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- LIGO -
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aLIGO ISC Beam Steering: Tip-Tilt Suspension Design

Bram Slagmolen, Adam Mullavey, John Miller, David McClelland
The Australian National University

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Interferometer Sensing and Control

Draft

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

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1 Introduction

This document describes the design of the Tip-Tilt suspensions used to isolate selected small optics for Interferometer Sensing and Control (ISC) in Advanced LIGO. The original Tip-Tilt design [1] was modified based on experience gained in eLIGO. These changes are discussed herein.

The Tip-Tilt is designed to house 2" optics. Seismic isolation is provided by means of a single stage pendulum and cantilever blade springs. Four Birmingham OSEMs [2] permit actuation in POS, PIT and YAW degrees of freedom. An image of a prototype Tip-Tilt is shown in figure 1. The overall height of the structure is ∼250 mm.

In addition to providing attenuation of external disturbances, the Tip-Tilt suspensions are capable of performing two other tasks. Due to their strong actuators and low masses, the Tip-Tilts' suspended optics can be dithered at high frequencies (>1 kHz) to generate alignment control signals. A Tip-Tilt can also act as a shutter (e.g. to protect sensitive photodetectors) by rapidly applying a large alignment offset.

As part of the ISC system, Tip-Tilts will be installed at three ports. Table 1 lists the required number of Tip-Tilts by location.

Table 1: Distribution of Tip-Tilts throughout a single interferometer.

Sensing port	Chamber	Number
REFL	HAM 1	2
POP	HAM 1	2
AS (OMC path)	HAM 6	2
Spare	—	2
Total		8

2 Requirements

Table 2 lists the permissible range of Tip-Tilt eigenmode frequencies for each degree of freedom. Modelled values [3] are also presented. The Tip-Tilt uses cantilever blade springs to provide vertical isolation, the three option columns in table 2 present results for different blade thicknesses – 254 µm, 400 µm and 500 µm. With these values vertical resonant frequencies lie between 5 Hz and 8 Hz. The properties of the blade springs are examined further in section 3.2.

3 Mechanical Design

The design of the aLIGO Tip-Tilt suspension is based on that of the original Tip-Tilt stages. LIGO-D1001396-v1 [4] provides an overview of the original design.

Table 2: The permissible and modelled (using the Mathematica notebook 'TwoWireSimpleBlades') resonant frequencies of the Tip-Tilt.

Mode	**Allowable Frequency Range [Hz]**	**Modelled Frequency [Hz]**		
		Option 1 (254 µm)	**Option 2** (400 µm)	**Option 3** (500 µm)
Pendulum	1 - 1.5	1.29	1.29	1.29
Pitch	1 - 2	1.53	1.53	1.53
Yaw	1 - 2	1.74	1.74	1.74
Side	1 - 2	1.34	1.34	1.34
Vertical	2 - 10	5.52	5.75	8.01
Roll	2 - 20	7.79	8.11	11.34

For aLIGO the suspension point has been raised to give a pendulum length of 140 mm. Vertical isolation has also been added. The aLIGO design is such that an original Tip-Tilt can easily be retrofitted with these improvements, only the side and top plates need be replaced.

3.1 Overview

The Tip-Tilt suspension is designed to accommodate a 2" ⌀ × 3/8" tk. (50.8 × 9.52 mm) optic. The optic is held inside an aluminium ring by a small cylinder of Teflon PFA-440HP whose position is locked by a set screw. The suspension wires are clamped onto the sides of the aluminium ring. The ring also houses 4 magnets and their associated BOSEM flags.

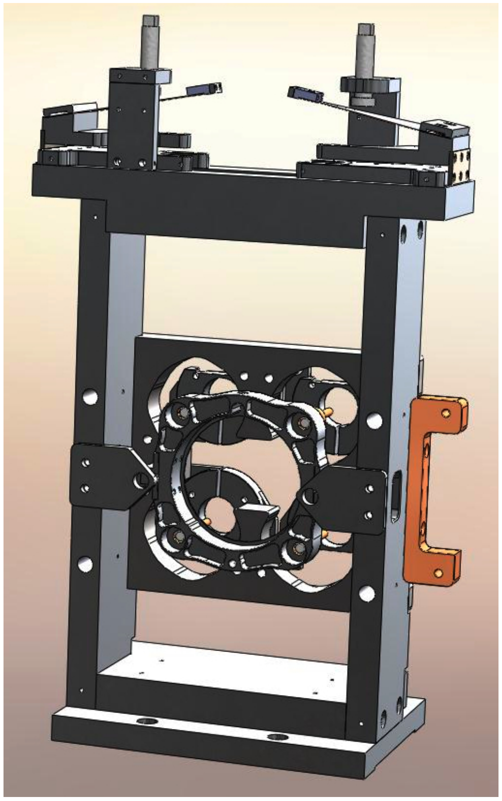
The pendulum length has been increased from 55 mm to 140 mm to lower the resonant frequency and reduce the angles of the wires with respect to the vertical at the break-off point. The suspension wire diameter has also been reduced to 127 µm, mitigating wire stiffness.

Vertical isolation is realised using two Be-Cu cantilever blades. Be-Cu is preferred due to its high Young's modulus. It is perceived that the blades could also be made from stainless steel. The vertical, side and roll modes are controlled using eddy current damping.

