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NASA TECHNICAL MEMORANDUM

NASA TM-78260

(NASA-TM-78260) FINITE ELEMENT MODELS OF THE SPACE SHUTTLE MAIN ENGINE (NASA) 70 p HC A04/MF A01 CSCL 21H

N80-17140

Unclas

G3/20 47208

FINITE ELEMENT MODELS OF THE SPACE SHUTTLE MAIN ENGINE

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January 1980

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	THE HPFTP ROTOR MODEL	2
III.	THE HPFTP CASE MODEL	2
IV.	THE COUPLED HPFTP ROTOR AND CASE (RPL)	3
V.	THE HPOTP ROTOR MODEL	4
VI.	THE HPOTP CASE MODEL	5
VII.	THE COUPLED HPOTP ROTOR AND CASE (RPL)	5
VIII.	THE SSME MODEL (RPL)	6
IX.	SUMMARY	7
BIBLIOGRAPHY		61

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LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	HPFTP rotor model	8
2.	HPFTP rotor, mode 7	9
3.	HPFTP rotor, mode 11	9
4.	HPFTP case model	10
5.	Intrinsic stiffness element notation	11
6.	HPFTP case, mode 4	12
7.	HPFTP case, mode 5	12
8.	Coupled HPFTP rotor and case (RPL), mode 8	13
9.	Coupled HPFTP rotor and case (RPL), mode 10	13
10.	Coupled HPFTP rotor and case (RPL), mode 14	14
11.	HPOTP rotor model	15
12.	HPOTP rotor, mode 7	16
13.	HPOTP rotor, mode 10	16
14.	HPOTP case model	17
15.	HPOTP case, mode 3	18
16.	HPOTP case, mode 5	18
17.	Coupled HPOTP rotor and case (RPL), mode 5	19
18.	Coupled HPOTP rotor and case (RPL), mode 9	19
19.	Coupled HPOTP rotor and case (RPL), mode 11	20

LIST OF ILLUSTRATIONS (Concluded)

Figure	Title	Page
20.	Coupled HPOTP rotor and case (RPL), mode 13	20
21.	SSME model	21
22.	SSME (excluding turbopumps), mode 12	22
23.	SSME (excluding turbopumps), mode 15	22
24.	SSME (excluding turbopumps), mode 18	23
25.	SSME (excluding turbopumps), mode 19	23
26.	SSME (including turbopumps), mode 23..............	24
27.	SSME (including turbopumps), mode 30..............	24
28.	SSME (including turbopumps), mode 33..............	25
29.	SSME (including turbopumps), mode 34..............	25
30.	SSME and major component spectra	26
31.	SSME measurement points	27
32.	Comparison of SSME model and HPOTP modal survey frequencies	28

LIST OF TABLES

Table	Title	Page
1.	HPFTP Rotor Model Data	29
2.	HPFTP Rotor Modes	31
3.	HPFTP Case Model Data	32
4.	HPFTP Case Modes	35
5.	HPFTP Parametric Configurations	36
6.	HPFTP Case and Rotor Coupling Elements	37
7.	Coupled HPFTP Rotor and Case Modes (RPL)	38
8.	HPOTP Rotor Model Data	39
9.	HPOTP Rotor Modes	41
10.	HPOTP Case Model Data	42
11.	HPOTP Case Modes	45
12.	HPOTP Rotor and Case Coupling Elements	46
13.	Coupled HPOTP Rotor and Case Modes (RPL)	49
14.	SSME Model Data	50
15.	SSME Modes (Excluding Turbopumps)	57
16.	SSME Modes (Including Turbopumps)	58
17.	Comparison of SSME Model and HPOTP Modal Survey Frequencies	60

TECHNICAL MEMORANDUM

FINITE ELEMENT MODELS OF THE SPACE SHUTTLE MAIN ENGINE

I. INTRODUCTION

This report documents the culmination of a 2 year effort from May 1976 to April 1978 to develop finite element models as input to dynamic simulations of the High Pressure Fuel Turbopump (HPFTP), the High Pressure Oxidizer Turbopump (HPOTP), and the Space Shuttle Main Engine (SSME).

These models were developed using the SPAR finite element computer program maintained by Engineering Information Systems, Inc., San Jose, California.

Mass distribution, seal and bearing stiffnesses, and empirical test data for the individual turbopumps were supplied through working papers and internal letters furnished through the SSME prime contractor, Rocketdyne Division, Rockwell International, Canoga Park, California.

Mass distribution and actuator stiffness for the SSME were provided by the Shuttle Projects Office, George C. Marshall Space Flight Center (MSFC), Alabama.

Engineering drawings were obtained from the Documentation Repository, MSFC, Alabama.

Descriptions are provided for the five basic finite element models: HPFTP rotor, HPFTP case, HPOTP rotor, HPOTP case, and SSME (excluding turbopumps).

Modal results are presented for the HPFTP rotor, HPFTP case, coupled HPFTP rotor and case, HPOTP rotor, HPOTP case, coupled HPOTP rotor and case, SSME (excluding turbopumps), and SSME (including turbopumps).

Results for the SSME (including turbopumps) model are compared to data from a SSME HPOTP modal survey conducted at the NSTL, Bay St. Louis, Mississippi.

II. THE HPFTP ROTOR MODEL

The HPFTP rotor (Fig. 1) consists of a stack of three centrifugal impellers held together by a common central tie-bolt under tension. These three impellers act as a three-stage centrifugal pump when driven by the two-stage hot gas turbine threaded to the head of the tie-bolt. The rotor is supported within the HPFTP case by double ball bearings at either end, pump interstage seals, and a balance piston to limit axial translation. Nominal operating speed of the rotor is between 23 700 rpm (Minimum Power Level, MPL) and 37 360 rpm (Full Power Level, FPL).

