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# TEST STAND DESIGN AND ANALYSIS FOR TITAN 34D STATIC FIRING[1]

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**ABSTRACT**

The Test Stand 1C at the Air Force Astronautics Laboratory (AFAL), Edwards AFB, CA, was originally designed for F-1 liquid propellant engines. The stand was modified to handle a 5½-segment Solid Rocket Motor (SRM) Titan 34D vertical static firing test. The new configuration is the only nozzle-down test stand of long SRM's in the United States, which had to withstand 6.2MN (1.4M pounds) thrust load, and 2444 KN (550 Kips) rocket weight, as well as seismic and wind loads. The 3230 cm (106 feet) high stand was made of stainless steel truss system supported by a massive reinforced concrete foundation. The vertical and lateral thrust loads were mainly resisted by a four-legged pylon structure attached to the test stand and foundation. A superstructure was designed to house the rocket and provide working platforms for stacking operations. Several finite element models of the combined test stand-pylon-rocket were developed on ANSYS, NASTRAN and IMAGES-3D softwares. The models were analyzed for a variety of static, dynamic and transient loads to ensure the structural integrity of the test stand. This paper discusses the main design drivers and analysis effort utilized in the modification of the test stand.

## INTRODUCTION

The Test Stand 1C located at the Air Force Astronautics Laboratory (AFAL) at Edwards Air Force Base (EAFB) was one of the three nearby identical stands which were

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(1)Prepared under contract to the United Technologies Corporation, Chemical Systems Division, UTC-CSD Contract Number 268024.

designed, built and used to test liquid F-1 engines during the 1960's and was used for the last time in the early 1970's. The Titan 34D mishap in 1984 brought about a new Recovery Program that proposed the modified version of the existing test stand for static firing test of the Titan 34D Solid Rocket Motor (SRM) in the vertical nozzle-down configuration.

The main objectives of the program were as follows:

1. Perform a nozzle-down static firing test of a full scale 5½-segment solid rocket motor to evaluate the motor segment joints, to evaluate the accept/reject criteria established from the non-destructive tests on the candidate insulation material and to inspect and evaluate fleet motors. Criteria to meet primarily this objective were:

- o normal test conditions and motor performance
- o adequate measurements of motor performance
- o reasonable ablation rates calculated from insulation measurements

The motor would be conditioned cold (4.4°C or +40°F mean bulk) and test fired without thrust vector control or axial thrust measurement. A water quench system would be used to extinguish post test residual insulation burning and reduce soak-out temperatures.

2. Perform nozzle-down short burn and inert gas pressurization test of 2-segment fullscale motor configurations to evaluate the dynamics and the integrity of the joints at joint temperature and motor case pressurization rates

## ORIGINAL DESIGN

The Test Stand 1C was originally designed for liquid rocket engines and was configured for the Rocketdyne F-1 engines with 305 cm (120 in.) diameter and 406 cm (160 in.) long and a thrust force of 6.67 MN (1.5 Mlb) on liquid oxygen/RP-1 fuel. The engine was supported on a four-legged pylon which could support vertical upward loads of up to 35.56 MN (8 Mlb) and horizontal loads of 4.44 MN (1 Mlb).

## NEW REQUIREMENTS

The test stand had to modified to configure to the 305 cm

(120 in.) diameter, 1859 cm (61 feet) long Titan 34D SRM dimensions, 2444 KN (550 kips) weight and 6.2 MN (1.4 Mlb) thrust load for 2 minutes burntime with a nozzle canting of $6^{o}$ outward. A superstructure was required to be built on the existing stand to protect the rocket from wind loads, provide fixed and removable platforms for stacking operations, and to provide a lateral restraining structure at the forward end of the motor. The configuration was set up primarily for static firing test without any thrust vector control or axial thrust measurement. The load vectors that are imposed on the motor at launch and under planned test setup for the two conditions of the pre-firing static and the post-lift-off burn are shown in Figures 1 and 2. The test setup did not exactly reproduce the external loads on the motor because the test stand supported and restrained the motor uniformly at the aft stub skirt. This arrangement was acceptable based on the following reasons:

- There were no requirements for thrust vector control or axial thrust measurement
- The aft stub skirt was able to react the total thrust with an adequate margin of safety
- Lateral thrust loads resulting from the $6^{o}$ nozzle cant could be reacted through the aft stub skirt interface tooling
- Motor case and joint loads induced by motor pressurization during firing were considerably in excess of those resulting from externally applied loads, so it was not necessary to simulate external loading conditions.

The other loading criteria were as follows:

- wind load of 31.3 m/sec (70 mph)
- seismic load of 0.5 g (Zone 4) in the two horizontal axes acting simultaneously
- flight restraint lateral loads of 1280 KN (288 kips) in front-to-back and 364 KN (82 kips) in side-to-side directions applied to the superstructure at the forward end of the motor
- platforms in the superstructure had to carry a load of 12 persons per level

**NEW DESIGN**

The following modifications were made to the original stand (Fig.3) to adapt to the new requirements of Titan 34D static firing tests on the modified stand (Fig.4):

- o removal of the following

  five tone jib crane and liquid oxygen tanks from the top platforms above the tanks
  Two 36 WF beams from the top of the existing stand
  plumbing between the tanks
  Firex piping
  engine mount and thrust measuring H-beam
  tank support columns

- o Superstructure of K-type A36 steel frame added to the existing stand. The superstructure was to provide wind protection to the motor, fixed and removable platform for stacking operations and lateral restraint at the forward ring attachment at the 1463 cm (48 feet) level above the existing stand.

- o A forward ring (Fig.5) at the forward end of the motor that provided axial restraint through the anti-flight restraint cables and lateral restraint through snubber connection to the superstructure in both horizontal directions.

- o Pylon adaptor made of A36 steel and aft skirt fixture made of 4130 steel both designed to 44.4 MN (10 Mlb) vertical thrust load to provide interface between the pylon and the rocket aft end (Fig.6). The pylon adapter was designed to connect the existing rectangular pylon opening with the 305 cm (10 feet) diameter thrust cylinder. The aft skirt fixture was designed to provide the interface between the pylon adapter fixture and the motor aft stub skirt.

- o The pylon was attached to the test stand to provide better dynamic stability of the motor-pylon assembly. This improvement will be discussed later in the paper in more detail.