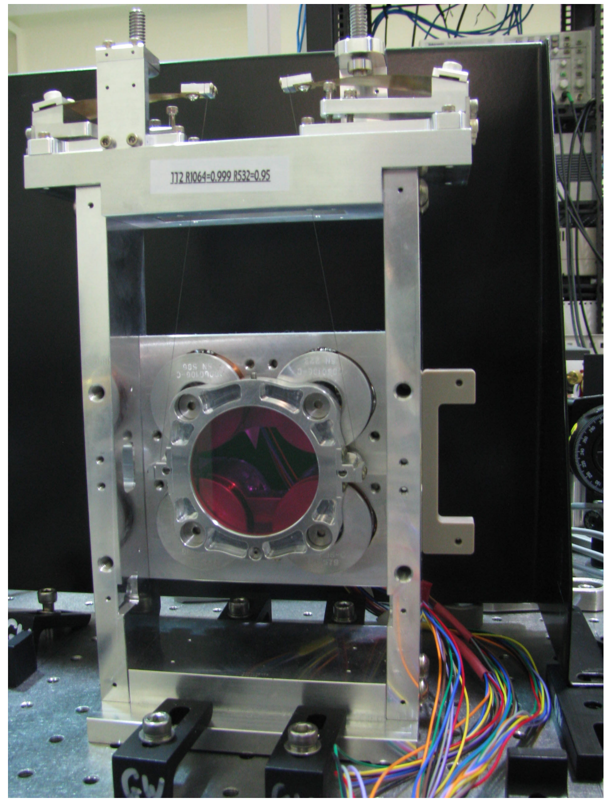
Four BOSEMs are installed for POS/PIT/YAW actuation and local control. It is also possible to utilise standard AOSEMs in applications which do not require fast actuation or large forces.

The Tip-Tilt structure is manufactured from standard vacuum compatible materials (aluminium and stainless steel). The eddy current dampers will be made from copper. Including a 2" mirror and four BOSEMs this material choice results in a total mass of ∼2.3 kg.

The Tip-Tilt occupies a footprint of 124 mm × 90 mm on an optical table. Including the overhanging plate on which the blades are mounted, the overall extent is 160.6 mm × 90 mm (neglecting the BOSEM wiring and any dog clamps).



(a) Drawing of the Tip-Tilt Mirror.



(b) Photo of the prototype Tip-Tilt at The Australian National University.

Figure 1: Design drawging and photo of the prototype fo the Tip-Tilt mirror.

Table 3 provides a listing of selected Tip-Tilt parameters.

Table 3: Selected Tip-Tilt parameters.

Effective optic diameter (inc. ring)	76.2 mm (3")
Effective optic mass (inc. ring)	~124 g
Optic size	50.8 mm x 9.5 mm ($2" \times 3/8"$)
Transmission aperture (diameter, centred)	28 mm vertical ~ 35 mm horizontal
Beam height	101.6 mm (4")
Suspension wire length	140 mm
Suspension wire diameter	127 µm
d-pitch	1.5 mm
d-yaw	35 mm
Total mass	~ 2.3 kg

3.2 Vertical Isolation - Blade Design

Vertical isolation is provided by triangular shaped Beryllium Copper cantilever blade springs. These blades are of a similar design to those used in aLIGO's triple suspensions. Due to more stringent noise requirements, the triple suspension blades are made from maraging steel, heat treated to reduce creep and pre-curved [5]. These measures have not been adopted in our design so as to simplify production of the blades.

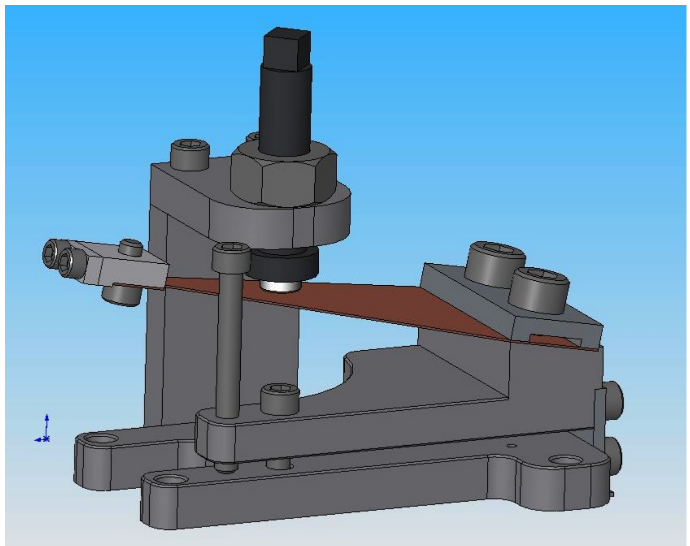


Figure 2: Single blade units with height adjuster.

Modelling of the blades was carried out using a Matlab version (see appendix A) of the Excel spreadsheet developed by N. Robertson and C. Torrie [6, 7]. Key parameters used in our model are given in table 4. The table lists three options, over which the blade thickness varies. The vertical resonant frequency is determined by the blade thickness and length. For the Tip-Tilt it was desired to keep the blades as short as possible.

Each blade is mounted on an aluminium structure which allows the tip-height of the blade to be adjusted (and locked). This provide a means of adjusting the height of the optic with respect to the BOSEMs. Each blade is launched at an angle so that the suspension wires leaves the clamps at the blade tips as close to 90° as possible.

In calculating the correct launch angle the routing of the suspension wire itself must be taken into consideration. The separation of the two suspension points (d-yaw) is 35 mm while the two wire clamps of the mirror assembly are 76.2 mm (3") apart. The resulting angle of the wire from vertical at the blade tip is 8.4°. For the chosen blade thickness (254 µm), the blade tip becomes angled by 19.2° under load. The blade is thus mounted at an angle of 10.8° to ensure that the wire will be perpendicular to the clamp at the tip of the blade.