The SPAR model of the rotor, an adaptation of a Rocketdyne model based on rotor geometry, is composed of 12 joints with 72 degrees-of-freedom and 14 beam elements of which two are Bently arms at the pump end of the rotor shaft. Dimensions, mass distribution (neglecting entraped LH_2), and beam element connectivity and properties are listed in Table 1.

Table 2 lists HPFTP rotor free-free frequencies and modal descriptions through the first axial mode for the baseline "637 Hz" rotor and an interim parametric study "500 Hz" rotor which was obtained by artificially reducing Young's Modulus of the baseline rotor. The "500 Hz" rotor is discussed further in Section IV. Figures 2 and 3 depict the first two rotor free-free bending modes (dotted lines) relative to the HPFTP case. The short solid lines apparently connecting the rotor and case actually illustrate the displacement loci of rotor bearing and seal locations from the rotor neutral position.

III. THE HPFTP CASE MODEL

The HPFTP case (Fig. 4) which encloses and supports the HPFTP rotor is, in turn, cantilevered from the SSME via a hot gas manifold which ducts exhaust gases from the pump turbine into the SSME powerhead. A preburner powers the turbine. The case also supports two aluminum diffusers by means of internal lugs. These diffusers duct the LH_2 between the three rotor impellers. Instrumentation added to the case for single engine firing tests include three radial accelerometers attached to the case inlet flange; an axial and two radial accelerometers attached to the turbine flange; and an axial accelerometer, an axial Bently, and two radial Bentlys attached to the pump inlet case.

The SPAR model of the case was initially, like the rotor, an adaptation of a Rocketdyne model. However, as empirical data from Rocketdyne rap tests and static influence coefficients tests became available, the SPAR model was modified accordingly. Thus the beam element properties of the hot gas manifold were adjusted to match pump cantilever frequencies of 47 and 100 Hz. Static influence coefficients were obtained by bolting the turbine flange (joint 31) to a rigid fixture and radially loading the pump bearing support (joint 37), the first diffuser seal support (joint 35), the pump inlet flange (joint 49), and the turbine bearing support (joint 30). Stiffness values matched at these locations were 1.366×10^8 N/m at the pump bearing support, 2.066×10^8 N/m at the first diffuser seal support, 5.341×10^8 N/m at the pump inlet flange, and 2.995×10^8 N/m at the turbine bearing support.

The case model is composed of 19 joints with 108 degrees-of-freedom, two intrinsic stiffness elements which simulate lug contact between diffusers and case, and 19 beam elements of which seven are accelerometer or Bently arms. Dimensions, mass distribution, intrinsic element connectivity and stiffnesses, and beam element connectivity and properties are listed in Table 3.

An intrinsic stiffness element has the same orientation and notation as a beam element (Fig. 5), but its stiffness values, K_{11}, are input directly into the SPAR program rather than computed indirectly as are beam element stiffness values from the beam element properties.

Table 4 lists 21 HPFTP case cantilever frequencies and modal descriptions. Figures 6 and 7 depict two representative case modes (dotted lines) superimposed over the case neutral position.

IV. THE COUPLED HPFTP ROTOR AND CASE (RPL)

Ten parametric configurations of the coupled HPFTP rotor and case were studied for their effect on pump frequencies, stability, and operating loads. Eight of these configurations involved a combination of one of the rotors of Section II, a set of the seals of Table 5, and a set of the bearing carriers of Table 5. The remaining two configurations were a modification of the HPFTP rotor and case to replace the first diffuser seal (joints 22 and 35) with the pump bearing (joints 20 and 37).

The baseline configuration, number 7, couples the rotor and case together with five intrinsic stiffness elements: two elements for the double ball bearings

(1.313×10^8 N/m) and carriers in series, one element for the balance piston, and two elements for smooth seals between the impellers. The intrinsic stiffness elements for bearings/carriers and seals have only radial translational stiffnesses, and the balance piston element has only axial translational stiffness. All seal stiffness values listed in Table 6 are for the Rated Power Level (RPL) and are proportional to the square of the rotor speed.

Table 7 lists 21 frequencies and modal descriptions of the coupled baseline HPFTP rotor and case. Figures 8 through 10 depict three pump modes exhibiting significant rotor motion: translation, rocking, and bending. The short solid lines represent physical bearings/carriers and seals.

V. THE HPOTP ROTOR MODEL

The HPOTP rotor (Fig. 11) consists of a hollow shaft with an integral turbine disc. Over the shaft is a double centrifugal main impeller which inputs LOX at both ends and outputs at a common center. This impeller is clamped to the shaft by a nut at the pump end, splined at the center, and is free to slide axially at the turbine end. A smaller single centrifugal impeller is bolted to the pump end of the shaft and supports double ball bearings. A second turbine disc is bolted to the turbine end of the shaft. Double ball bearings and multiple seals interposed between the main impeller and the two stage turbine complete the rotor support. Nominal operating speed of the rotor is between 19 840 rpm (MPL) and 30 965 rpm (FPL).

Unlike the HPFTP rotor, the HPOTP rotor had Rocketdyne empirical data in the form of a free-free first bending frequency (dry and without turbine blades) of 475 Hz and its associated mode shape available as modeling aids. These empirical data and a rotor modeled initially upon geometry were used as input to the MOUSE (Model Optimization Using Statistical Estimation) program which computed pseudo rotor geometry necessary to match the empirical data.