- o A working platform was added at 244 cm (8 feet) below the top of the existing stand to support a 6800 Kg (15000 lb) x-ray machine. The 5½ segment setup and configuration of the platforms are shown in Figure 7.

## ANALYSIS OF NEW DESIGN

Finite element analyses of the modified test stand were performed to ensure the structural integrity of the new design concept. Preliminary finite element analysis of the existing stand had been performed by IMAGES-3D structural code (Fig. 8). Trusses T-4 and T-5 (also shown in Fig. 4) are the main load carrying members of the existing stand to support the superstructure weight of 411 KN (92.5 Kips). The structure would reach its yield condition at a vertical load of 711 KN (160 Kips). Two of 12 WF members were found inadequate and were replaced by 24 WF 76 beams members. ANSYS and NASTRAN codes were used to model the test stand, the pylon and the motor. Three stand-pylon configurations were analyzed to obtain the most effective design concept:

I. Unattached: the pylon-motor assembly was completely detached from the stand

II. Partially attached: the pylon-motor assembly was attached at its forward ring elevation to the superstructure via snubbers

III. Completely attached: the pylon-motor assembly was attached to the superstructure by snubbers at the forward end and the pylon was attached to the stand at the pylon top level by steel plates.

### DYNAMIC ANALYSIS

Dynamic analysis of the unattached configuration indicated fundamental frequencies of 1.16 Hz for the pylon-motor assembly and 3.89 Hz for the test stand. Concerns were made at the dynamic characteristic of the pylon motor assembly at such low frequencies (Fig. 9). The fundamental frequency increased to 2.51 Hz for configuration II and to 2.79 Hz for configuration III with the latter one being adopted as an improved design over the unattached or partially attached concepts. Natural frequencies of the completely attached configuration are shown in Table 1.

### WIND LOAD ANALYSIS

The finite element model of the completely attached configuration was analyzed for wind load of 70 mph. The worst combination of wind loading on a rectangular cross section was considered as being 1693 $N/m^2$ (36 psf) on the front face, 1317 $N/m^2$ (28 psf) on the back face in the direction of the wind and 1317 $N/m^2$ (28 psf) sideway pressures acting outward. Analyses were performed separately for the major and minor axes of the stand. Results of the stress analysis are shown in Table 2. Factor of safety of order of 6 against the yield was reported for the wind loading.

## SEISMIC ANALYSIS

The combined model was analyzed for simultaneous application of 0.5 g seismic acceleration acting in the two horizontal axes of the stand. The lowest factor of safety of 1.47 against the yield was identified for a localized beam on the top of the existing stand which was considered insignificant due to large structural redundancies already built into the stand.

## THRUST LOAD ANALYSIS

The SRM thrust profile was enveloped to a ramp function reaching its peak of 6.2 MN (1.4 Mlb) at 0.30 seconds and staying flat up to 120 seconds at burnout.

Transient behavior of the stand was studied for the first few seconds after the start of firing. A maximum overshoot of 25% was observed in the displacement responses at 0.3 second, when the thrust force reached its peak, but it quickly damped out to its stationary value after one second from the start of firing. Transient responses of displacements and forces at the top and bottom of the motor are shown in Figure 11. A stress factor of safety of better than 3 was obtained under different stages of the thrust load.

## REACTION ANALYSIS

Reactions at the base of the stand and pylon were analyzed for two conditions during the firing and at the end of burnout (Tables 3 and 4). It can be seen that most of the thrust load is carried by the pylon structure.

The pylon is mounted to concrete with forty steel anchors - ten anchors per leg. Each anchor is 5.72 cm (2.25 inches) in diameter and 1158 cm (38 feet) long. The anchors are made of 4340 quenched and tempered steel with an ultimate strength of 677 $MN/m^2$ (100 ksi) and yield strength of 542 $MN/m^2$ (80 ksi).

Detailed analysis of anchor/concrete interface has been performed taking into account anchor/concrete relative stiffness and specified anchor bolt preload of 889 KN (200 kips). The results of the analysis limit maximum postulated thrust force to 35.56 MN (8 Mlb) which was consistent with the original design for liquid F-1 engine tests. The maximum required postulated thrust force of 44.44 MN (10 Mlb) did not exceed the ultimate strength of the anchor.

## CONCLUSIONS

The main design drivers in the modification of the F-1 liquid propellant engine Test Stand 1C to accommodate for the Titan 34D solid rocket booster nozzle-down static firing test were:

- o vertical thrust load and lateral thrust load (caused by $6^o$ nozzle cant) of the SRM are an order of magnitude larger than liquid engines and they have to be resisted primarily by the pylon structure.

- o due to a much heavier and taller SRM with respect to liquid engines, resonance frequencies of the motor-pylon assembly will become a critical factor in the stability of the assembly under dynamic environments such as earthquake, wind and transient thrust loads. For this reason, the motor-pylon assembly had to be tied-in to the test stand at the pylon level and the motor forward end had to be attached to the superstructure. This tied-in configuration increased the fundamental frequency of the assembly by a factor of 2.4.

- o no thrust vector control or axial thrust measurement was required for this Titan 34D static firing test. The anti-flight forward end restraint cables and snubbers and the uniform restraint pylon system at the aft end considered to be acceptable in lieu of the actual restraint system of the SRM to the core vehicle.

TABLE 1. - GLOBAL NATURAL FREQUENCIES (Hz)

| | ANSYS | NASTRAN | MODE DIRECTION |
|---|---|---|---|
| **UNATTACHED PYLON-STAND (CASE I)** | | | |
| Pylon | 1.16 | 1.18 | 1x(*) |
| | 1.25 | 1.31 | 1z |
| Stand | 3.89 | 4.29 | 1z |
| | 5.42 | 6.38 | 1x |
| **PARTIALLY ATTACHED (CASE II)** | | | |
| | 2.51 | 2.74 | 1z |
| | 2.70 | 2.98 | 1x |
| | 5.12 | 5.26 | Combined |
| | 7.11 | 7.35 | 2z |
| | 7.31 | 7.49 | 2x |
| **COMPLETELY ATTACHED (CASE III)** | | | |
| | 2.79 | 3.0 | 1x |
| | 2.84 | 3.0 | 1z |
| | 7.09 | 7.36 | 2z |
| | 7.44 | 7.69 | 2x |

(*) x, y, z correspond to side-to-side, vertical and road-to-flame directions respectively.