3.3 Eddy Current Damping

Due to their relatively small magnets and large apertures the BOSEM structures provide little passive damping. To effectively control vertical, side and roll motion, additional magnets

Table 4: Blade parameters and modelled results. Option 1 was selected for the final Tip-Tilt design.

	Option 1	**Option 2**	**Option 3**
Blade thickness	254 µm	400 µm	500 µm
Base width	26 mm	20 mm	20 mm
Blade length	50 mm	70 mm	80 mm
Shape factor (triangular)	1.5	1.5	1.5
Vertical resonance	5.12 Hz	5.8 Hz	6.6 Hz
Effective spring constant (single blade)	74.4 N/m	81.4 N/m	107 N/m
Deflection at tip (with 62.6g load)	8.25 mm	7.5 mm	5.7 mm
Blade curvature radius (under load)	151.48 mm	325 mm	555 mm
Angle of the blade-tip (under load)	19.2 deg	12.4 deg	8.3 deg
First internal mode	382 Hz	307 Hz	294 Hz

are installed in two positions to provide eddy current damping.

To damp vertical and roll motion magnets are located immediately above the loaded blades, 1/3 of the way along their length beginning from the tip (see figure 2). The magnet is mounted on a threaded rod, allowing its separation from the blade to be optimised.

Two further magnets are installed on the aluminium ring (on the BOSEM side of each wire clamp). These magnets will damp both side and vertical motion.

4 Actuation

The local motion of the suspended Tip-Tilt mirror is sensed and controlled by its four BOSEMs. The centres of the four BOSEMs form a square of side 48.22 mm. Working in imperial dimensions may result in small misalignments of the BOSEM centres of the order of $\pm$0.05 mm ($\sim$0.002 inch).

4.1 Magnets

The standard Tip-Tilt BOSEM magnets are Nickel plated SmCo (Sm_2Co_{17}/SmCo 2:17) items,
5 mm ⌀ × 10 mm long. These dimensions are different from the original BOSEM magnets (10 mm ⌀ × 10 mm long) to mitigate magnetic couplings (observed in eLIGO).

The magnets are arranged with alternating polarities to reduce the overall moment of the mirror assembly. The centre of the standard magnet (5 mm ⌀ × 10 mm long) should be 7.6 mm away from the centre of the BOSEM coil[8].

Our design retains the possibility of installing larger magnets at a later date should it be found necessary.

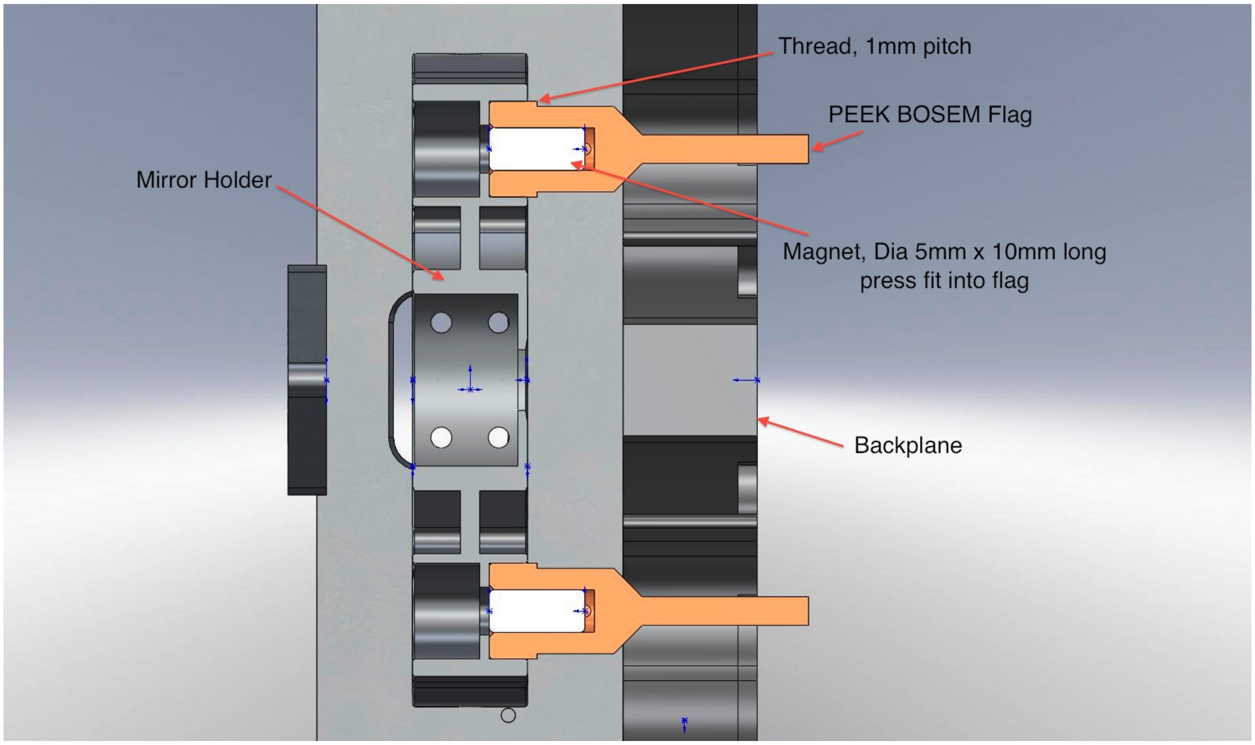


Figure 3: Flag assembly with magnets press fitted into PEEK flags.