The SPAR model of the rotor is composed of 15 joints with 90 degrees-of-freedom and 14 beam elements. Dimensions, mass distribution (wet, i.e., including entraped LOX and turbine blades), and beam element connectivity and properties are listed in Table 8.

Table 9 lists HPOTP rotor free-free frequencies and modal descriptions through the first axial mode. Note that entraped LOX and the turbine blades reduce the first bending frequency of the model to 470.4 Hz. Figures 12 and 13 depict the first two rotor free-free bending modes (dotted lines) relative to the HPOTP case. The short solid lines illustrate the displacement loci of rotor bearing and seal locations from the rotor neutral position.

VI. THE HPOTP CASE MODEL

The HPOTP case (Fig. 14) which encloses and supports the HPOTP rotor is, in turn, cantilevered from the opposite side of the SSME from the HPFTP case via its own hot gas manifold from the SSME power head. A preburner powers the turbine. Instrumentation added to the case for single engine firing tests include three radial accelerometers attached to the turbine flange and three axial and three radial accelerometers attached to the preburner pump case.

The SPAR model of the HPOTP case, like the rotor, was not developed by Rocketdyne, but, like the HPFTP case, benefited from Rocketdyne rap tests and static influence coefficients tests. Thus the beam element properties of the hot gas manifold were adjusted to match pump cantilever frequencies of 70 Hz and 115 Hz. Static influence coefficients were obtained by bolting the turbine flange (joint 69) to a rigid fixture and loading the pump flange (between joints 65 and 67) axially and radially in the radial y and z directions. Deflection values matched at the pump flange were 1.892×10^{-4} m in the radial y direction and 1.969×10^{-4} in the radial z direction.

The case model is composed of 23 joints with 132 degrees-of-freedom, one intrinsic stiffness element which simulates the interstage ring support within the case, and 22 beam elements of which six are accelerometer arms. Dimensions, mass distribution, intrinsic stiffness element connectivity and stiffnesses, and beam element connectivity and properties are listed in Table 10.

Table 11 lists 16 HPOTP case cantilever frequencies and modal descriptions. Figures 15 and 16 depict two representative case modes (dotted lines) superimposed over the case neutral position.

VII. THE COUPLED HPOTP ROTOR AND CASE (RPL)

The HPOTP model was initially configured to have the capability to incorporate nine seals: two preburner impeller seals, four seals including a labyrinth seal and a hot gas seal between the turbine bearing and the two stage turbine, two turbine disc seals, and a turbine interstage seal. However, only the hot gas seal was ultimately modeled of the four seals between the turbine bearing and the two-stage turbine. Thus the HPOTP rotor and case are coupled together by nine intrinsic stiffness elements: two elements for the preburner impeller seals, one element for the pump double bearings (1.401×10^8 N/m) and carrier in series, one element for the balance piston, one element for the turbine double bearings (2.102×10^8 N/m) and carrier in series, one element for the hot gas seal, two elements for the turbine disc seals, and one element for the turbine interstage seal. The intrinsic stiffness elements for bearings/carriers and seals have only radial translational stiffnesses, and the balance piston element has only axial translational stiffness. All seal stiffness values listed in Table 12 are for RPL and are proportional to the square of the rotor speed.

Table 13 lists 21 frequencies and modal descriptions of the coupled HPOTP rotor and case. Figures 17 through 20 depict four pump modes exhibiting significant rotor motion: rocking, bending, translation and, again, bending. The short solid lines represent physical bearings/carriers and seals.

VIII. THE SSME MODEL (RPL)

The SSME, Figure 21, consists of an expansion nozzle, combustion chamber, two actuator quadrapods, the HPFTP of Section IV, and the HPOTP of Section VII.

As the SPAR program is incapable of direct input of beam elements of nonuniform cross section, it was necessary to create finite element models of short segments of the expansion nozzle (joints 1 through 11) and apply appropriate static loads and boundary conditions to these models to obtain data for equivalent intrinsic stiffness elements. Because of structural complexity, similar models were created to obtain equivalent intrinsic stiffness elements for the lower combustion chamber (joints 11 and 12), the upper powerhead (joints 14 and 15), and bipod subassemblies of the actuator quadrapods (joints 16 and 17). Not shown in Figure 21 are joints 18 and 19 which serve as actuator attach points of the single engine test fixture.

The SPAR model of the SSME (excluding turbopumps) is composed of 19 joints with 98 degrees-of-freedom; two beam elements; and 18 intrinsic stiffness elements: ten elements for the expansion nozzle, two elements for the combustion chamber and powerhead, four elements for the actuator quadrapods, and two elements for the actuators (axial translational stiffness only). Dimensions, mass distribution (wet, i.e., filled lines and pumps), intrinsic stiffness element connectivity and stiffnesses, and beam element connectivity and properties are listed in Table 14.

Table 15 lists 30 frequencies and modal descriptions of the SSME (excluding turbopumps). Figures 22 through 25 depict four representative bending modes (dotted lines) of the SSME (excluding turbopumps) superimposed over its neutral position.

Table 16 lists 80 frequencies and modal descriptions of the SSME (including turbopumps). Figures 26 through 29 depict four representative modes (dotted lines) of the SSME (including turbopumps) exhibiting significant motion of the pump rotors.

Figure 30 depicts the frequency spectra for each cantilevered pump and the SSME. Of special note is the large "deadband" for the HPOTP between 300 and 500 Hz which disappears when the pumps are coupled to the SSME.

