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Subject: **Preliminary Study of Thermal Creak of a Trim Tab on the FAME Spacecraft**

1 Introduction

The Full-sky Astrometric Mapping Explorer, FAME, uses nine trim tabs to align the center of pressure from the solar wind with the center of mass of the spacecraft, see Figure 1. As the spacecraft slowly rotates once every 40 minutes, the three rectangular trim tabs can pass through positions of full sunlight and full shadow, subjecting them to large temperature changes. The induced thermal expansion and contraction have the potential of causing creaks and pops at the hinges, and bending deformation. This memorandum describes an analysis of this condition with the intent of bounding the creak problem using preliminary properties and models.

The fact that a trim tab could be designed to minimize the thermal creak potential, say, by the use of hinge flexures, is outside of the scope of this memorandum. Instead, the current design (which may be a worst case design) is explored to calculate the upper limits on creak.

The trim tab is only part of the creak story of FAME, but it is the one that can most easily be addressed. A complete plan to study all creak effects is described in [1]. For a full discussion of the terms "thermal creak" and "thermal jitter", refer to [2].

2 Summary of Results

Results from this preliminary analysis are summarized below. They are for open loop analysis, without interaction from the control system. It is easy to see that most of the creak jitter

Table 1 Summary of Results Open Loop	Freq. Band (Hz)	Instrument Jitter (µrad, 0-peak)		
		Along the Scan Direction, θz	In the Cross Scan Dir., θx	θy
From a thermal creak of a rectangular trim tab with two hinges	0 (DC shift)	0.0477	0.0057	0.0136
	1 - 7	0.0001	0.0018	0.0002
	7 - 25	0.0001	0.0003	0.0043
	25 - 50	0.0010	0.0029	0.0030
	50 - 100	0.0192	0.0220	0.0044
	0 - 100 (all)	0.0681	0.0326	0.0254

From out-of-plane thermal bending of all trim tabs	0 - 0.01	0	454.0	467.0
	0 - 100 (all)	0	454.0	467.0

comes from the sudden DC shift, and the high frequency response above 50 Hz. For thermal bending, it is unclear whether or not this should be included as jitter. All of it is a very low frequency, <0.01 Hz. For comparison, the jitter requirements are discussed in Section 7.

It is important to note that this jitter is caused by very small disturbances in the nearly 1500 lb spacecraft. From the creak, 1.68 lb moves through 0.000475 inches, for only 0.0008 in-lb of work. From the thermal bending, the disturbance from one tab is only 0.002 in-lb.

3 Finite Element Model

A detailed structural dynamic model of the deployed s/c has been assembled using the NASTRAN code. It is described on Table 2 and sketched in Figure 2. Modes go to 100 Hz. The low frequency modes at 6 Hz are due to the three rectangular trim tabs. The pie-shaped tabs are not included in the model.

Table 2 Dynamic Properties of the FAME Finite Element Model

Total weight = 1489.8 lb Center-of-mass MOI, Ixx = 2460.4 in-lb-s^2
Iyy = 2388.5 in-lb-s^2
Trim tab fixed at both hinges. Izz = 3029.7 in-lb-s^2

Mode No.	Nat. Freq. (Hz)	Damp. Ratio (%)	Mode No.	Nat. Freq. (Hz)	Damp. Ratio (%)	Mode No.	Nat. Freq. (Hz)	Damp. Ratio (%)
1-6	0.0	0	16	35.8	0.5	24	40.7	0.5
7-9	6.4	0.5	17	36.8	"	25	43.3	"
10	9.2	"	18	39.0	"	26	45.1	"
11	17.2	"	19	39.4	"	27	47.6	"
12	21.6	"	20	40.0	"	28	50.3	"
13	29.7	"	21	40.1	"	29	53.4	"
14	29.9	"	22	40.4	"	…	…	
15	31.3	"	23	40.4	"	58	98.0	"

For a rectangular trim tab, the hardware is shown on Figure 3. This is the item that is assumed to grow (or shrink) in-plane when its temperature changes and bend out-of-plane when a thermal gradient is produced through its thickness. The trim tabs are assumed to be of aluminum honeycomb construction, 6061-T6, for which,

Coeff. of thermal expansion = $24 \times 10^{-6} / {}^0C$

and have reflective surface coatings to minimize the temperature change. The stiffness of each hinge is only an engineering approximation of,

$K_{11} = K_{22} = K_{33} = 1000$ lb/in,

K_{44} = 500 in-lb/rad,
K_{55} = 2000 in-lb/rad, and
K_{66} = 0.