4.2 Sensor Flag

The flags of the original Tip-Tilt were tapered along their length to broaden the useful sensing range to ∼4 mm [9]. During commissioning work in eLIGO it was discovered that several of the flags were mis-centred, leading to unreliable sensing. Further, any error in suspension wire length translated directly into a location error of the flags in the BOSEMs.

Both of these issues have been addressed in the design of the aLIGO Tip-Tilt. Untapered flags will be used and the height of the blade tips can be adjusted to align the flags inside the BOSEMs.

The construction of the flag assembly is shown in figure 3. The magnet is press fitted into a threaded PEEK flag which is subsequently screwed into the aluminium mirror ring.

4.3 AOSEM

If large forces and/or rapid actuation are not required, it is possible to operate the Tip-Tilt using AOSEMs. To accommodate the smaller AOSEM magnets a replacement 'backplane' structure must be fitted. The use of smaller magnets and the removal of the long BOSEM flags will modify the inertia of the mirror holder. These changes are not expected to have any serious consequences for Tip-Tilt operation.

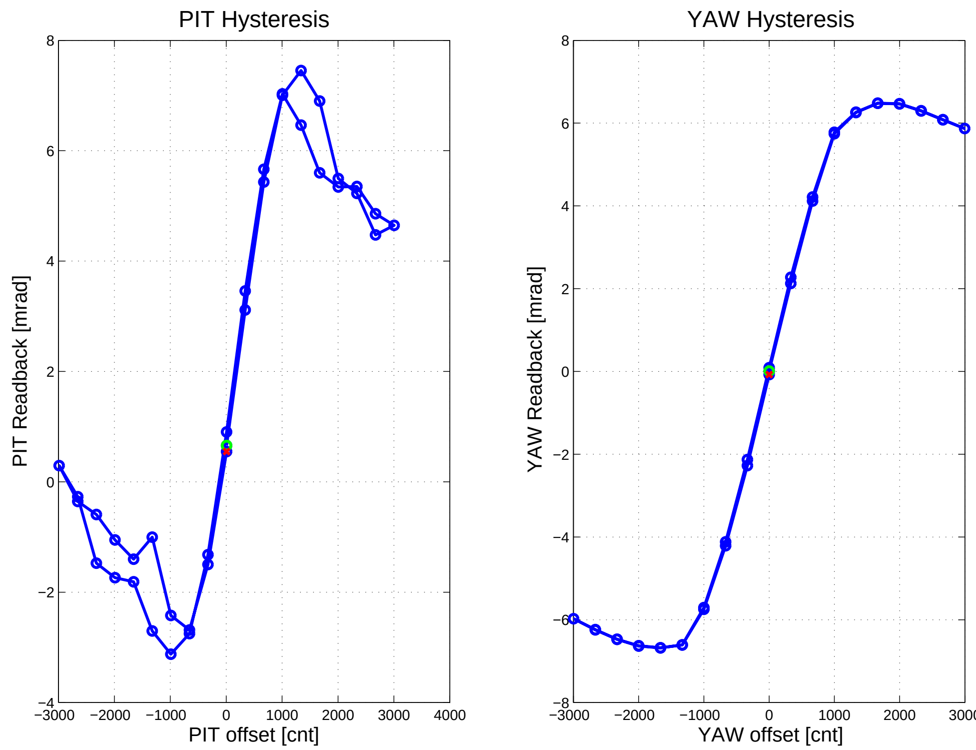


Figure 4: Hysteresis of the Tip-Tilt suspension measured using the BOSEMs. The start position is indicated by the green dot. Offsets were first increased to a maximum before cycling through a minimum and back to zero. The red dot indicates the end position.

5 Performance

5.1 Pitch and Yaw Hysteresis

Figure 4 shows the hysteresis exhibited by the Tip-Tilt suspension. The hysteresis was quantified by applying a series of DC pitch (or yaw) offsets via the four BOSEM coils and recording the pitch (yaw) values sensed by the same BOSEMs. After each offset step (330 counts) the Tip-Tilt was allowed to reach equilibrium before the sensed offset was measured with a 5 s averaging time. Both degrees of freedom are linear and show minimal hysteresis over a ± 6 mrad range.

5.2 Transfer Functions

Figures 5, 6, 7, 8 and 9 show the transfer functions of the Tip-Tilt measured at ANU. Recorded data has been fitted with second order functions to obtain the frequency and quality factor of each resonance. Modelled results, obtained using M. Barton's Simulink model, are also presented.