TABLE 2. - STRESS AND DISPLACEMENT SUMMARY

| Loading/Condition | Maximum Stress $MN/m^2$ (ksi) | Factor of Safety (Against Yield) | Displacement cm (inches) |
|---|---|---|---|
| Dead Load (DL) | 22.35 (3.3) | 10.91 | .28 (.11y)(2) |
| Front wind and DL | 39.97 (5.9) | 6.10 | .08 (.03z) |
| Side wind and DL | 35.22 (5.2) | 6.92 | .05 (.02x) |
| Seismic (combined x & z) and DL | 165.96 (24.5) | 1.47 | 2.29 (.9 x and z) |
| Thrust and DL (Case II) | 29.81 (4.4) | 8.18 | .15 (.06y) |
| Thrust and DL (Case III) | 63 (9.3) | 3.87 | .05 (.02y) |
| Thrust (end of burnout) and DL (Case III) | 75.87 (11.2) | 3.21 | .28 (.11y) |
| Ultimate load(1) at top and DL | 216.77 (32) | 1.13 | 3.38 (1.33z) |

(1) 1280 KN (288 kips) in z- and 364 KN (82 kips) in x-directions applied at strut elevation.

(2) x, y, z correspond to side-to-side, vertical and road-to-flame directions respectively.

TABLE 3. - REACTION FORCES OF THE RESTRAINT SYSTEM DURING THE STATIC FIRING TEST

| Item | Fx | Fy | Fz | Mx | My | Mz |
|---|---|---|---|---|---|---|
| Stand | 44 (10) | 329 (74) | -49 (-11) | -497 (-44) | 226 (20) | 858 (76) |
| Base Reactions | 44 (-10) | 329 (74) | -53 (-12) | -576 (-51) | -226 (-20) | -835 (-74) |
| | 62 (14) | 271 (61) | 4 (1) | -2213 (-196) | 293 (26) | 847 (75) |
| | -62 (-14) | 267 (60) | 9 (2) | -2303 (-204) | -305 (-27) | -926 (-82) |
| Stand Subtotal | 0 (0) | 1196 (269) | -89 (-20) | -5589 (-495) | -12 (-1) | -56 (-5) |
| Pylon | -169 (-38) | -124 (-28) | 36 (8) | 2371 (210) | 5159 (457) | 13953 (1236) |
| Base Reactions | 169 (38) | -124 (-28) | 36 (8) | 2303 (204) | -5159 (-457) | -13885 (-1230) |
| | 573 (129) | -676 (-152) | -302 (-68) | -10792 (-956) | -1897 (-168) | -14867 (-1317) |
| | -573 (-129) | -676 (-152) | -302 (-68) | -10770 (-954) | 1818 (161) | 15082 (1336) |
| Pylon Subtotal | 0 (0) | -1600 (-360) | -533 (-120) | -16888 (-1496) | -79 (-7) | 283 (25) |
| TOTAL | 0 (0) | -404 (-91) | -622 (-140) | -22476 (-991) | -90 (-8) | 226 (20) |

Notes:

(1) Force units are in KN, Kips in parentheses. Moments units are in KN-cm, Kips-in. in parentheses.
(2) (+) sign is in direction of positive global coordinates.
(3) Maximum force at top strut is 3316 N (746 lbs).
(4) Forces at the pylon to the stand connection are distributed as follows:

| | Fy | Fz |
|---|---|---|
| To the pylon | 2631 (592) | 542 (122) |
| To the stand | 1013 (228) | 80 (18) |
| TOTAL | 3644 (820) | 622 (140) |

(5) Rocket weight is 2444 KN (550 Kips).

(6) Force Checkout in vertical direction:

| | Fy |
|---|---|
| Rocket and pylon weight | -3604 (-811) |
| Stand Weight | -2213 (-498) |
| Thrust Load | 6222 (+1400) |
| Reaction at pylon | -1600 (-360) |
| Reaction at stand | 1195 (+269) |
| TOTAL | 0 (0) |

## TABLE 4. - REACTION FORCES OF THE RESTRAINT SYSTEM AT THE END OF FIRING

| Item | Fx | Fy | Fz | Mx | My | Mz |
|---|---|---|---|---|---|---|
| Stand | 13 (3) | 271 (61) | -49 (-11) | -542 (-48) | 214 (19) | 982 (87) |
| Base Reactions | -13 (-3) | 271 (61) | -52 (-12) | -610 (-54) | -214 (-19) | -948 (-84) |
| | 31 (7) | 213 (48) | 4 (1) | -2156 (-191) | 305 (27) | 971 (86) |
| | -31 (-7) | 209 (47) | 9 (2) | -2235 (-198) | -305 (-27) | -1027 (-91) |
| Stand Subtotal | 0 (0) | 964 (217) | -88 (-20) | -5543 (-491) | 0 (-0) | -22 (-2) |
| Pylon | -529 (-119) | 622 (-140) | 209 (47) | 1558 (138) | 5069 (449) | 11966 (1060) |
| Base Reactions | 529 (119) | -622 (-140) | 209 (47) | 1479 (131) | -5035 (-446) | -11763 (-1042) |
| | 933 (210) | -1173 (-264) | -476 (-107) | -9968 (-883) | -2021 (-179) | -12745 (-1129) |
| | -933 (-210) | -1173 (-264) | -476 (-107) | -9968 (-883) | 1919 (170) | 13095 (1160) |
| Pylon Subtotal | 0 (0) | -3590 (-808) | -534 (-120) | -16899 (-1497) | -68 (-6) | 553 (49) |
| TOTAL | 0 (0) | -2626 (-591) | -622 (-140) | -22442 (-1988) | -68 (-6) | 531 (47) |

Notes:

(1) Force units are in KN, Kips in parentheses. Moment units are in KN-cm, Kips-in. in parentheses.

(2) (+) sign is in direction of positive global coordinates.

(3) Maximum force at top strut is 3467 N (780 lbs).

(4) Forces at the pylon to the stand connection are distributed as follows:

| | Fy | Fz |
|---|---|---|
| To the pylon | 4622 (1040) | 542 (122) |
| To the stand | 1244 (280) | 80 (18) |
| TOTAL | 5866 (1320) | 622 (140) |

(5) Rocket weight at the end of firing is 222 KN (50 Kips).