When a hinge slips, its friction properties are assumed to be represented by a Coulomb-type model,

Coulomb stiffness = 1000 lb/in, the same as a hinge
Static friction limit = 4.715 lb, selected near the top of its range
Sliding friction = 4.243 lb, 10% less than the static friction
Dashpot damping coef= 0.400 lb-s/in, a small value that reduces some ringing.

These will be discussed further in Section 5. Other properties and dimensions of the tab are shown on Figure 3.

This places the trim tab natural frequencies at about 6 and 80 Hz, modes 7 and 41, for out-of-plane bending and in-plane translation. A special version of the FEM allowed the trim tab to slip in the X-direction at one of its two hinges by freeing this d-o-f.

4 Thermal Analysis

The first step in all thermal creak studies is the thermal analysis. From this, the extremes of a rectangular trim tab have been computed and provided for this analysis as,

Max. temp -59 ^{0}C Max. change through thickness, 0.5 ^{0}C
Min. temp. -66 ^{0}C

5 Thermal Creak Analysis

The analysis of the high frequency thermal creak is complicated and nonlinear. However, its effect on the spacecraft is to excite the fundamental modes that cause line-of-sight vibration, and these modes are within the range of the FEM modal properties. With this in mind, an enveloping analysis is possible.

Referring to Fig. 3, the motor driven hinge is assumed fixed and the other hinge is assumed to slide in the X-direction when thermal growth occurs. The computed thermal condition is then,

Max. change in length between hinges = $\alpha \, \Delta T \, L$ = 0.00475 in
Max. force at hinge in slip direction = $K_{11} \, \Delta x$ = 4.75 lb

The model is heated by applying simulated slowly changing forces, equal and opposite, at the trim tab hinge until the static friction value is overcome. Studies have shown that it is overly conservative and unrealistic to suddenly release the entire trim tab force. Instead, at this hinge in the X-direction, a nonlinear Coulomb friction element is implanted using the TRONS computer code. Friction allows the slipping hinge to come to rest in a new equilibrium position without unloading the entire friction force.

When the thermal force reaches the static friction limit, the hinge suddenly slips and vibrates until it settles into its new position. Figure 4 plots the hinge force and instrument response to the creak. Most of the dynamics occur at the sudden shift and at the tabs' natural frequencies of 6.4 and 80 Hz. Notice that the roll, pitch and yaw of the instrument are affected, even though the creak is in the X-direction which should interact only with the roll, θz. The other directions are coupled by the mass matrix. They all settle into a new position indicated by the DC (0 frequency) shift. The responses have been analyzed in frequency bands by excluding all but a few mode shapes whose natural frequencies fall with the band of interest. The results are reported in Table 1 on page 1. A detailed breakdown by mode shape is provided in Section 7 after discussing the jitter requirements.

The difference between static and sliding friction has a large impact on the results. The 10% difference is chosen as a reasonable estimate.

6 Thermal Distortion Analysis

When a temperature difference is produced through the thickness of the trim tab, it bends out-of-plane in the Z-direction in a manner described on Figure 5. This bending creates a slight change in mass location which must be balanced by rotation of the spacecraft. Referring to Fig. 5, the amount of displacement of the outer tip of the trim tab is,

$$U_{TIP} = 0.5\, L^2\, \alpha\, \Delta T / t$$

where,

L = trim tab length = 14.0 in (from Fig. 3)
α = coeff. of thermal expansion
ΔT = temperature difference through thickness = 0.5 ^{0}C (from Section 4),
t = trim tab thickness = 0.25 in (from Fig. 3)

Thus,

U_{TIP} = 0.0047 inch in the Z-direction.

The net displacement of the center-of-mass is also taken from Fig. 5 as,

$$(WU)_{TOTAL} = W\, U_{TIP} / 3 = 0.002 \text{ in-lb}$$

where,

W = trim tab weight = 1.27 lb, honeycomb structure only, hinge mass ignored.

This is balanced by rotation of the spacecraft. On the sun side, the upward trim tab motion is balanced by a downward s/c rotation. On the dark side, the downward trim tab motion as again balanced by a downward s/c rotation. Assuming that the pie-shaped trim tabs have only 1/4 the effect of the rectangular ones, then the net s/c pitch or yaw rotation per revolution for 3 rectangular trim tabs and 6 pie-shaped ones is computed from,

$$I_{S/C}\, \theta_{S/C} = 2\,(3 + 6/4)\, R_O\, (WU)_{TOTAL}$$

where,

$I_{S/C}$ = moment of inertia of the s/c from Table 2, page 2
$\theta_{S/C}$ = s/c rigid body rotation (rad)
R_O = distance from s/c centerline to trim tab center ≈ 62 in

Hence,

$\theta_{S/C\ X}$ = 454 μrad, quasi-static open loop
$\theta_{S/C\ Y}$ = 467 μrad

This must be overcome by the FAME control system during every rotational period of about 40 minutes.