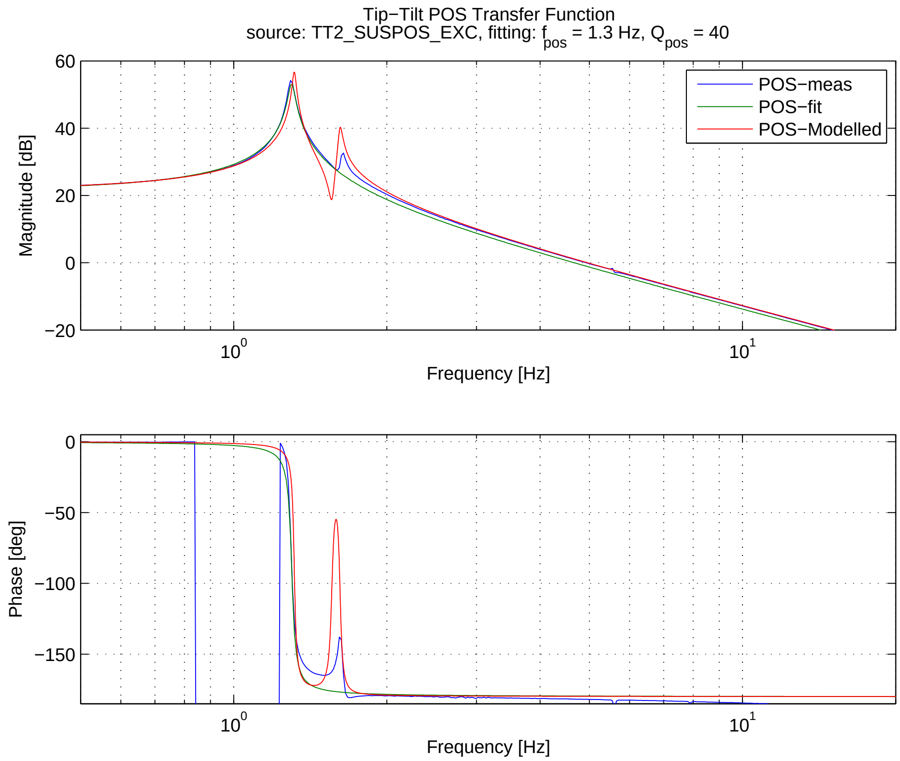


Figure 5: Tip-Tilt POS transfer function.

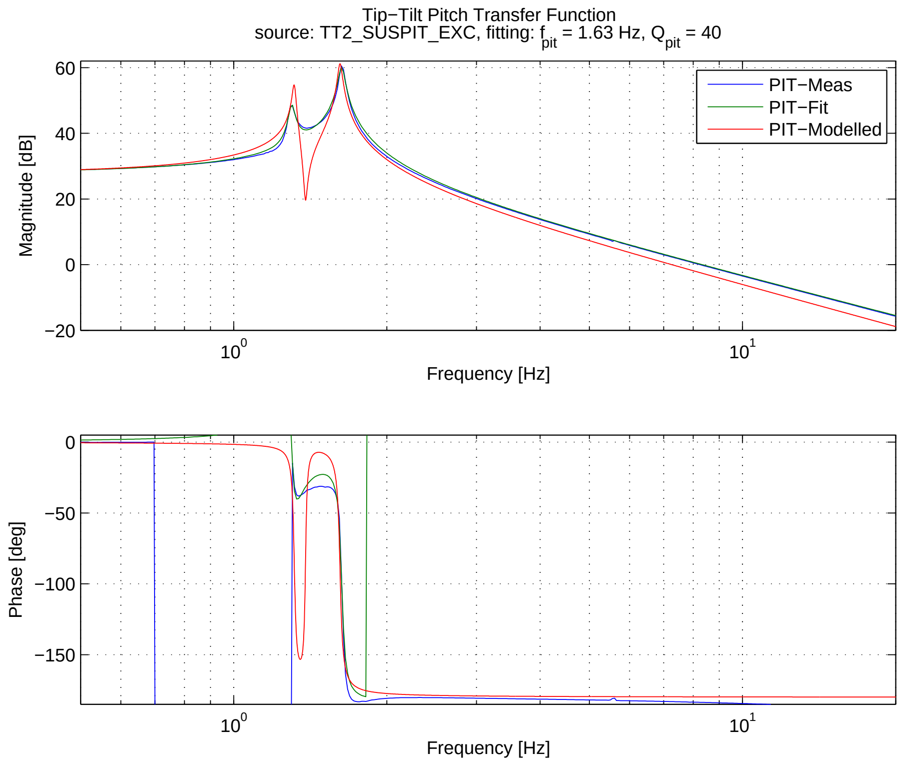


Figure 6: Tip-Tilt PIT transfer function.

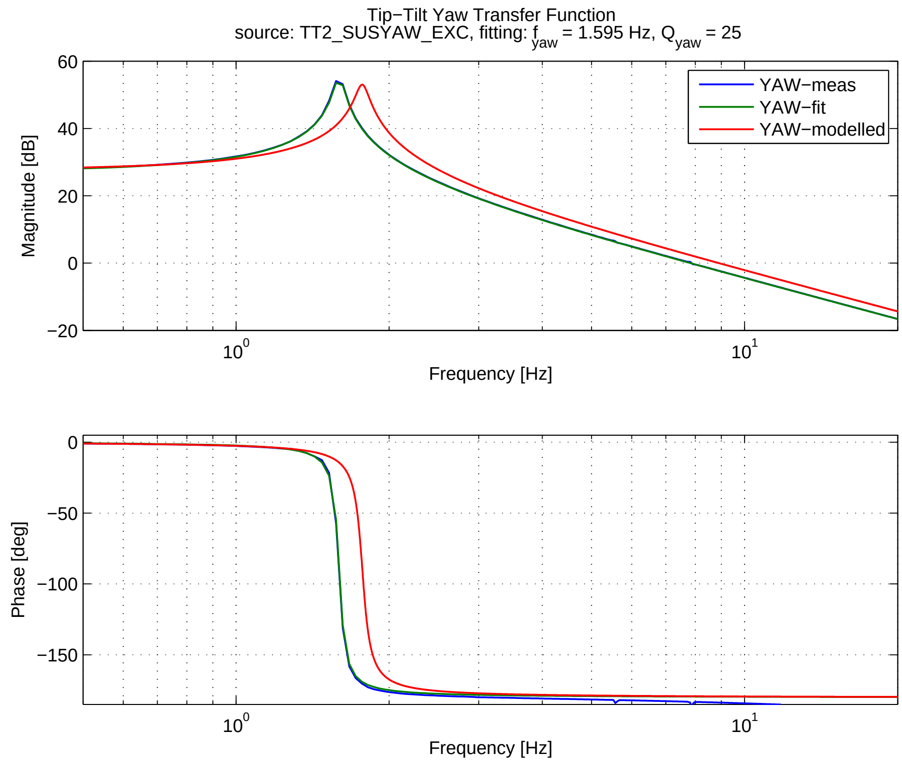


Figure 7: Tip-Tilt YAW transfer function.