IX. SUMMARY

Between August 29 and September 1, 1977, the Structural Dynamics Research Corporation (SDRC) performed a modal survey test of an SSME at the National Space Technology Laboratory, Bay St. Louis, Mississippi. The test was conducted by exciting the SSME structure with a load cell equipped hammer and measuring the response with a triaxial accelerometer at the 22 locations as noted in Figure 31. Documented results of the test comprise transfer functions, natural frequencies, modal damping valves, and mode shapes for fifteen selected modes.

The natural frequencies for the fifteen modes are compared graphically (Fig. 32) to the natural frequencies predicted by the SSME (including turbopumps) model.

Table 17 lists the 15 modes together with the SDRC modal descriptions against the equivalent math model frequencies. For the given frequency sample, the math model predicted nine modes within ±5 percent, three modes within ±10 percent, and failed to predict three modes.

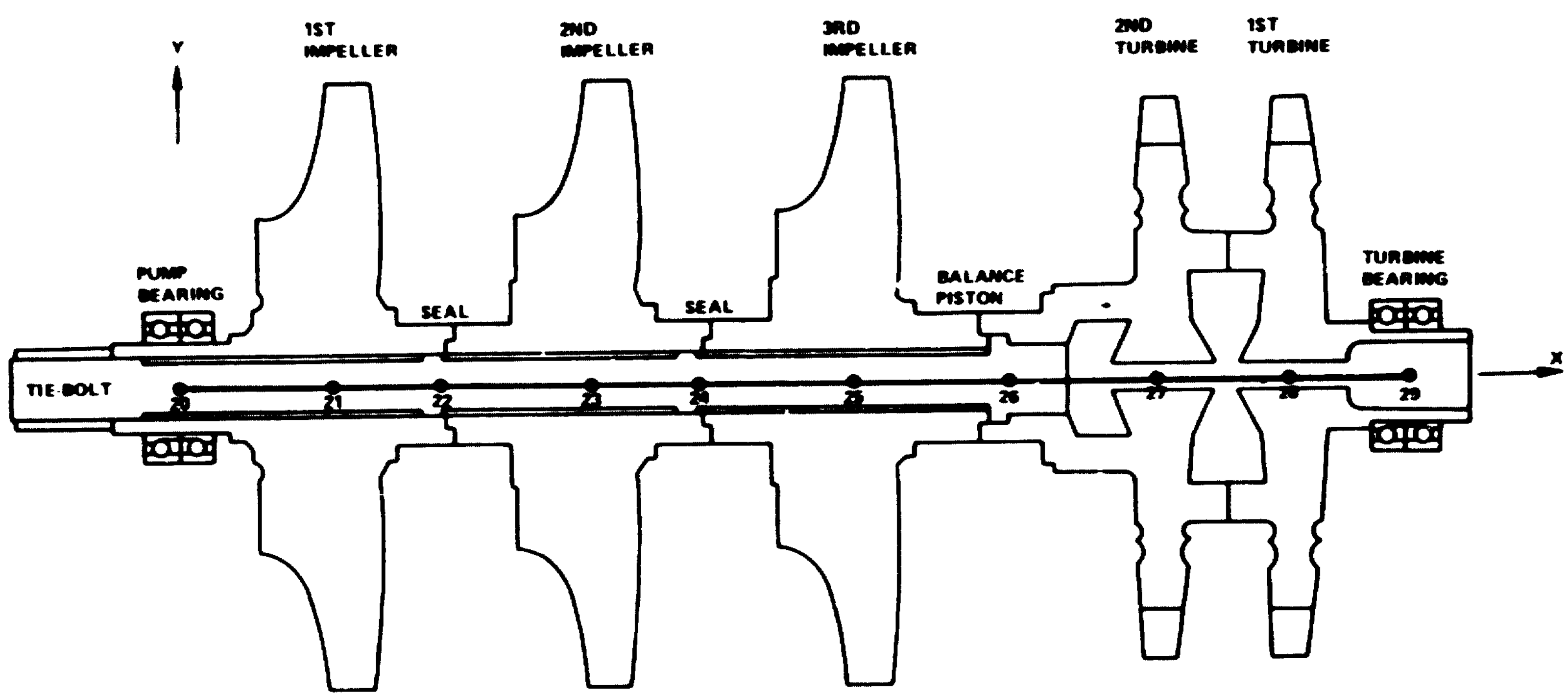
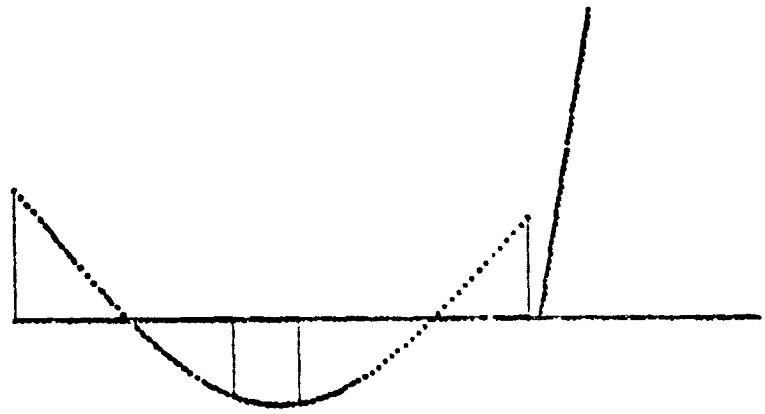
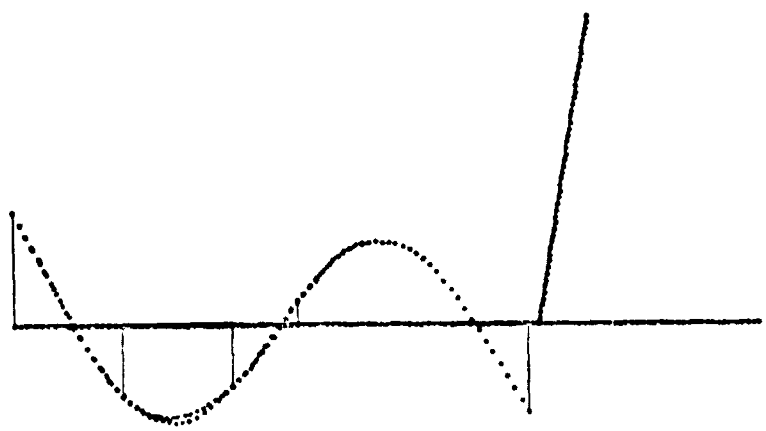