7 Application of the Jitter Requirements

The current FAME jitter requirements are copied on Table 3. The form of the requirements implies that the disturbance is steady state and continuous in time. However, this does not apply to the two forms of thermal disturbance studied in this memorandum. Creak, is very short duration — lasting for only a few periods of its fundamental natural frequency as seen on Figure 4. The thermal distortion happens continuously over an entire revolution. Thus, application of the requirement to these events is unclear.

Table 3 FAME Top Level Science Collection Jitter Requirements

	Freq. (Hz)	Along the scan direction θ_Z Amplitude μrad)	In the cross scan directions θ_X and θ_Y Amplitude (μrad)
Applicable to "unmodelable" jitter disturbances	0.2	0.010	0.100
	1	0.001	0.025
	10	0.003	0.030
	100	0.010	0.100

For example, assume the results from a creak can be represented as an instantaneous shift in position and a set of decaying sinusoids at each natural frequency. This is written for response variable X as,

$$X(t) = C_0 + \sum C_i\, e^{-\zeta \omega t} \sin(\omega_i t + \varphi_i)$$

where, C_i are coefficients determined in the creak analysis, C_0 is for the DC shift,
ω_i is the natural frequency of vibration mode i (rad/s)
ζ_i is the equivalent viscous damping ratio of mode i, and,
φ_i is the phase angle.

If ζ_i is very small, then the response over one cycle can be as high as, DC shift, $X_{DC} = C_0$ and, $X_{RMS} = (0.5 \sum C_i^2)^{0.5}$ and, $X_{AMPLITUDE} = \sum |C_i|$

Breaking these into bands of natural frequency will allow comparison with the jitter requirements. For creak, this amounts to simply computing the jitter from each mode of vibration at each natural frequency since, after the occurrence of a creak, the structure is freely ringing. Thus, it is probably acceptable to ignore damping and require that, after creak friction dissipation, the residual motion must conform to limits listed below in Table 4.

Table 4 Proposed FAME Thermal Creak Requirements

For residual motion after a creak with linear interpolation between frequency points

Nat. Freq. (Hz)	Along the scan direction θ_Z Sinusoidal Ampl., (peak-peak)/2 (μrad)	In the cross scan directions θ_X and θ_Y Sinusoidal Ampl., (peak-peak)/2 (μrad)
Shift	< 0.010	< 0.100
1	< 0.001	< 0.025
10	< 0.003	< 0.030
100	< 0.010	< 0.100

When this is done for thermal creak, Table 5 is produced. Note that the units are nano-radians. The response in each mode shape is shown compared to the proposed limits. For the creak selected, the only problems occurs at the shift and at the trim tab mode at 83 Hz. The large DC shift is computed from the zero-to-peak jump just after the creak has completed. Results could grow or shrink depending on the sliding friction force chosen. The value used was 90% of the static friction force which is a reasonable assumption.

Without the control system interaction, it is not possible to evaluate the effect of the out-of-plane steady thermal deformation.

8 References

[1] SAI-TM-1991, "A Plan to Address Thermal Creak of the FAME Spacecraft", from William Haile to C. Williams, Swales Aerospace, 4 Feb. 2002.

[2] SAI-TM-1981, "A Discussion of Thermal Jitter for the FAME Spacecraft", from William Haile to C. Williams, Swales Aerospace, 22 Jan. 2002.

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Table 5 Breakdown of Thermal Creak from a Rectangular Trim Tab