(6) Force Checkout in vertical direction:

| | Fy |
|---|---|
| Rocket and pylon weight | -1382 (-311) |
| Stand Weight | -2213 (-498) |
| Thrust Load | 6222 (+1400) |
| Reaction at pylon | -3591 (-808) |
| Reaction at stand | 964 (217) |
| TOTAL | 0 (0) |

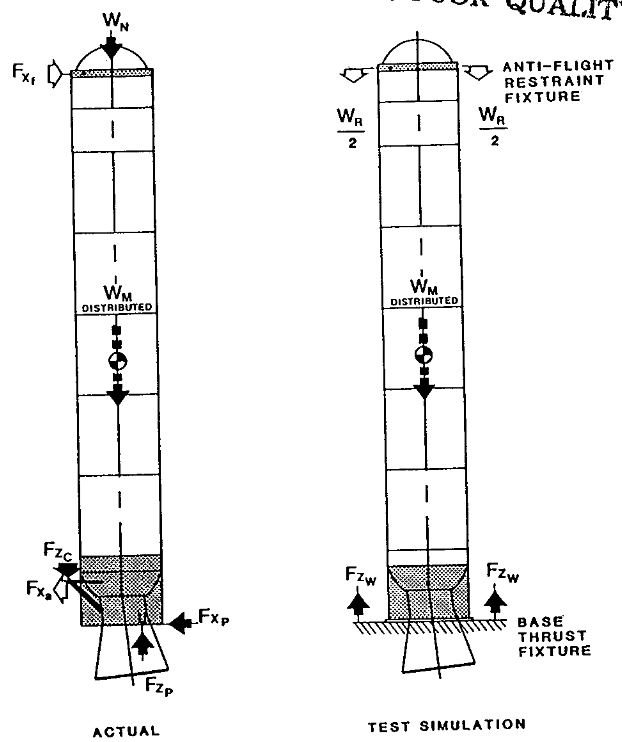


FIGURE 1. COMPARISON OF THE LOAD RESTRAINT SYSTEM BETWEEN ACTUAL AND TEST SIMULATION - PREFIRE

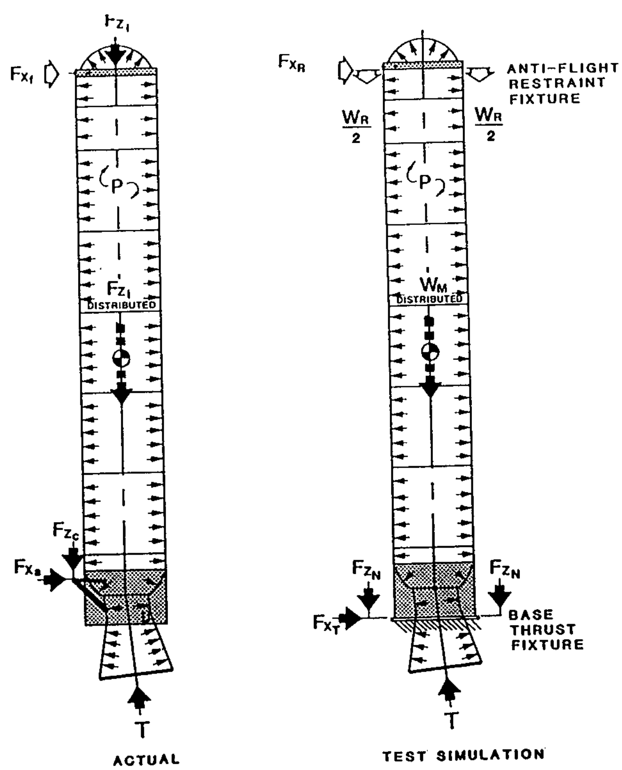


FIGURE 2. COMPARISON OF THE LOAD RESTRAINT SYSTEM BETWEEN ACTUAL AND TEST SIMULATION - POST LIFTOFF

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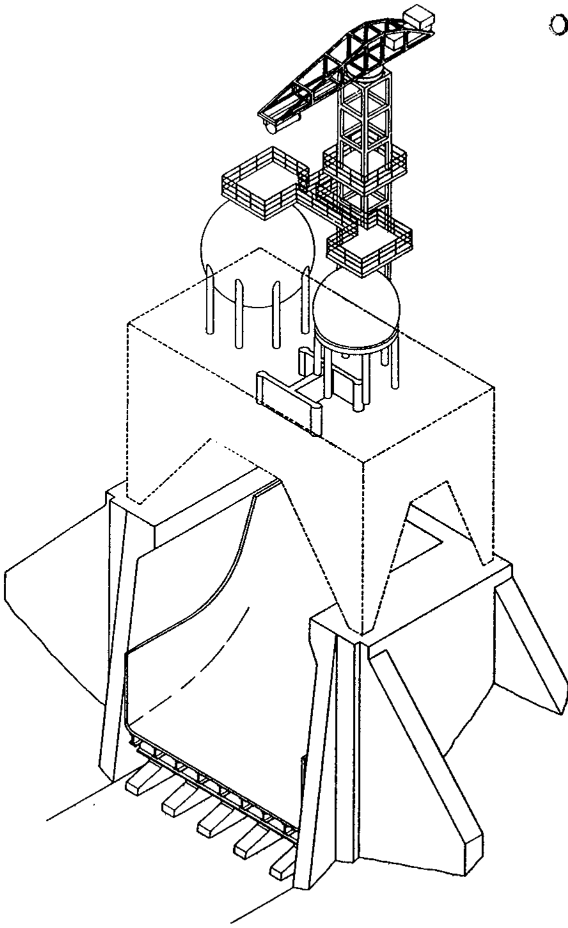