Figure 1. HPFTP rotor model.



FREQUENCY (Hz) 0.637474 × 10^{+03}

Figure 2. HPFTP rotor, mode 7.



FREQUENCY (Hz) 0.150708 × 10^{+04}

Figure 3. HPFTP rotor, mode 11.

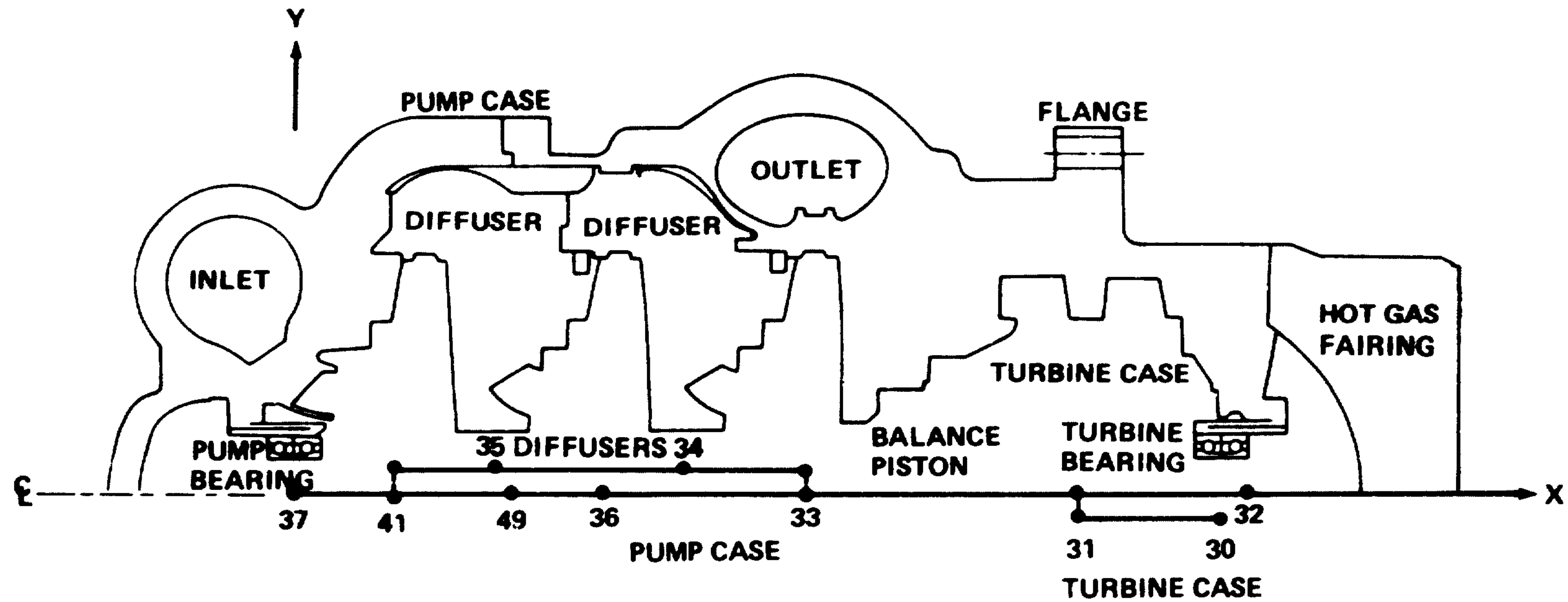


Figure 4. HPF1P case model.

