LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Design Notes for Production Blades for HAM Suspensions

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v3 includes the FEA results for the HSTS highly curved blades which Mike Meyer has produced, and shows the rev number for each drawing. Also for HLTS lower blade, revised alpha factor info used, as referenced in text.

v4 has update to HLTS lower blade with compromise design between that produced using the blade equations in EXCEL spreadsheet and that produced using FEA in ANSYS. See 5.2.

1 Introduction

The purpose of this document is to capture the design information, with references, for the production blades for the OMC-SUS, HSTS and HLTS. These notes will be used for producing the drawings for procurement.

2 Summary of equations used

Justin Greenhalgh (RAL) has written up several documents, see T030285, T040116, T040155, G040059, which capture the relevant equations, and these include reference to previous work in GEO by Calum Torrie and Mike Plissi, see for example T030107, and to the Virgo work. A brief summary of the key equations is given here, taken from page 11 of G040059.

Parameter	Equation	Significance
Deflection	$\lambda = \alpha \frac{4m_t g l^3}{Eah^3}$	Engineering
Uncoupled frequency	$f = \frac{1}{2\pi}\sqrt{\frac{Eah^3}{4ml^3\alpha}}$	Science
Stress	$\sigma = \frac{6Pl}{ah^2}$	Engineering
Lowest internal mode	$f_i \propto \frac{h}{l^2}$	Science

The relevant parameters are;

blade dimensions: length (not including clamp region) = l, width at wide end = a, thickness = h

E = Young's modulus of blade material, m_t = total mass supported by blade, P = $m_t g$

α is known as the shape factor. This is 1 for a rectangular blade and 1.5 for a triangular blade. Our blades are not simple triangles to allow for attachment at the tip. We have found the appropriate value of α from experience with getting prototype blades made and finding their deflection and also from comparison to FEA of blades. We have found values ranging from ~1.3 to ~1.55 depending on the size and shape. In fact as Justin pointed out it is a combination of α/E which we have really been fitting. For example for the quad blades, work at RAL established that α = 1.36 with E = 186 GPa fitted the data from their prototype blades. For smaller HSTS (formerly IMC) prototype blades the upper ones fitted better to 1.32 and lower ones to 1.54 with the same value of E.

Our blades are made curved so that they flatten with load. For making drawings of blades we need their dimensions, the deflection, λ, and the radius of curvature, R. The latter is found using the relationship between λ and R

$$\lambda = R\left(1 - \cos\left(\frac{l}{R}\right)\right) \qquad (1)$$

Calum Torrie has written an EXCEL spreadsheet which can be adapted to any suspension and takes all the relevant input information to find λ and R, as well as stress and first internal mode frequency. These spreadsheets have been used for designing the blades discussed below and references are given in the relevant sections.

SUS were asked to increase isolation for the HLTS and HSTS. To do this, we proposed blades thinner and more highly stressed than earlier designs. See T080267. We have prototyped highly curved HSTS lower blades, and the results were acceptable, so that use of such blades has been approved, see RODA M1000116-v1. These blades were so highly curved that equation (1) above cannot be applied, since the blade curves more than ¼ of a circle. To design those prototype blades (D080019) we used FEA (see T1000262-v1) to find the shape, i.e. curvature and deflection, which flattened when loaded with the appropriate load. Such analysis is also required for the HSTS upper blades. An approximate value for the radius of curvature can be found using the beam bending relationship

$$R = EI/M \qquad (2)$$

(see for example T040115) where I = second moment of area and M = bending moment. For a triangular blade $I = ah^3/12$ at the root where $M = Pl$, and the radius is constant along the blade since M and I vary in the same way along the blade.

3 OMC-SUS Blades

The relevant EXCEL spreadsheet is T0900365-v2. The data needed for drawings are as follows.

3.1 Upper blades D080018-v1 (new revision)

length 250.0 mm, width 39.878 mm, thickness 1.5 mm

radius of curvature 160.4 mm, centre to centre height 158.4 mm

The notes for adding to the drawing as internal notes are as follows:

2.1 EXCEL SPREADSHEET REF T0900365-v2

2.2 SHAPE FACTOR FOR UPPER BLADE = 1.32 AND YOUNGS

MODULUS USED IS 1.86e11 Pa.