Nat. Freq. (Hz)	Proposed Spec. Jitter Limits Rx (nrad)	Ry (nrad)	Rz (nrad)	Jitter from a Creak Rx (n-rad)	Ry (n-rad)	Rz (n-rad)	Ratio Rx	Ratio Ry	Ratio Rz
Shift	100.0	100.0	10.0	5.63	-13.64	***47.50***	.05	.14	***4.75***
.0	100.0	100.0	10.0	.00	.00	.00	.00	.00	.00
6.4	28.0	28.0	2.2	-.04	.14	-.01	.00	.00	.00
6.4	28.0	28.0	2.2	-6.67	2.90	.00	-.24	.10	.00
6.4	28.0	28.0	2.2	-1.25	-2.94	.01	-.04	-.11	.00
9.2	29.5	29.5	2.8	.00	.00	.00	.00	.00	.00
17.2	35.6	35.6	3.6	-.10	1.46	.00	.00	.04	.00
21.6	39.0	39.0	3.9	.17	2.93	.05	.00	.08	.01
29.7	45.3	45.3	4.5	-.01	.01	.53	.00	.00	.12
29.9	45.5	45.5	4.5	-.10	1.07	-.03	.00	.02	-.01
31.3	46.5	46.5	4.7	.00	.00	.00	.00	.00	.00
35.8	50.1	50.1	5.0	-.02	-.03	.05	.00	.00	.01
36.8	50.8	50.8	5.1	-.24	.03	-.20	.00	.00	-.04
39.0	52.5	52.5	5.3	-.01	.00	.00	.00	.00	.00
39.4	52.8	52.8	5.3	-.14	.01	-.17	.00	.00	-.03
40.0	53.3	53.3	5.3	1.06	-.73	.01	.02	-.01	.00
40.1	53.4	53.4	5.3	-.03	.00	.01	.00	.00	.00
40.4	53.6	53.6	5.4	-.54	.20	-.05	-.01	.00	-.01
40.4	53.7	53.7	5.4	-.84	.39	.08	-.02	.01	.01
40.7	53.9	53.9	5.4	-.45	-.44	.10	-.01	-.01	.02
43.3	55.9	55.9	5.6	.73	-.20	-.05	.01	.00	-.01
45.1	57.3	57.3	5.7	.24	-.88	.00	.00	-.02	.00
47.6	59.3	59.3	5.9	-.22	-.14	.08	.00	.00	.01
50.3	61.4	61.4	6.1	.40	-.50	.07	.01	-.01	.01
53.4	63.7	63.7	6.4	-.07	-.90	.17	.00	-.01	.03
55.4	65.3	65.3	6.5	.00	.01	-.01	.00	.00	.00
57.2	66.7	66.7	6.7	-1.14	.78	.22	-.02	.01	.03
58.9	68.0	68.0	6.8	2.24	-.42	-.38	.03	-.01	-.06
59.0	68.1	68.1	6.8	.16	-.05	.14	.00	.00	.02
61.0	69.7	69.7	7.0	-8.70	2.52	-1.00	-.12	.04	-.14
61.1	69.8	69.8	7.0	-1.96	.25	.33	-.03	.00	.05
61.8	70.3	70.3	7.0	-.01	-.14	-.16	.00	.00	-.02
63.4	71.5	71.5	7.2	11.32	-2.29	.31	.16	-.03	.04
64.9	72.7	72.7	7.3	2.98	-2.57	.79	.04	-.04	.11
67.3	74.6	74.6	7.5	-.22	.05	.00	.00	.00	.00
68.2	75.2	75.2	7.5	1.69	.04	-1.39	.02	.00	-.18
69.8	76.5	76.5	7.7	1.81	.20	3.28	.02	.00	.43
69.9	76.6	76.6	7.7	-.13	-.72	.95	.00	-.01	.12
70.0	76.6	76.6	7.7	.37	-.56	-.68	.00	-.01	-.09
70.8	77.3	77.3	7.7	-.08	-.23	.02	.00	.00	.00
73.7	79.5	79.5	8.0	-.25	-.99	.23	.00	-.01	.03
74.8	80.4	80.4	8.0	-.34	-1.25	.54	.00	-.02	.07
77.0	82.1	82.1	8.2	-.53	-.96	-.24	-.01	-.01	-.03
78.3	83.2	83.2	8.3	.20	.81	.39	.00	.01	.05
79.8	84.3	84.3	8.4	-.33	.80	-.88	.00	.01	-.10
80.6	84.9	84.9	8.5	-1.12	-3.24	-1.39	-.01	-.04	-.16
82.6	86.5	86.5	8.7	.14	.10	.20	.00	.00	.02
83.2	86.9	86.9	8.7	1.80	3.15	***10.14***	.02	.04	***1.17***
84.7	88.1	88.1	8.8	.67	2.28	-6.43	.01	.03	-.73