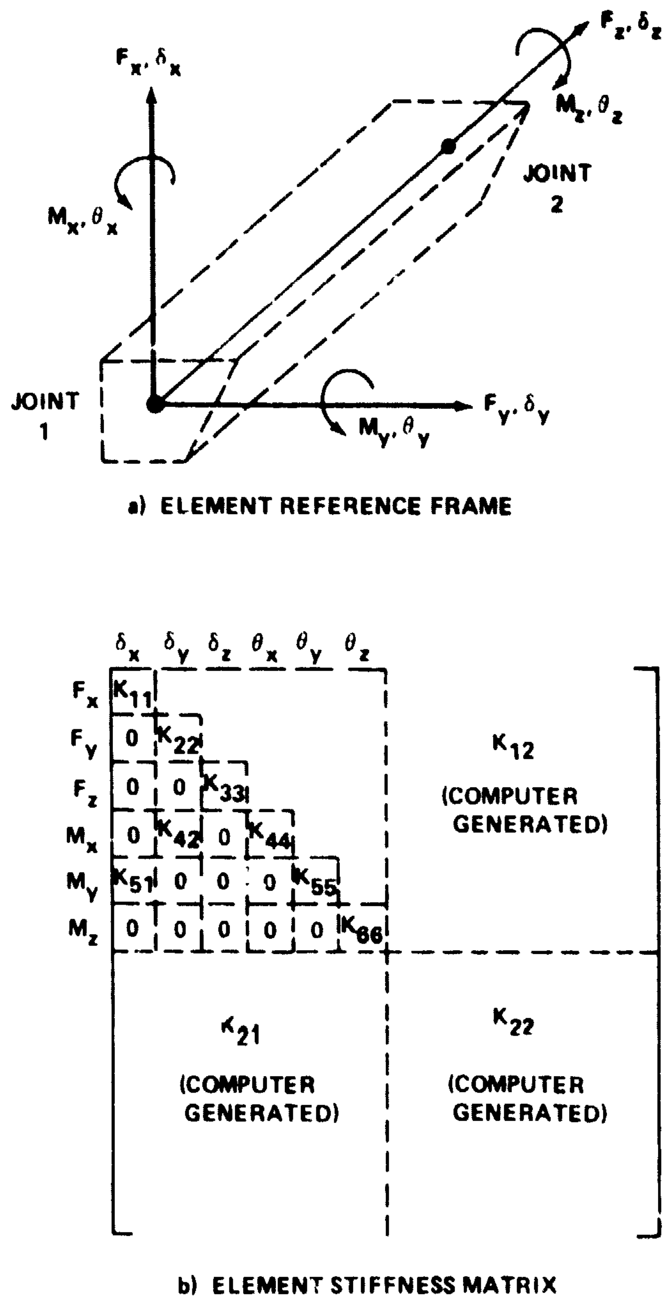
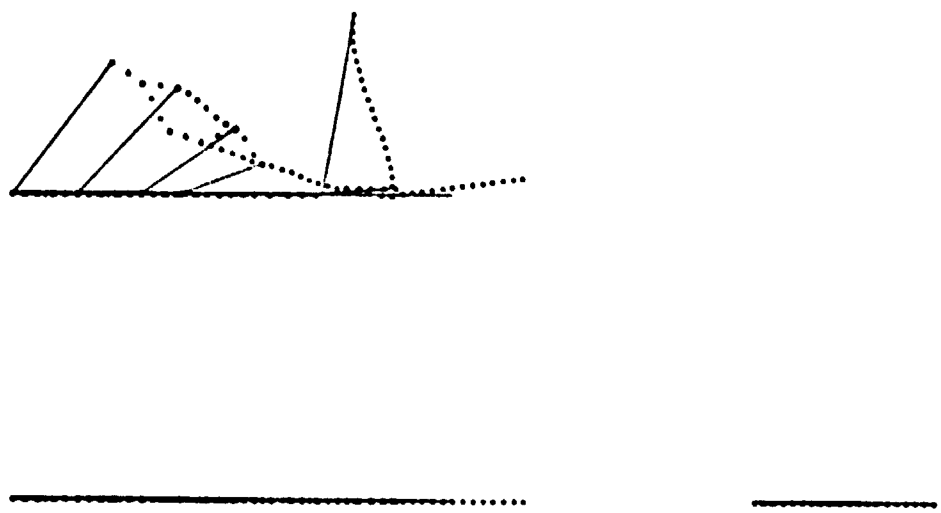
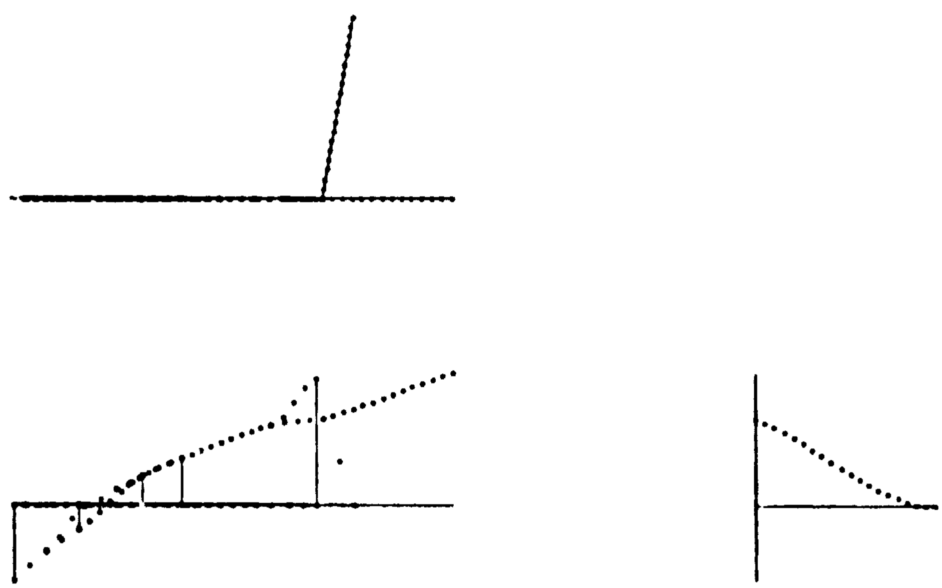


Figure 5. Intrinsic stiffness element notation.



