difficult, but not as important either.



(a) perspective view: The black lines on the far right represent the centerlines of the first FCT in the next structural group from the bellows to a fixed support. The gap between the purple lines and the black lines represent the bellows. Each of the 500 random instances of the structural group are rotated about the fixed support position to zero the bellows shear (i.e. match the X and Z coordinates of its mating bellows end from the next structural group)



(b) end view: deviations from FC axis are "squeezed" a little from yaw into pitch and biased downward

Figure 20 Case 6: Non-Straight tubes with tube curvature clocked down, flange parallelism/perpendicularity randomly clocked, and the structural group rotated to zero bellows shear

The histogram of the lateral positioning errors at each of the three guided supports indicates that for ~97% of the instances the lateral (horizontal or vertical) positioning error is < 7 mm, which is approximately equal to the gap size for the guided shoes. Consequently we can expect that ~97% of the time no correction to the guided pipe shoe will be required.

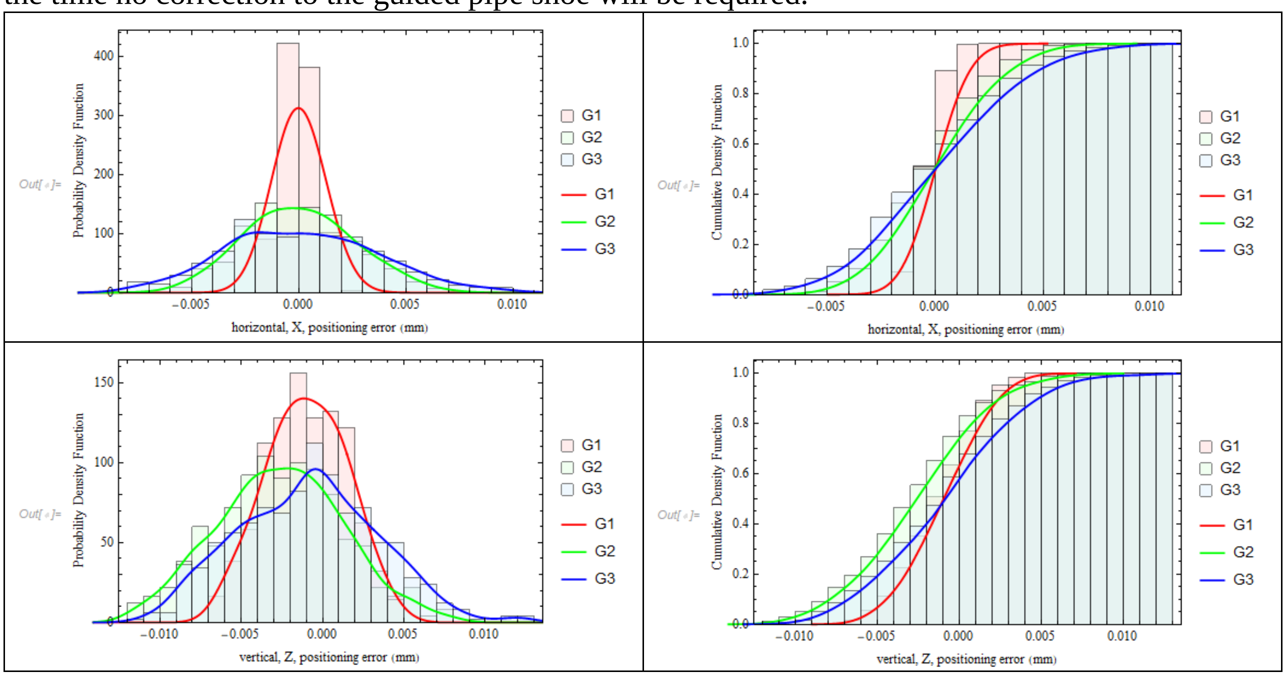


Figure 21 Case 6: PDF and CDF plots of the horizontal and vertical positioning errors at the locations of the Guided Supports (G1, G2 and G3), based on 500 random samples

9 Recommended alignment approach

The following is a brief description of a recommended alignment approach informed by the Monte Carlo simulations reported above. The alignment procedure will detail all the steps. Each structural group is to be aligned on its own and isolated from the influence of the next group (proceeding +Y) by clamping at the Fixed Support.

1) Set the positions (X and Z) of each support appropriate for their Y location by surveying the center of the alignment fixture (LIGO-D2100130); see the tables in the alignment procedure[15].
2) Mark the lateral and vertical locations of the pipe shoes on each support as a reference to the ideal (surveyed) locations.
3) Choose a set of FCT components for the structural group. No need to pick specific serial numbers, or to match components based on their measured deviations.
4) Find the orientation (clocking angle) for the maximum non-straightness deviation by eye, and mark this on one of the flanges.
5) Assemble the structural group from its component parts atop the supports for the structural group. Orient the maximum non-straightness deviation downward. Bolt the structural group to the –Y side bellows (but not yet the +Y side bellows).
6) Shim the pitch of the Fixed Support to match the tube pitch angle and allow the shoe to rotate to match the tube's yaw angle. Clamp the Fixed Support to the tube.
7) Check to see if the FCT has forced any of the Guided Supports to be pegged up against their stops (vertical or horizontal). If so (or if the Guided Support Pipe Shoes are not well centered within their stops), then loosen the base plates for all Guided Supports and let the Guided Support Pipe Shoes move with the unconstrained FCT.
8) Loosen the Base Plate for each Guided Support Pipe Shoe that is against its lateral stops and shift the base plate until it is centered on the FCT. Measure the lateral (X) shift in position relative to the ideal alignment mark created in Step 2). As long as this shift is less than 0.7" (18 mm), there is no problem.
9) If a Guided Support Pipe Shoe is against it's vertical stop, then raise (+Z) the Pipe Shoe until the Pipe Shoe is firmly against its Base Plate. Measure the vertical (Z) shift it position relative to the ideal alignment mark created in Step 2). As long as this shift is less than 0.7" (18 mm) there is no problem.
10) Shim and rotate the Guided Support Pipe Shoes to match the FCT pitch angle and yaw angle respectively. Clamp down the Guided Support, Pipe Shoe, Base plates.
11) Proceed to the next +Y structural group.

In the unlikely event that the lateral or vertical deviation from the ideal (surveyed) position at any Guided Support exceeds 0.7" (18 mm), then a different set of components may be chosen for this structural group, or a different set of clocking angles may be chosen to mitigate the deviation from the filter cavity axis.

[15] LIGO-E2100080, A+ Project, Filter Cavity, Tube Supports Installation & Alignment Procedure