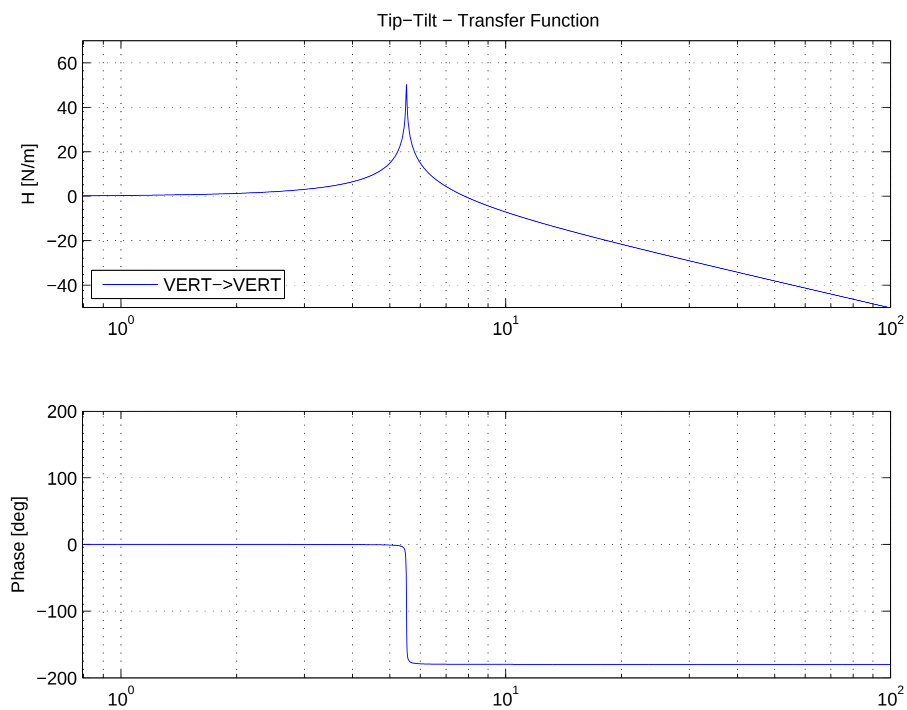


Figure 8: Vertical ground motion (GND) to vertical optic motion transfer function.

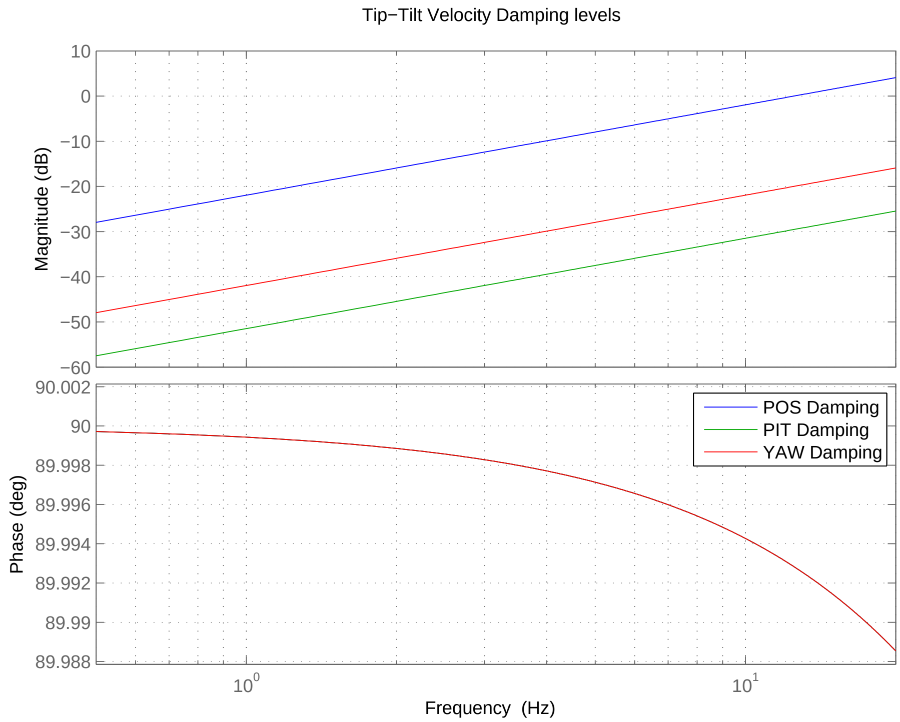
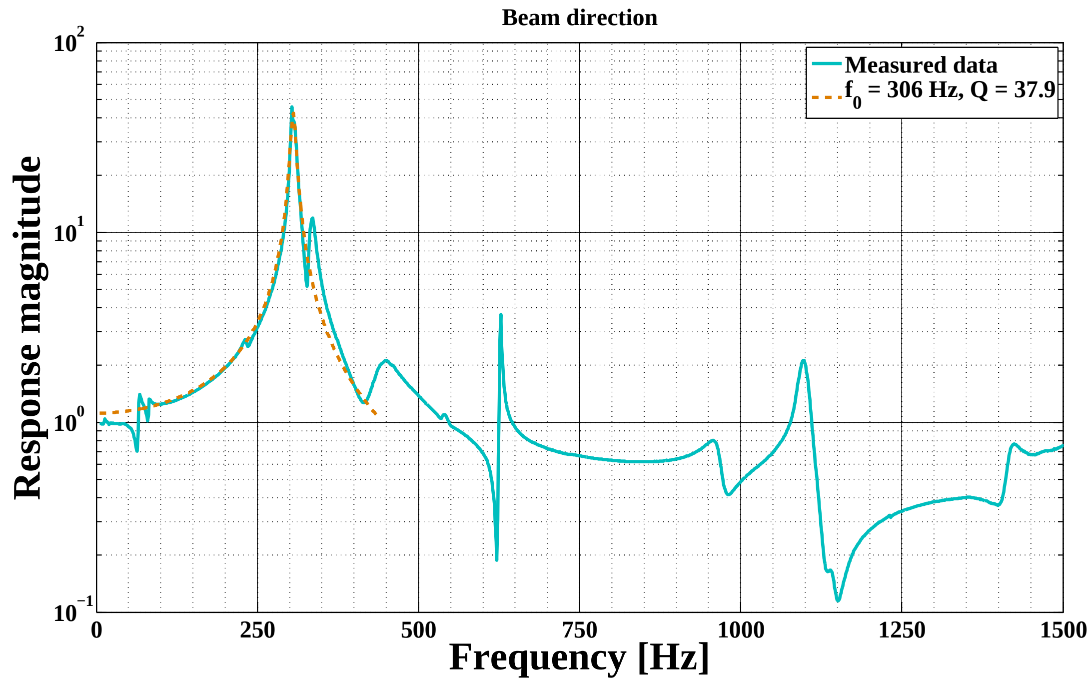