FIGURE 3. ORIGINAL TEST STAND

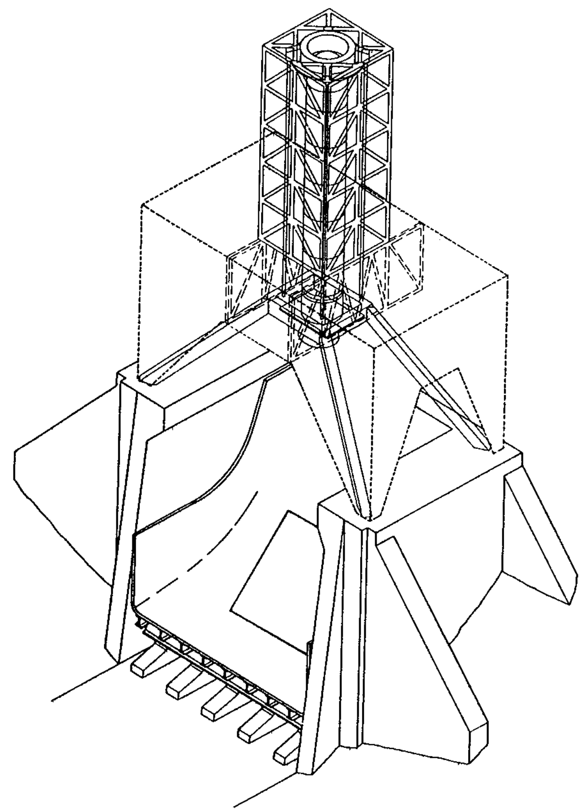

FIGURE 4. MODIFIED TEST STAND

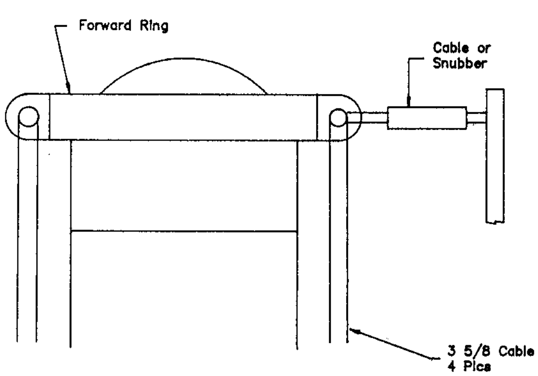


FIGURE 5. FORWARD END RESTRAINT SYSTEM

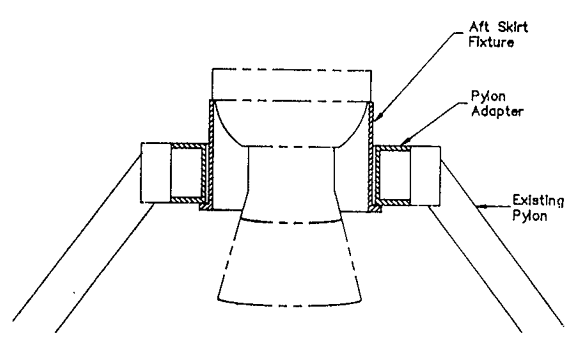


FIGURE 6. AFT END RESTRAINT SYSTEM

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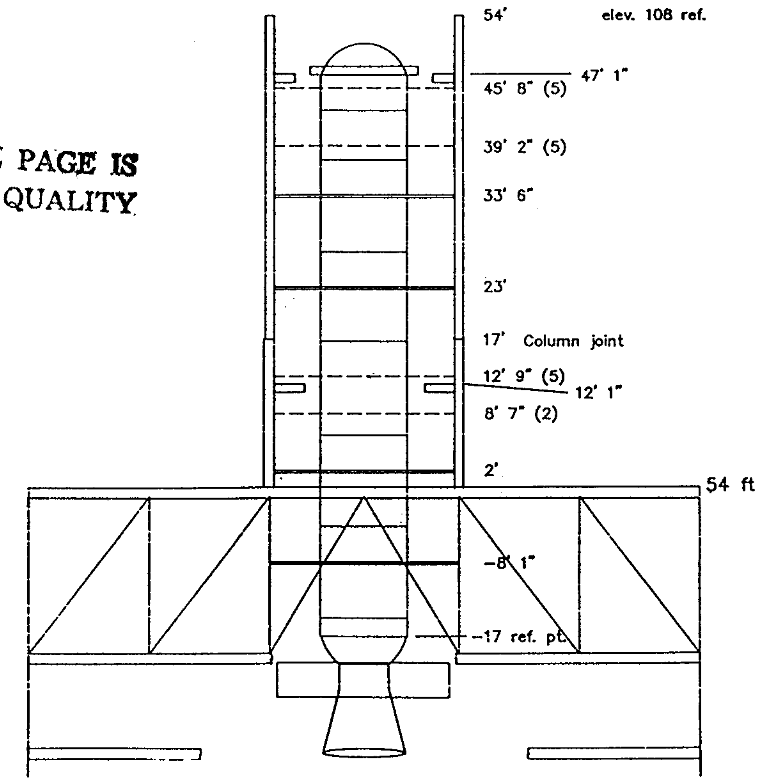