2.3 LOAD ON UPPER BLADE (FLAT) = 4.90 KG AND UNCOUPLED

LOAD = 1.40 KG.

2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.34 Hz

2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 90 Hz

2.6 MAXIMUM STRESS = 804 MPa

2.7 MID TO MID DEFLECTION = 158.4 mm

2.8 LENGTH IS 250 mm (270 mm INCLUDING CLAMPING LENGTH), THICKNESS is 1.5 mm AND WIDTH IS 39.78mm.

2.9 RADIUS IS 160.4mm CALCULATED USING BLADE EQUATIONS

2.10 IN THE CURVED SKETCH IN SW PART ADD MID TO MID DEFLECTION AND ADJUST RADIUS UNTIL ATTAIN DESIRED LENGTH.

2.11 IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED VERTICALLY DOWNWARDS

2.12 ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.

3.2 Lower blades D080019-v1 (new revision)

length 120.0 mm, width 18.0 mm, thickness 1.0 mm

radius of curvature 121.5 mm, centre to centre height 54.6 mm

The notes for adding to the drawing as internal notes are as follows:

2.1 EXCEL SPREADSHEET REF T0900365-v2

2.2 SHAPE FACTOR FOR LOWER BLADE = 1.54 AND YOUNGS MODULUS USED IS 1.86e11 Pa.

2.3 LOAD ON LOWER BLADE (FLAT) = 1.75 KG AND UNCOUPLED LOAD = 1.75 KG.

2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.13 Hz

2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 261 Hz

2.6 MAXIMUM STRESS = 687 MPa

2.7 MID TO MID DEFLECTION = 54.6 mm

2.8 LENGTH IS 120mm (130mm INCLUDING CLAMPING LENGTH), THICKNESS is 1mm AND WIDTH IS 18mm.

2.9 RADIUS IS 121.5 mm CALCULATED USING BLADE EQUATIONS

2.10 IN THE CURVED SKETCH IN SW PART ADD MID TO MID DEFLECTION AND ADJUST RADIUS UNTIL ATTAIN DESIRED LENGTH.

2.11 IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED

VERTICALLY DOWNWARDS

2.12 ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE

MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.

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4 HSTS Blades

The relevant EXCEL spreadsheet is T1000352-v2

4.1 Upper blades: New drawing needed since highly curved (early prototype was D020205, not highly curved.)

New drawing is D1001812-v1

length 250.0 mm, width 39.878 mm, thickness 1.3 mm

The EXCEL spreadsheet cannot be used to find the deflection and radius since the curvature is larger than ¼ of a circle. FEA is required.

The total mass load to be used for flattening blade in the FEA is 4.483 kg = 43.98 N.

We can extract some data from the spreadsheet and this is given below for the internal notes.

2.1 EXCEL SPREADSHEET REF T1000352-v1

2.2 SHAPE FACTOR FOR UPPER BLADE = 1.32 AND YOUNGS

MODULUS USED IS 1.86e11 Pa.

2.3 LOAD ON UPPER BLADE (FLAT) = 4.483 KG AND UNCOUPLED

LOAD = 1.564 KG.

2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 1.79 Hz

2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 78 Hz

2.6 MAXIMUM STRESS = 979 MPa

2.7 MID TO MID DEFLECTION = 223 mm FROM THE EXCEL

SPREADSHEET. NOT VALID FOR EXTREME CURVATURE

2.8 MID TO MID DEFLECTION (MEASURED TOP TO TOP) FROM FEA is 176.4

FOR RADIUS OF CURVATURE 126.0 mm

2.9 LENGTH IS 250mm (270mm INCLUDING CLAMPING LENGTH),

THICKNESS IS 1.3mm AND WIDTH IS 39.878mm.