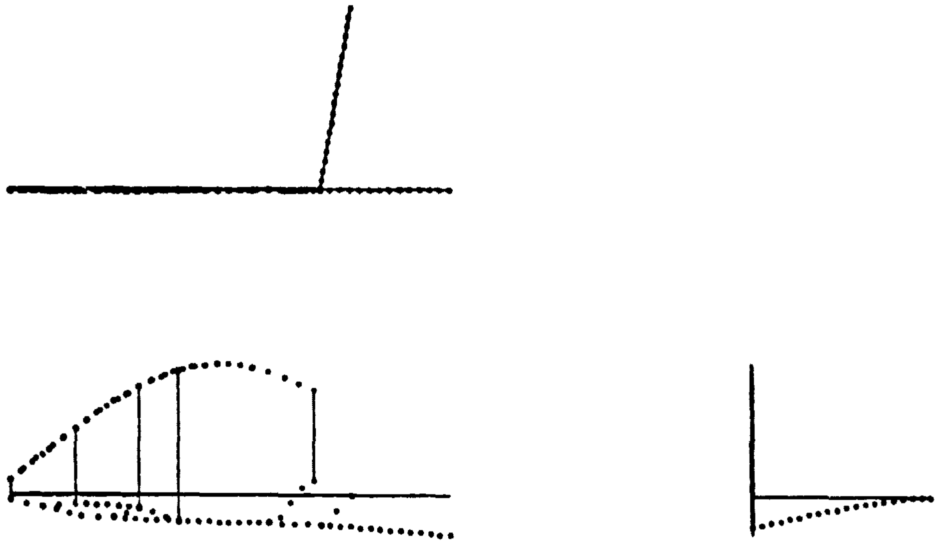
FREQUENCY (Hz) 0.214439 × 10^{+03}

Figure 6. HPFTP case, mode 4.



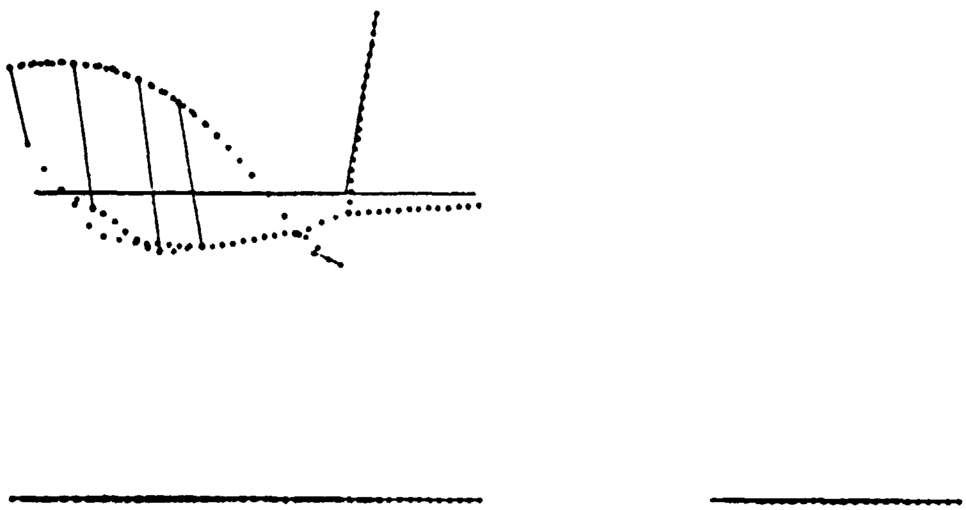
FREQUENCY (Hz) 0.275479 × 10^{+03}

Figure 7. HPFTP case, mode 5.



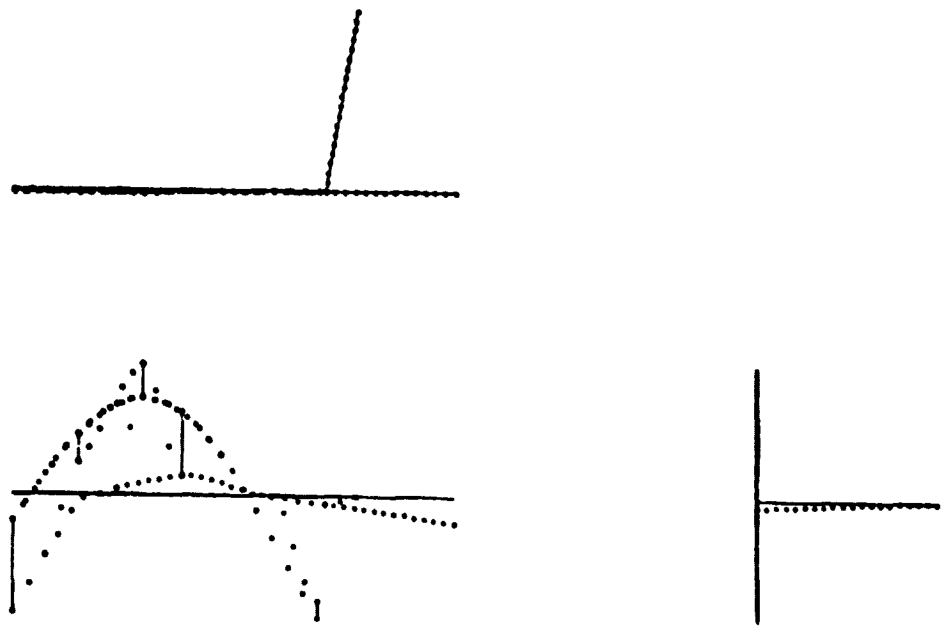
FREQUENCY (Hz) 0.320980 x 10^{+03}

Figure 8. Coupled HPFTP rotor and case (RPL), mode 8.