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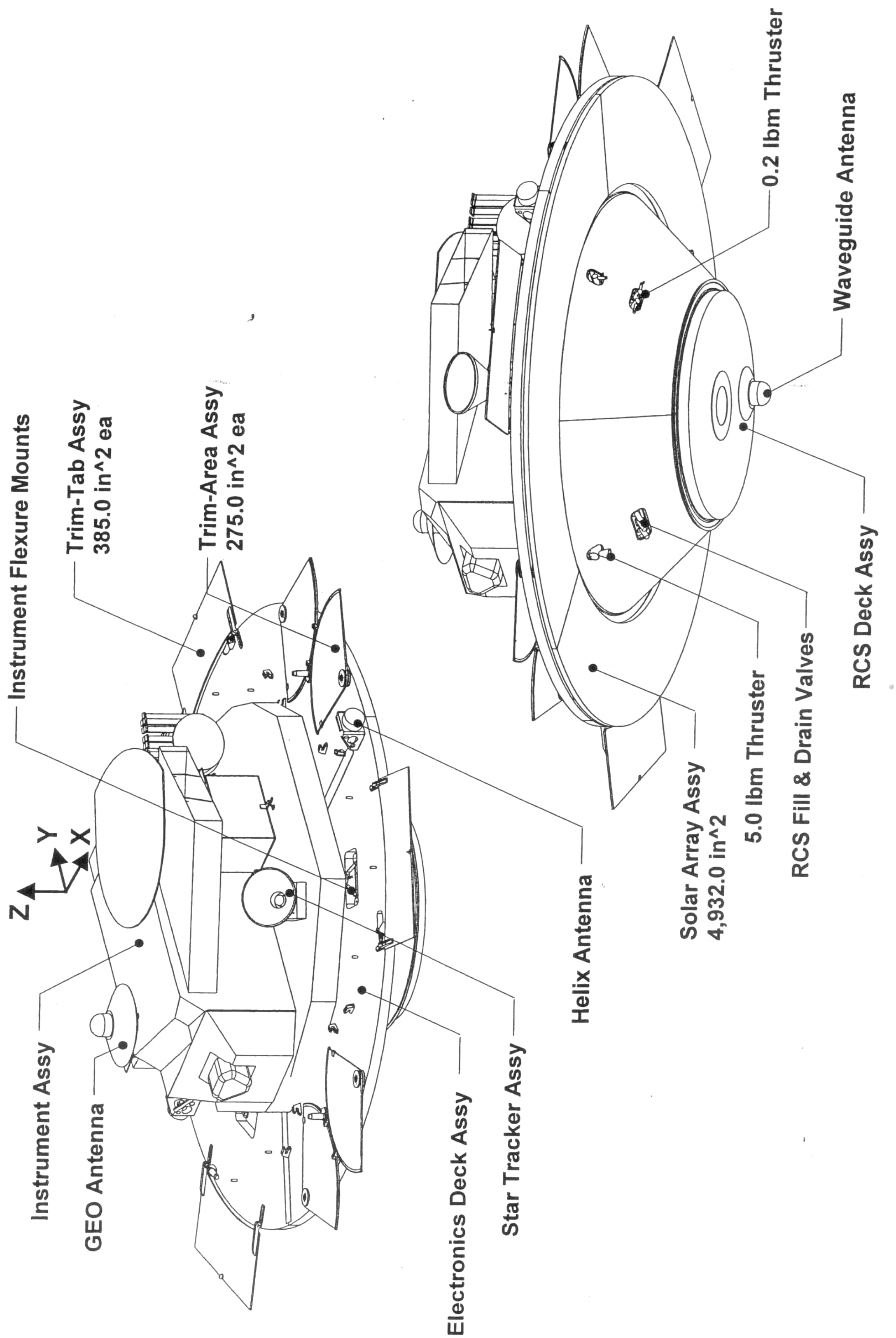