2.10 RADIUS IS 126.0 mm DETERMINED BY FEA

Compare to R = EI/M = 120 mm

2.11 IN THE CURVED SKETCH IN SW PART ADD MID TO MID

DEFLECTION AND ADJUST RADIUS UNTIL ATTAIN DESIRED LENGTH.

2.12 IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED

VERTICALLY DOWNWARDS

2.13 ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE

MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.

4.2 Lower Blades: D080761 (needs new revision) – new revision is v3

length 120.0 mm, width 18.0 mm, thickness 0.76 mm

The EXCEL spreadsheet cannot be used to find the deflection and radius since the curvature is larger than ¼ of a circle. FEA is required. This was done for prototypes by Calum Torrie – see T1000262-v1. The analysis needs revised for slightly changed masses for production.

The total mass load to be used for flattening blade in the revised FEA is 1.4595 kg = 14.32 N.

We can extract some data from the spreadsheet and this is given below for the internal notes.

2.1 EXCEL SPREADSHEET REF T1000352-v2

2.2 SHAPE FACTOR FOR LOWER BLADE = 1.54 AND YOUNGS

MODULUS USED IS 1.86e11 Pa.

2.3 LOAD ON LOWER BLADE (FLAT) = 1.4595 KG AND UNCOUPLED

LOAD = 0.7422 KG.

2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.17 Hz

2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 199 Hz

2.6 MAXIMUM STRESS = 992 MPa

2.7 MID TO MID DEFLECTION = 103.7 mm FROM THE EXCEL

SPREADSHEET. NOT VALID FOR EXTREME CURVATURE

2.8 MID TO MID DEFLECTION (MEASURED TOP TO TOP) FROM FEA is 77.9 mm

FOR RADIUS OF CURVATURE 73.4 mm

2.9 LENGTH IS 120mm (130mm INCLUDING CLAMPING LENGTH),

THICKNESS IS 0.76mm AND WIDTH IS 18mm.

2.10 RADIUS IS 73.4 mm DETERMINED BY FEA

Compare to R = EI/M = 71.3 mm

2.11 IN THE CURVED SKETCH IN SW PART ADD MID TO MID

DEFLECTION AND ADJUST RADIUS UNTIL ATTAIN DESIRED LENGTH.

2.12 IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED VERTICALLY DOWNWARDS
2.13 ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.

5 HLTS Blades

The relevant EXCEL spreadsheet is T1000353-v1

5.1 Upper Blades: D020617 (needs new revision) - new revision D020617-v2

length 250.0 mm, width 65.0 mm, thickness 2.05 mm
radius of curvature 182.8 mm, centre to centre height 145.9 mm

The notes for adding to the drawing as internal notes are as follows:

2.1 EXCEL SPREADSHEET REF T1000353-v1
2.2 SHAPE FACTOR FOR UPPER BLADE = 1.36 AND YOUNGS MODULUS USED IS 1.86e11 Pa.
2.3 LOAD ON UPPER BLADE (FLAT) = 18.225 KG AND UNCOUPLED LOAD = 6.05 KG.
2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.27 Hz
2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 123 Hz
2.6 MAXIMUM STRESS = 982 MPa
2.7 MID TO MID DEFLECTION = 145.9 mm
2.8 LENGTH IS 250 mm (275 mm INCLUDING CLAMPING LENGTH), THICKNESS is 2.05 mm AND WIDTH IS 65 mm.
2.9 RADIUS IS 182.8mm CALCULATED USING BLADE EQUATIONS
2.10 IN THE CURVED SKETCH IN SW PART ADD MID TO MID DEFLECTION AND ADJUST RADIUS UNTIL ATTAIN DESIRED LENGTH.
2.11 IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED VERTICALLY DOWNWARDS
2.12 ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.

