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Design Notes for Production Blades for HAM Suspensions

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## 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	$\lambda = \alpha \frac{4m_t g l^3}{E a h^3}$	Engineering
Uncoupled frequency	$f = \frac{1}{2\pi} \sqrt{\frac{E a h^3}{4 m l^3 \alpha}}$	Science
Stress	$\sigma = \frac{6 P l}{a h^2}$	Engineering
Lowest internal mode	$f_l \propto \frac{h}{l^2}$	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,  $P = m_t g$

$\alpha$  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  $\alpha$  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  $\alpha/E$  which we have really been fitting. For example for the quad blades, work at RAL established that  $\alpha = 1.36$  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,  $\lambda$ , and the radius of curvature,  $R$ . The latter is found using the relationship between  $\lambda$  and  $R$

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

Calum Torrie has written an EXCEL spreadsheet which can be adapted to any suspension and takes all the relevant input information to find  $\lambda$  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  $\frac{1}{4}$  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

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

(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 (needs 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:

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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.

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### **3.2 Lower blades D080019 (needs 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-v1

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

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  $\frac{1}{4}$  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.

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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 XXX (TBD) FOR RADIUS OF CURVATURE YY.Y mm (TBD)

2.9 LENGTH IS 250mm (270mm INCLUDING CLAMPING LENGTH), THICKNESS IS 1.3mm AND WIDTH IS 39.878mm.

2.10 RADIUS IS YY.Ymm (TBD) 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.

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**4.2 Lower Blades: D080761 (needs new revision)**

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  $\frac{1}{4}$  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.

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2.1 EXCEL SPREADSHEET REF T1000352-v1

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 XXX (TBD)  
FOR RADIUS OF CURVATURE YY.Y mm (TBD)

2.9 LENGTH IS 120mm (130mm INCLUDING CLAMPING LENGTH),  
THICKNESS IS 0.76mm AND WIDTH IS 18mm.

2.10 RADIUS IS YY.Ymm (TBD) 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)

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:

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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.

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## 5.2 Lower Blades D020615 (needs new revision)

length 120.0 mm, width 32.0 mm, thickness 1.17 mm

radius of curvature 101.2 mm, centre to centre height 63.2 mm

We had several vendor prototype this blade, except that 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 1.46. See T000265-v2. This value has been used in the EXCEL spreadsheet calculations for this blade.

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

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2.1 EXCEL SPREADSHEET REF T1000353-v1

2.2 SHAPE FACTOR FOR LOWER BLADE = 1.46 AND YOUNGS  
MODULUS USED IS 1.86e11 Pa.

2.3 LOAD ON LOWER BLADE (FLAT) = 6.0875 KG AND UNCOUPLED  
LOAD = 3.0525 KG.

2.4 PREDICTED UNCOUPLED SUSPENSION FREQUENCY = 2.80 Hz

2.5 PREDICTED FIRST BLADE INTERNAL FREQUENCY = 306 Hz

2.6 MAXIMUM STRESS = 982 MPa

2.7 MID TO MID DEFLECTION = 63.2 mm

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

2.9 RADIUS IS 101.2 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.