FIGURE 7. 5-1/2 MOTOR SEGMENT SETUP

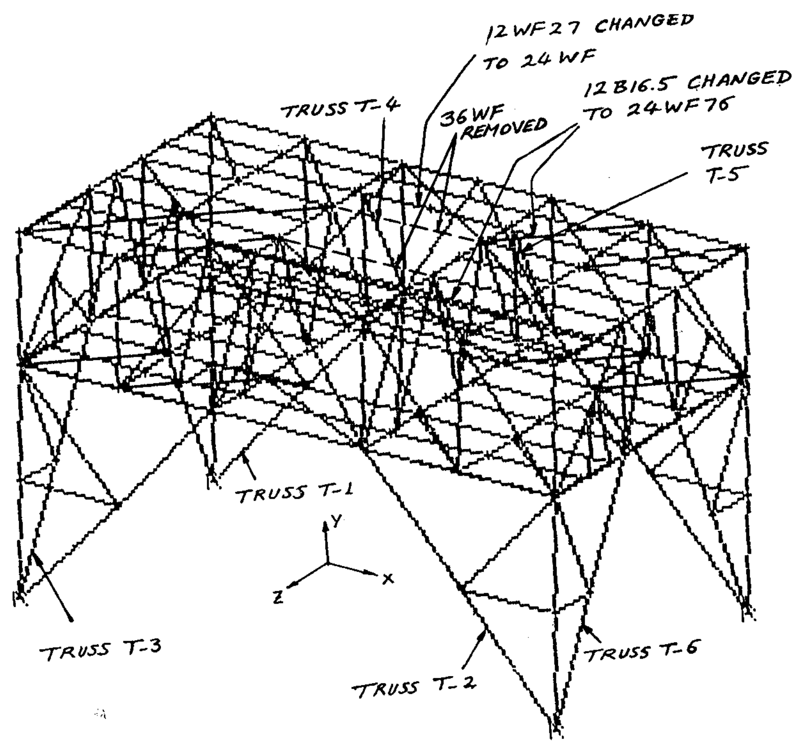
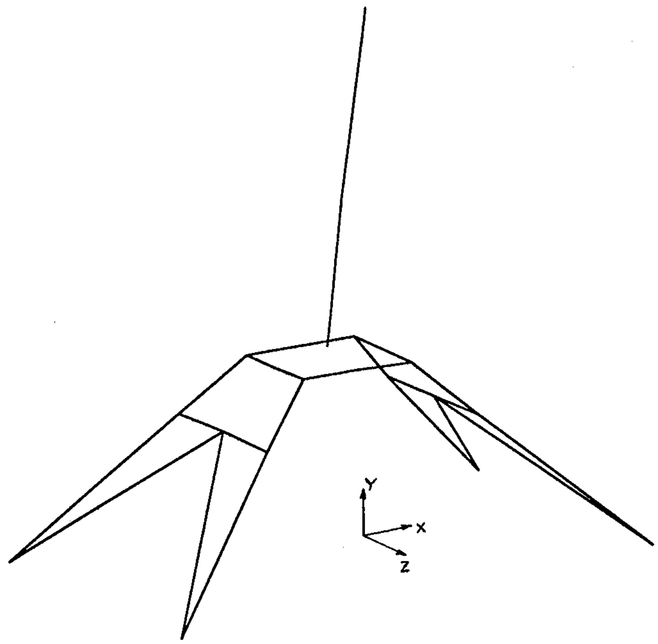
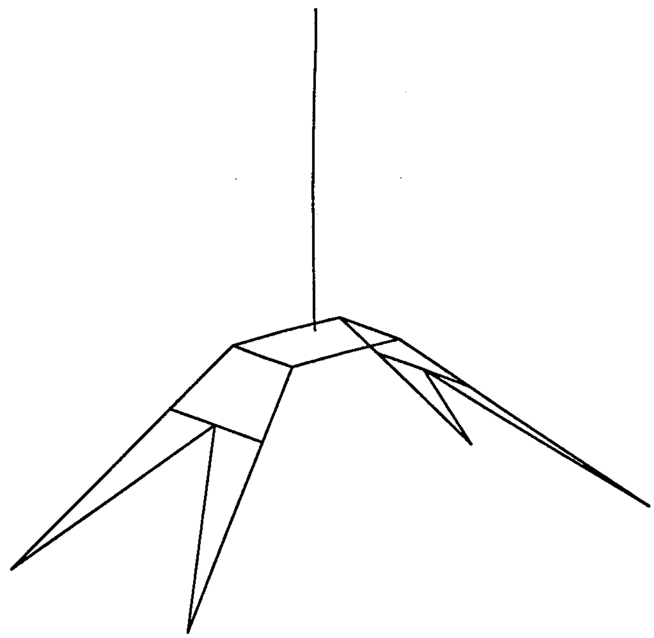