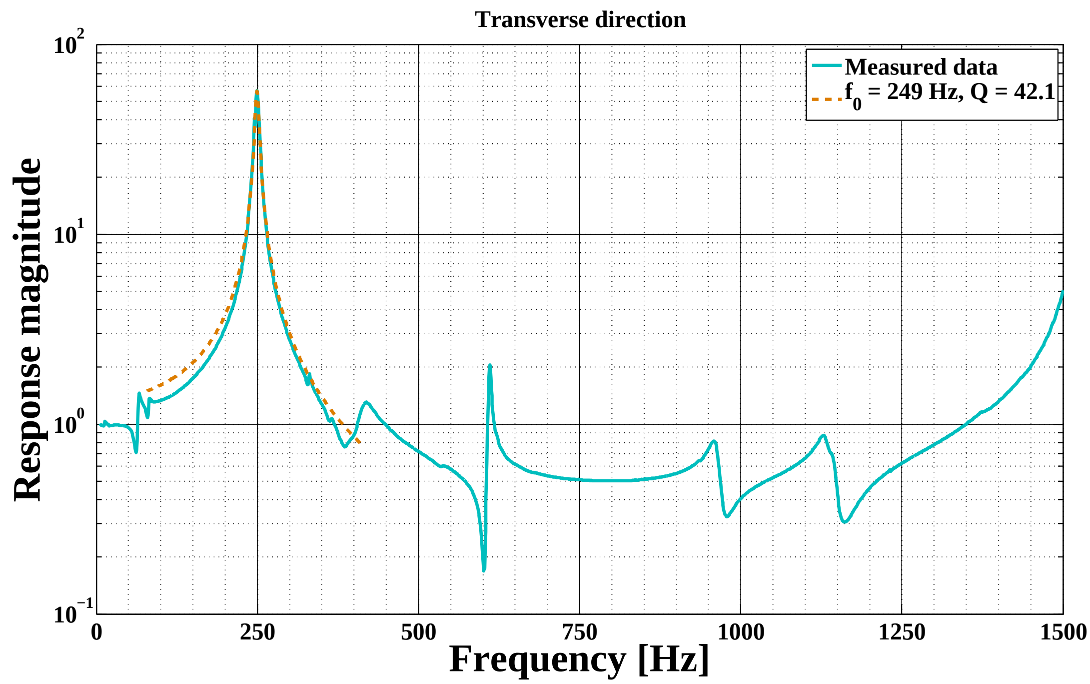
Figure 9: Simulink damping transfer functions used to match measured data – POS, PIT and YAW.

5.3 Eigenmodes of the Tip-Tilt Structure

The mechanical modes of the Tip-Tilt structure have been investigated using a vibration table (TIRA TV 55240/LS-340). Resonances were been found at ∼300 Hz along the beam direction and at ∼250 Hz in the transverse direction. Both resonances have a Q of around 40 (see figures 10(a) and 10(b)). Due to limitations of the available apparatus low frequency modes (below ∼5 Hz) could not be explored.



(a) beam direction (forward and backward motion).



(b) transverse direction (side to side motion).

Figure 10: Measured modal response of the Tip-Tilt structure.

6 Acknowledgements

We wish to thank Norna Robertson and Calum Torrie for their help in designing the Be-Cu blades and Horst Punzmann for his assistance with modal testing.