Figure 1 FAME showing the trim tabs

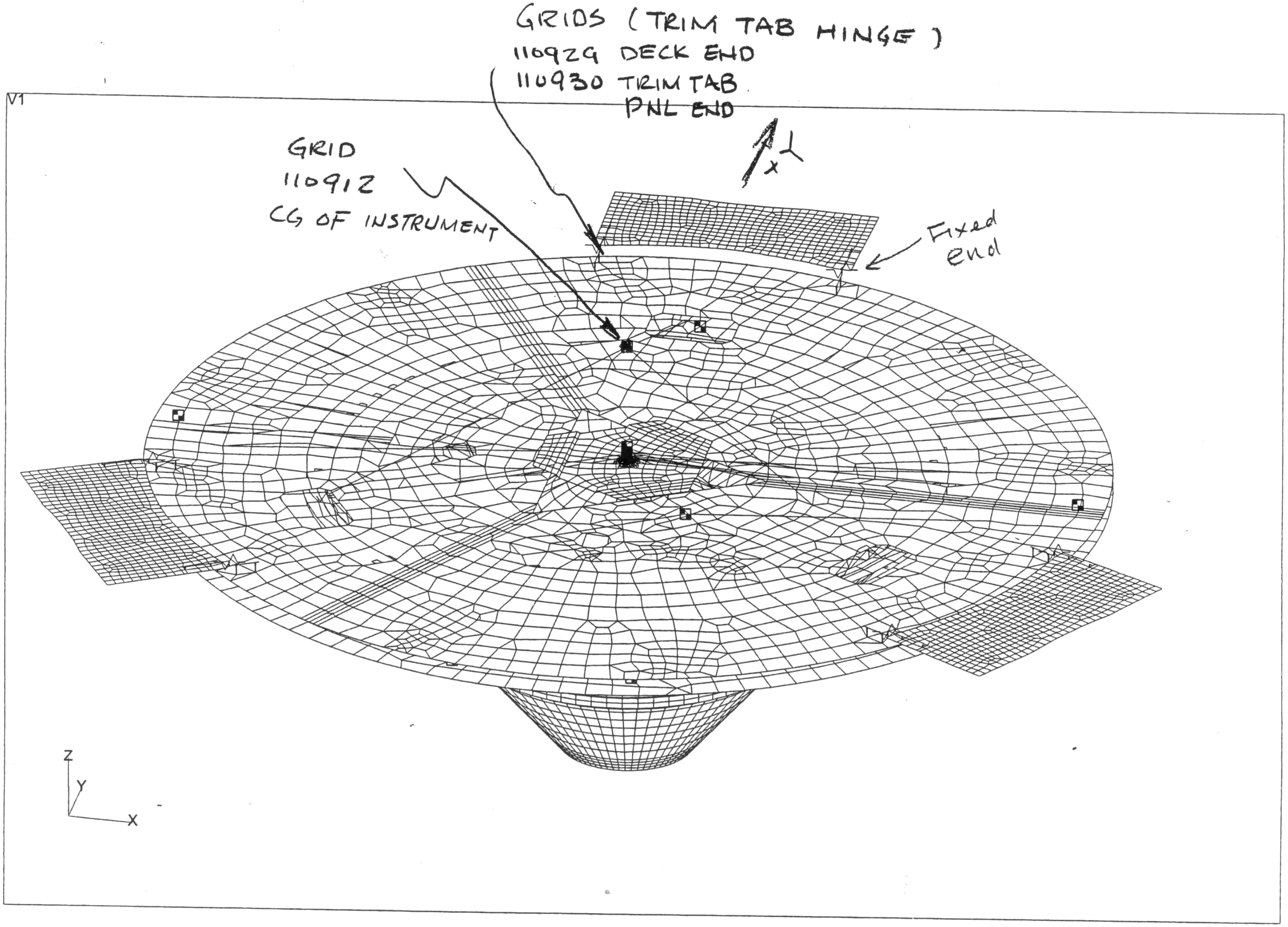


Figure 2 The Finite Element Model of FAME, deployed

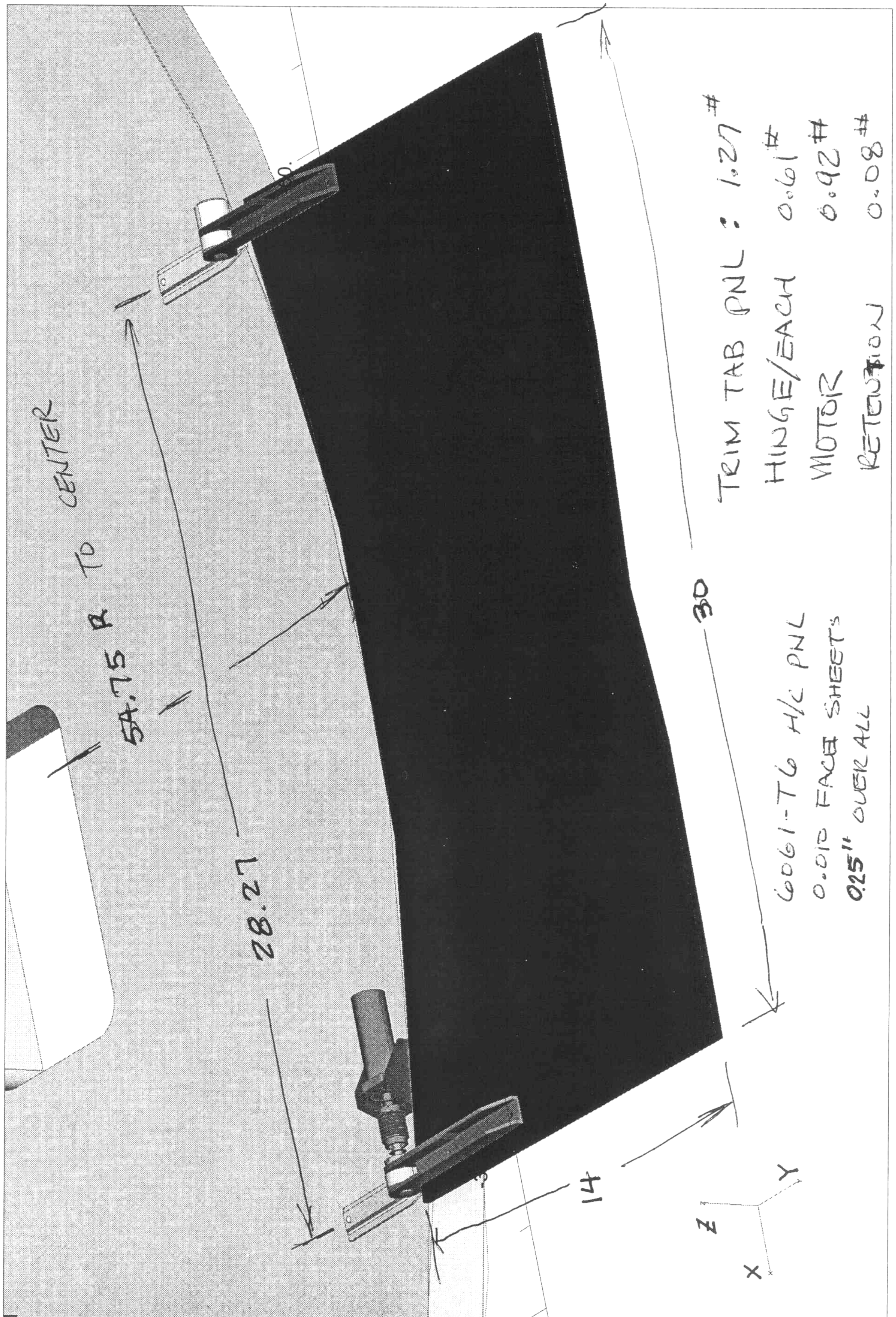


Figure 3 A rectangular trim tab with dimensions and properties

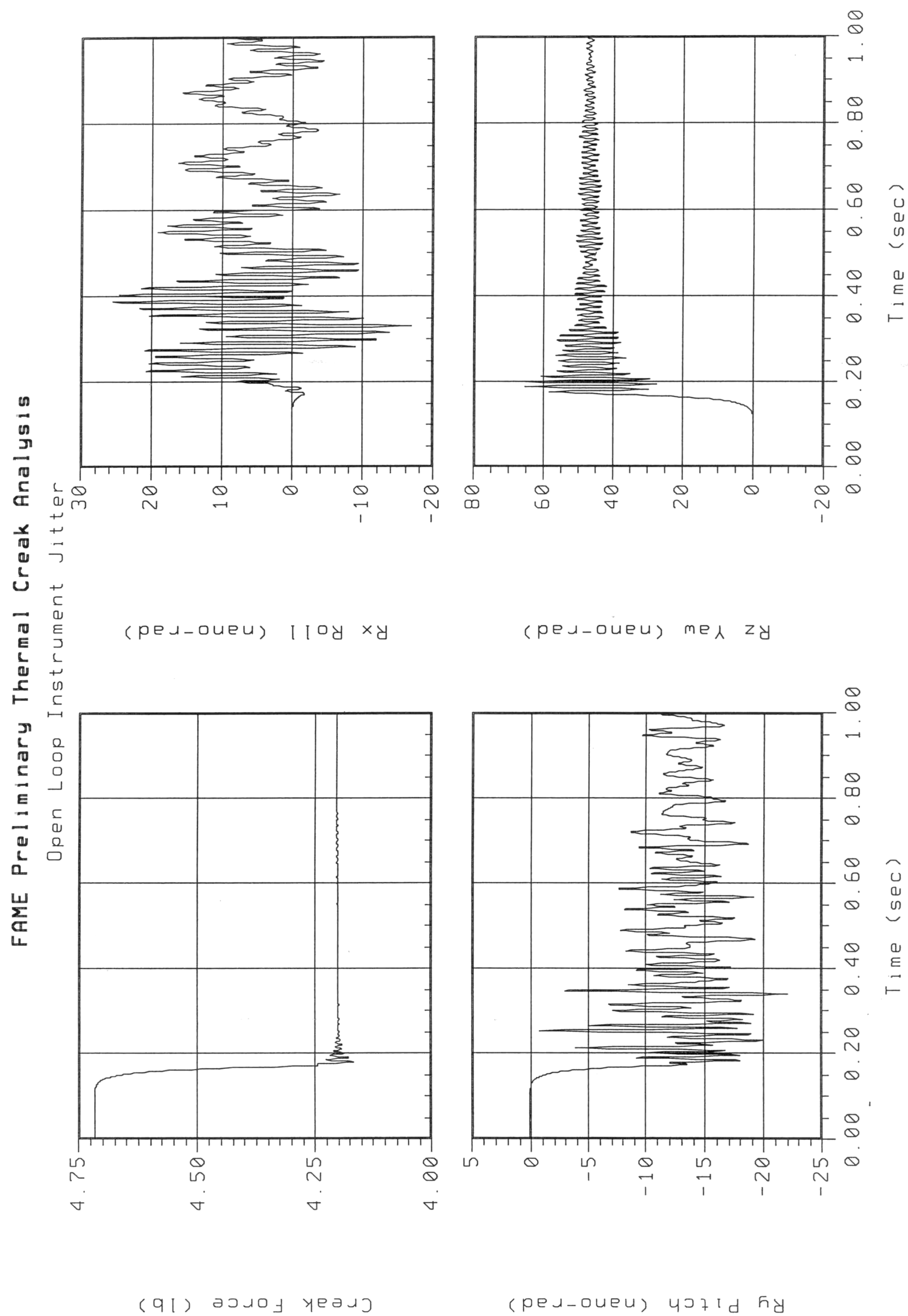
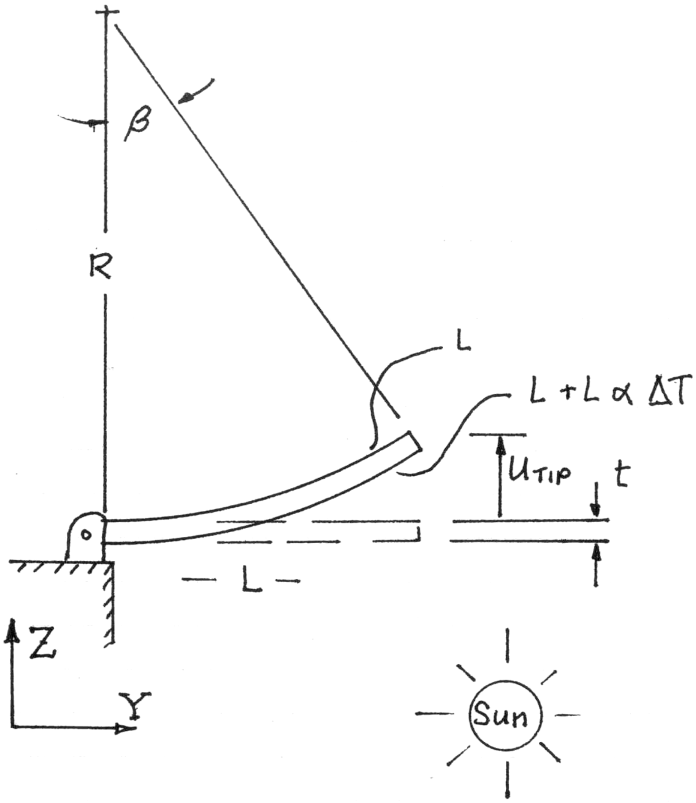


Figure 4 Dynamic Response to a Thermally Induced Creak at a Trim Tab Hinge



As the sunlight strikes the underside of the trim tab, it deflects out-of-plane causing a shift in mass.

ΔT = temp. gradient thru thickness

α = coef. of th. expan

Trim tab thermal defl. will be assumed circular, with constant radius R.

By geometry, $L = R\beta$

$$L + \alpha \Delta T L = (R + t)\beta$$

So, $R = \dfrac{t}{\alpha \Delta T}$, $\beta = \dfrac{L}{R}$

Trim tab tip displ., $u_{TIP} = R - R\cos\beta \approx \dfrac{R}{2}\beta^2 \approx \dfrac{L^2 \alpha \Delta T}{2t}$

Amount of out-of-plane mass shift

$$(W u)_{TOTAL} = \int_0^L \frac{W}{L} u \, dx = \frac{1}{3} W u_{TIP}$$

Figure 5 Trim Tab Bending Out-of-Plane from a Thermal Gradient