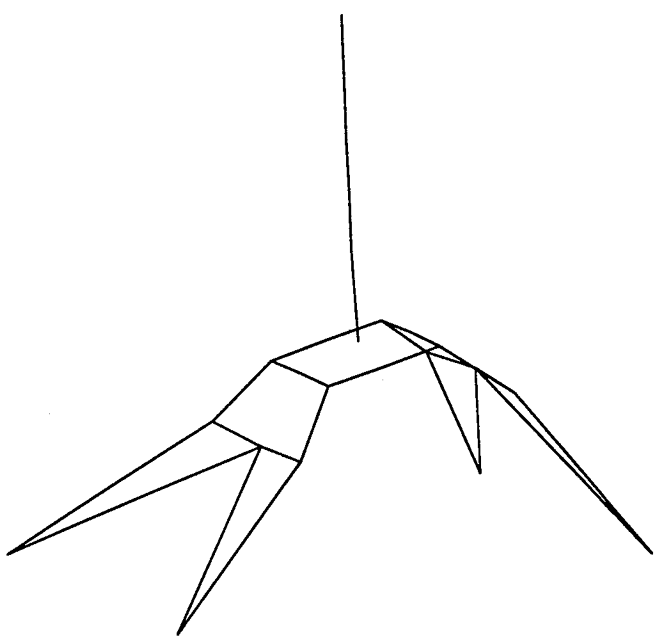

FIGURE 8. FINITE ELEMENT MODEL OF THE EXISTING STAND



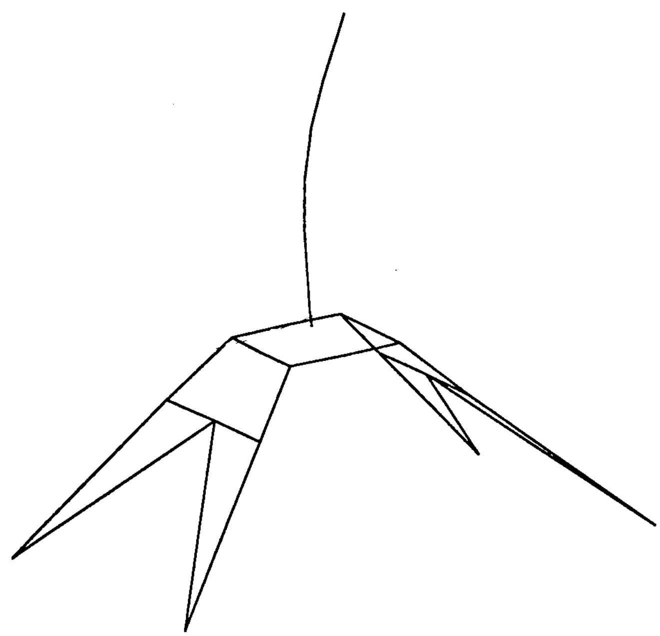

(A) MODE 1 - 1.16 Hz



(B) MODE 2 - 1.25 Hz

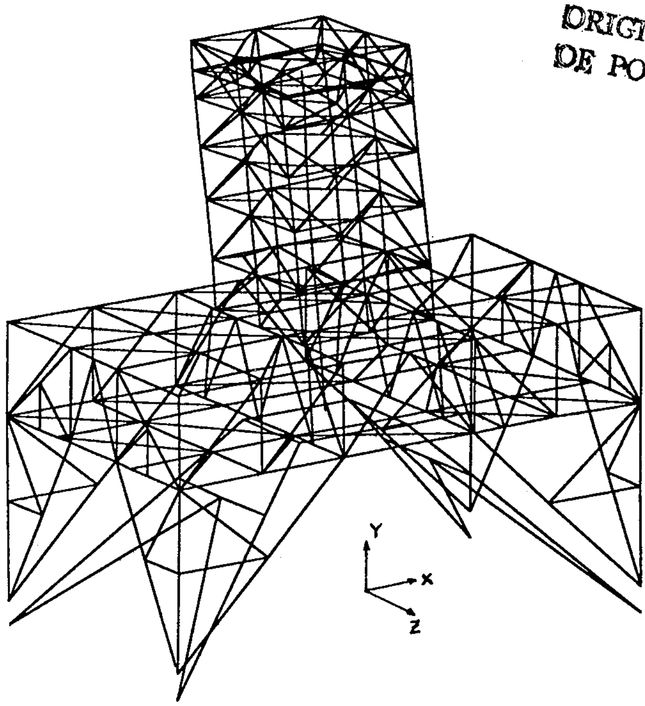


(C) MODE 3 - 5.99 Hz

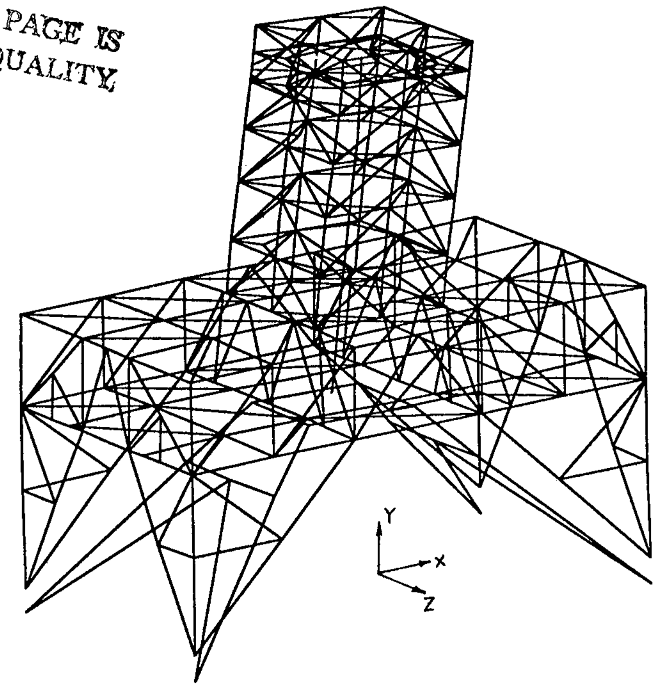


(D) MODE 4 - 7.47 Hz

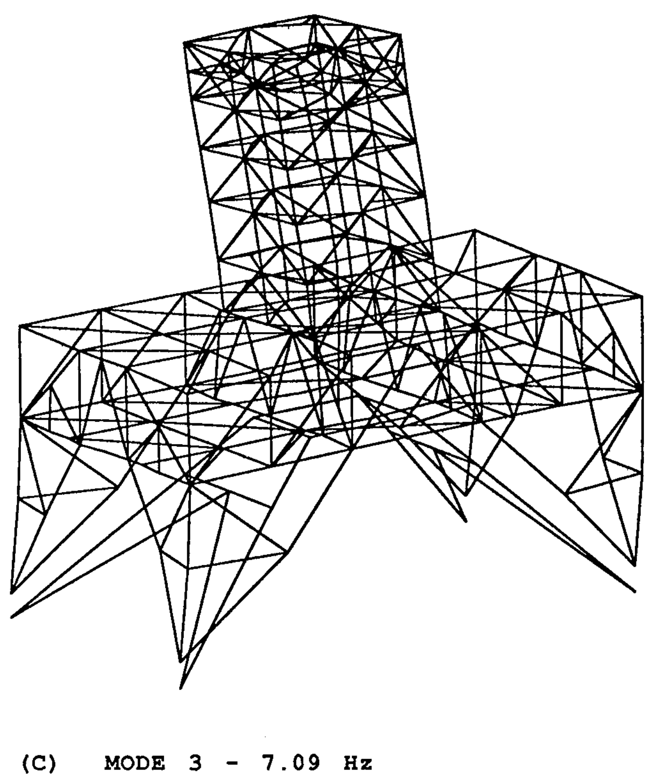
FIGURE 9. NATURAL FREQUENCIES OF THE PYLON-MOTOR ASSEMBLY



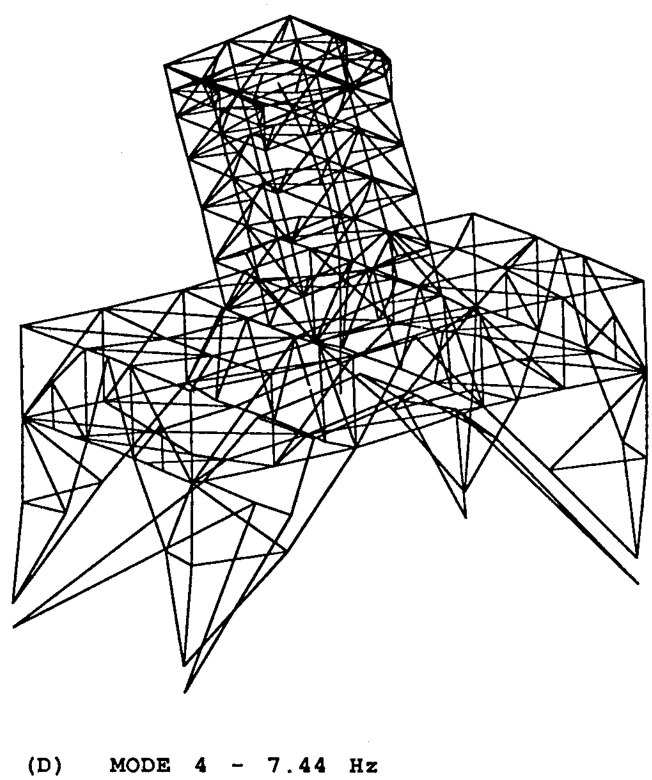

(A) MODE 1 - 2.79 Hz




(B) MODE 2 - 2.84 Hz

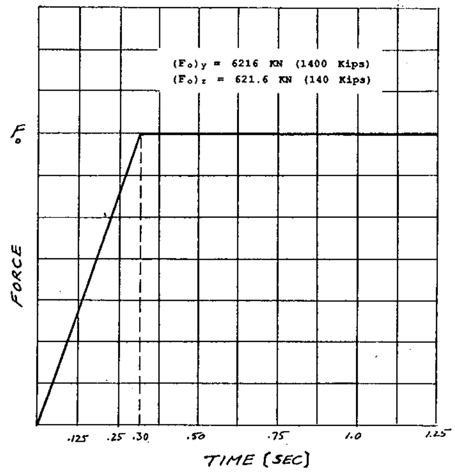


(C) MODE 3 - 7.09 Hz

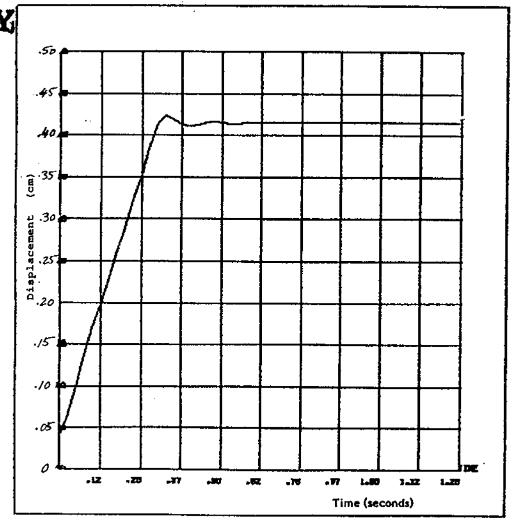