5.2 Lower Blades D020615 – new revision is D020615-v3

length 120.0 mm, width 32.0 mm, thickness 1.17 mm

Radius of curvature 107.8 mm and centre to centre height 59.9 mm

We had several vendors prototype this length and width blade, but the blade was thicker than the above production number since the prototyping preceded the request to improve isolation. The prototyping was done assuming an alpha value of 1.55, essentially the same as for a small triple lower blade. From the data, we found all the blades ended up not flattening completely (positive residual). This information can be used to deduce that a better fit to the behaviour of this shape of blade is to use an alpha factor of 1.48. See T1000265-v4 and T1000471-v1. This value has been used in the EXCEL spreadsheet calculations for this blade, giving centre to centre height 64.1 mm and radius of curvature 99.3 mm

However Mike Meyer also carried out an ANSYS FEA model for this blade, using clamping at "Holes and Edges" (reference to be added in here). This clamping has been shown to match well on comparing measurements of other blades to ANSYS modeling. It was found that using the EXCEL radius of curvature in the FEA model, that when loaded, the blade did not lie flat but the tip was found to be 6mm above flat. This is a larger discrepancy than we have seen for other blades between the EXCEL equations and ANSYS modeling. We need to bear in mind that we are using an alpha value deduced from results on a thicker blade which may not carry over well to thinner blades. We note 6 mm would be a large value to compensate for with angled blade clamps (0.5 degrees gives 1 mm). The ANSYS modeling which gives an approximately flat blade when loaded is for centre to centre height 59.9 mm and radius of curvature 107.8 mm. We have no way (without prototyping) to resolve which design will correspond more closely to what happens in reality. Thus we decided to compromise on the design of this blade by choosing a radius of curvature and corresponding centre to centre height between the values for which the EXCEL equations and the ANSYS FEA give a flat loaded blade. See notes below fro full details.

The notes for adding to the drawing as internal notes are as follows:

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1. EXCEL SPREADSHEET REF T1000353-v3
2. SHAPE FACTOR FOR LOWER BLADE = 1.48 AND YOUNGS MODULUS USED
IS 1.86e11 Pa.
3. LOAD ON LOWER BLADE (FLAT) = 6.0875 kg AND UNCOUPLED LOAD = 3.0525 kg.
4. PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.78 Hz.
5. PREDICTED FIRST BLADE INTERNAL FREQUENCY = 306 Hz.
6. MAXIMUM STRESS = 982 MPa
7. EXCEL SPREADSHEET VALUES OF A MID TO MID DISTANCE OF 64.1 mm AND A

RADIUS OF CURVATURE OF 99.3 mm GIVES A FLAT BLADE ON LOADING FROM THE EXCEL EQUATIONS. ANSYS PREDICTS WITH THESE MID-TO MID AND ROC VALUES A DEFLECTION OF 58.1 mm, HENCE 6 mm ABOVE FLAT WHEN LOADED.

8. FOR A MID TO MID DISTANCE OF 59.92 mm AND A RADIUS OF CURVATURE 107.8 mm, ANSYS PREDICTS A DEFLECTION OF 59.53 mm. i.e. VERY CLOSE TO FLAT.
9. THE CURRENT BLADE IS DESIGNED WITH A MID TO MID DISTANCE OF 62.01 AND RADIUS OF CURVATURE OF 103.15 mm, ANSYS PREDICTS A DEFLECTION OF 59.2 mm. THIS MID TO MID DISTANCE OF 62.01 mm IS HALF WAY BETWEEN THE EXCEL VALUE (64.1 MM) AND THE ANSYS VALUE (59.92 mm) FOR WHICH THE TWO DIFFERENT METHODS PREDICT A FLAT BLADE WHEN LOADED, AND IS A COMPROMISE DESIGN.
10. LENGTH IS 120 mm (135 mm INCLUDING CLAMPING LENGTH), THICKNESS IS 1.17 mm AND WIDTH IS 32 mm.
11. IN THE CURVED SKETCH IN SW PART ADD MID TO MID DEFLECTION AND ADJUST RADIUS UNTIL DESIRED LENGTH IS ATTAINED.
12. IN SW PART, BLADE IS DRAWN WITH SHEET METAL AND EXTRUDED VERTICALLY DOWNWARDS.
13. ON SW DRAWING, SOLIDWORKS RADIUS VALUE IS THE VALUE MEASURED DIRECT FROM SW USING THE DIMENSION TOOL.