A Blade Calculations

```
% Vertical Blade Spring Design
% which has a dual-triagular shape
% see Stefan Gossler's Thesis, as
% well as LIGO T030107, and Calum and
% Norna's blade spreadsheet
%
% Bram Slagmolen - July 09
%

fname = ['TT-' date '.txt'];
delete(fname);
diary(fname);   % turn on writing command window output saving to file

disp(' ');

material = 'BeCu';
%material = 'SS';

t = 0.254e-3;    % thickness of the Blade Spring, 306e-6 m, 0.006 inch  (0.152 mm),
                 % 0.01 inch (0.254 mm) or 0.016 inch (0.406 mm)
a = 26e-3;       % width of the base of the Blade Spring
a1 = 1e-10;      % width of the tip of the Blade, the 1e-10 constant is
                 % to keep Beta NOT 1.
L = 50e-3;       % length of the Leaf Spring

Beta = a1/a;
alpha = ((3/(2*(1-Beta))) * (3 - (2/(1-Beta)) * ...
          (1+Beta^2 * log10(Beta)/(1-Beta)))); % GEO value 1.36 - 1.45
alpha = 1.5;     % this is the shape factor, which for a triangular blade is 1.5
                 % and a rectangle 1.
g = 9.81;

%if material == 'ALU'
    E_al = 69e9;    % Youngs modulus of aluminium
    Y_al = 400e6;   % Yield strength
%elseif material == 'SS'
    E_ss = 210e9;   % Youngs modulus of Steel
    Y_ss = 600e6;   % Yield strength of Stainless Steel (approx.)
%elseif material == 'BeCu'
    E_becu = 131e9; % Youngs molulus Berrylium-Copper
```

```
    Y_becu = 620e6; % Yield Strength Berrylium-Copper
%else material == 'Maraging'
    E_maraging = 186e9; % Youngs modulus for Marval18 Maraging Steel
    Y_maraging = 186e9; % Yield Strength o Maraging Steel
%end

Y_pw = 2200e6;    % Yield strength of piano wire
Rho_becu = 8100;  % density of berillium copper

II = (a*t^3)/12; % second moment of inertia of the leaf spring

disp(fname);
disp('----------------------------');
disp(['blade material: ', material]);
disp(['blade thickness: ', num2str(t*1e3), ' mm (',num2str(t*1e3/25.4),' inch)']);
disp(['width at the base: ', num2str(a*1e3), ' mm (',num2str(a*1e3/25.4),' inch)']);
disp(['width at the tip: ', num2str(a1*1e3), ' mm (',num2str(a1*1e3/25.4),' inch)']);
disp(['blade length: ', num2str(L*1e3), ' mm (',num2str(L*1e3/25.4),' inch)']);
disp(['Beta (width at tip/width at base): ', num2str(Beta)]);
disp(['Alpha (1.3 - 1.45): ', num2str(alpha)]);
disp(['second moment of inertia (cross section): ', num2str(II), ' m^4']);
disp(' ');

% for a simple blade system
E = E_becu;
Y = Y_becu;

% Effective spring constant
k = (E* a * t^3)/(4*L^3 * alpha); % stiffness [N/m]
disp(['effective sping constant: ', num2str(k), ' N/m']);

% Effective suspended mass
mirrormass = 0.124;
clampmass = 0.6e-3;
m = mirrormass/2 + clampmass;
disp(['effective mass: ', num2str(m), ' kg']);

% Effective resonance frequency
f0 = sqrt(E*a*t^3 / (16*pi^2 * m * L^3 * alpha)); % from T030107
disp(['effective resonance frequency: ', num2str(f0), ' Hz']);

% Blade tip deflection
d = 4*m*g*L^3 * alpha / (E*a*t^3);  % from T030107
disp(['deflection: ', num2str(d*1e3), ' mm']);

% maximum stress
Tm = 6 * g * m * L / (a * t^2);
disp(['maximum stress: ', num2str(Tm/1e6), ' MPa']);
```

```
% Rc = E * a * t^3 / (12 * m * g * L); % from T030107
% From Norna's spreadsheet -> d = Rc * [1 - cos(L/R)],
% -> shoudln't this be d = Rc * [1 - cos(L/2R)]?
% using taylor series cos(x)=1 - x^2/2! + x^4/4!
% Rc = | L^2 / (2*d) |
Rc = L^2 / 2 / d;
disp(['pre-curved radius at rest: ', num2str(Rc), ' m']);

% blade base to tip length under load
% l = Rc * sqrt( 2 - 2*cos(L/Rc) )
l = Rc * sqrt(2 - 2*cos(L/Rc)  );
disp(['distance base to tip underload: ',num2str(l*1e3),' mm']);

% angle of the blade tip in respect to the base
theta = 90 - acos(L/Rc)*180/pi;
disp(['angle at blade tip is: ', num2str(theta), ' deg']);

% Angle of the suspension wire from the suspension point (blade tip)
% to the optic barrel. The d-yaw at suspension point is 35mm
% while the optic diamter is 3", and the supsension length is 140mm
dyaw = 35e-3;
doptic = 3*25.4e-3;
Lpend = 140e-3;
theta2 = ((doptic-dyaw)/2 /Lpend)*180/pi;
disp(['suspension wire angle: ', num2str(theta2), ' deg']);

% Angle which the blade will be mounted so the suspension wire
% leaves the blade at 90 deg (or as close as possible).
theta3 = theta - theta2;
disp(['angle blade base is mounted (90 deg of wire to clamp): ', ...
        num2str(theta3), ' deg']);

diary off;  % turn off diary, e.g. saving output to file

% Using Dennis calculations
B1 = a/a1;

lk0 = 1.3;
f00 = (1/2/pi) * (t/L^2) * lk0 * sqrt(E*g/12/Rho_becu);
```

References

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