(D) MODE 4 - 7.44 Hz

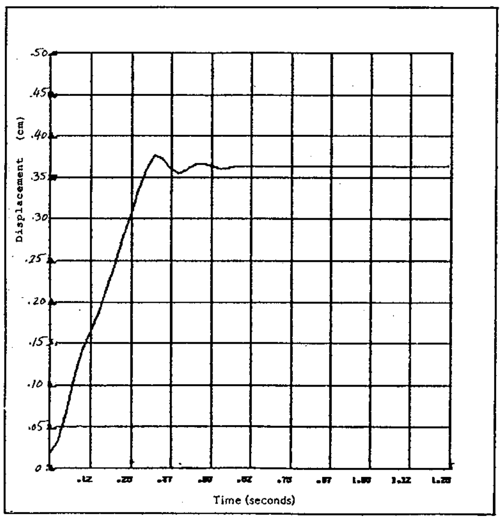
FIGURE 10. NATURAL FREQUENCIES OF THE COMPLETELY ATTACHED STAND-PYLON-MOTOR ASSEMBLY



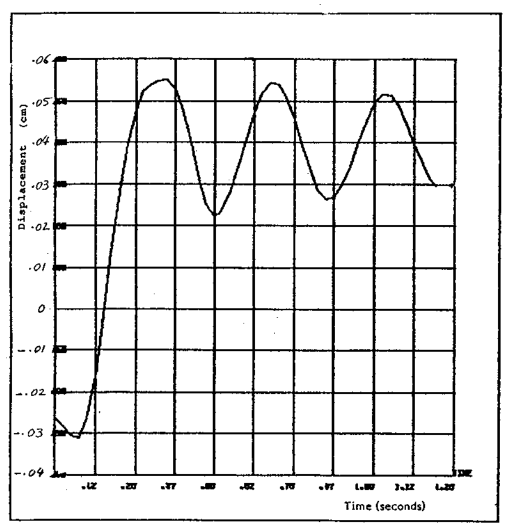

(A) IDEALIZED THRUST LOAD



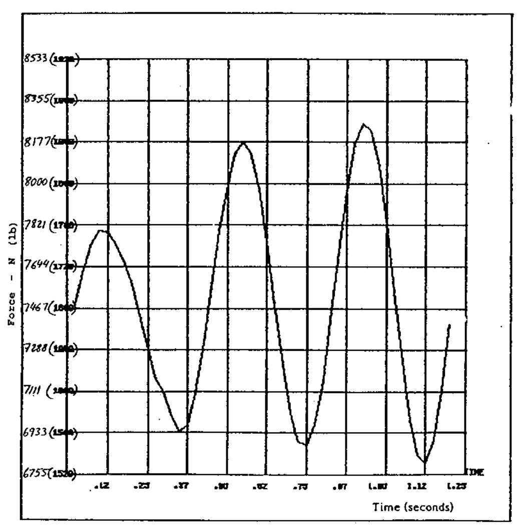

(B) VERTICAL DISPLACEMENT AT THE BASE OF THE MOTOR



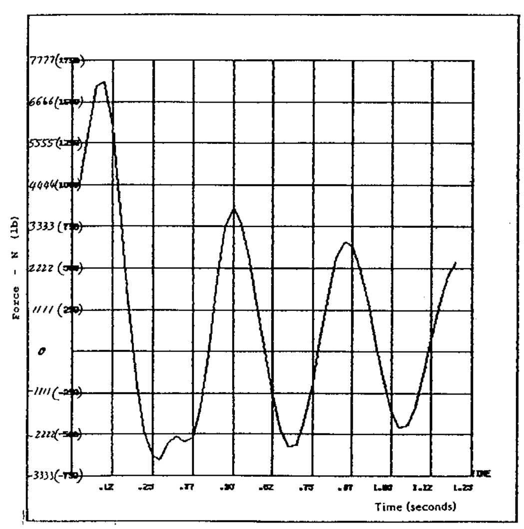

(C) VERTICAL DISPLACEMENT AT THE TOP OF THE MOTOR




(D) LATERAL DISPLACEMENT (Z) AT THE TOP OF THE MOTOR




(E) LATERAL FORCE (X) IN THE FORWARD END UNISTRUT




(F) LATERAL FORCE (Z) IN THE FORWARD END UNISTRUT

**FIGURE 11. TIME HISTORY RESULTS DUE TO THRUST LOADS**