FREQUENCY (Hz) 0.423953 x 10^{+03}

Figure 9. Coupled HPFTP rotor and case (RPL), mode 10.



FREQUENCY (Hz) 0.514957 x 10^{+03}

Figure 10. Coupled HPFTP rotor and case (RPL), mode 14.

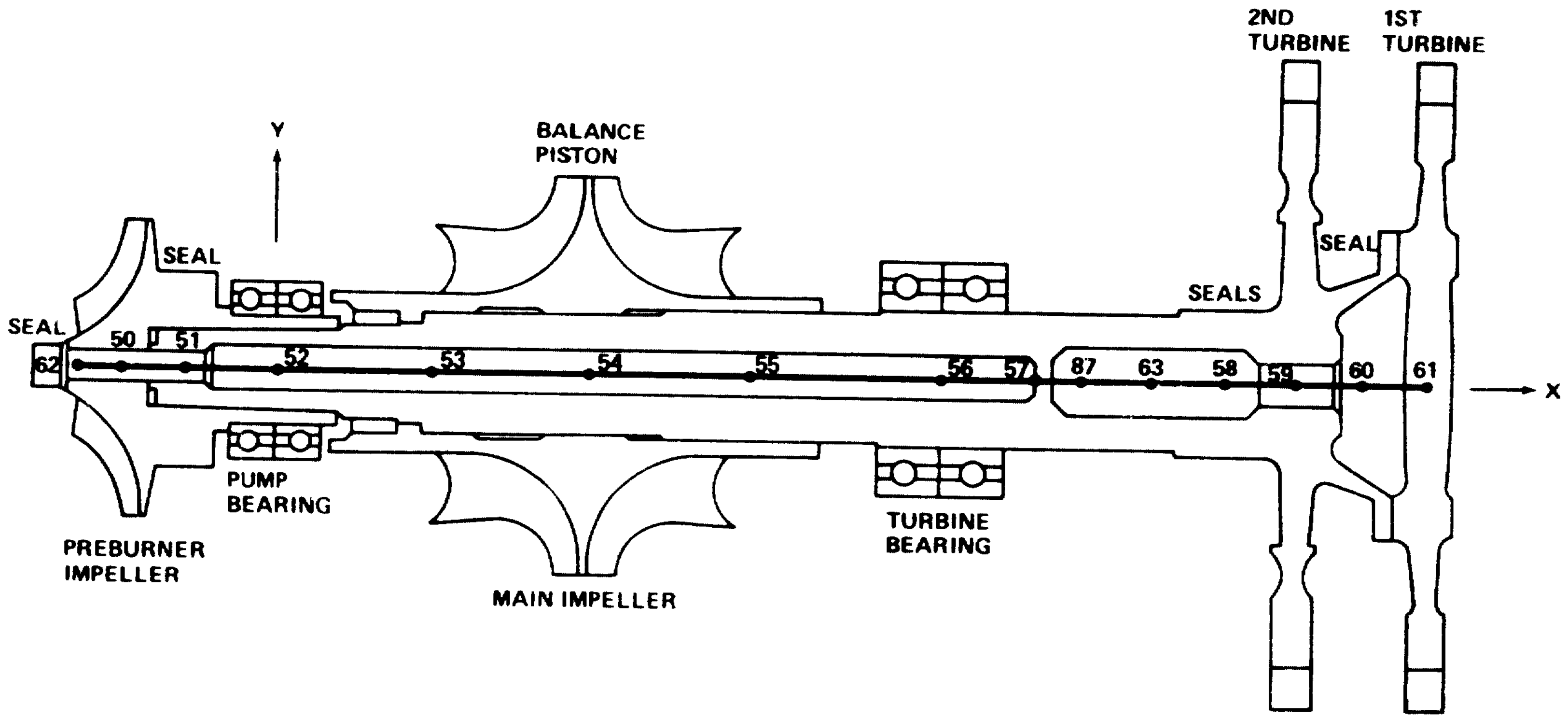


Figure 11. HPOTP rotor model.

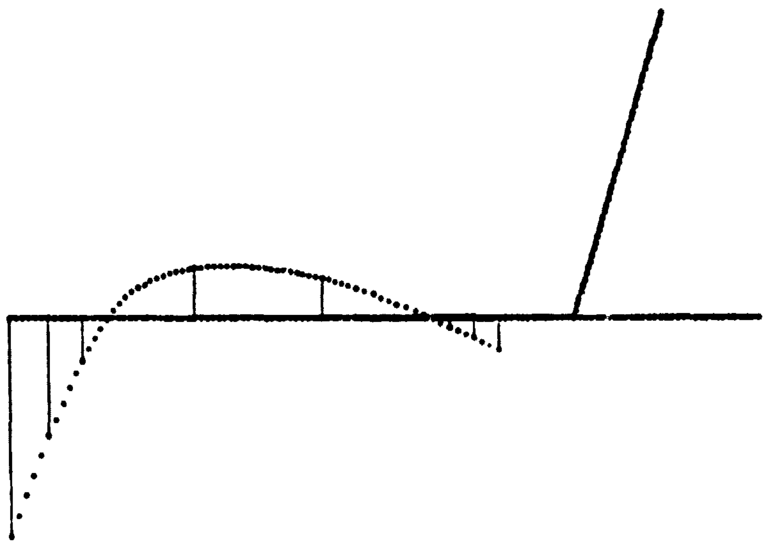


Figure 12. HPOTP rotor, mode 7.

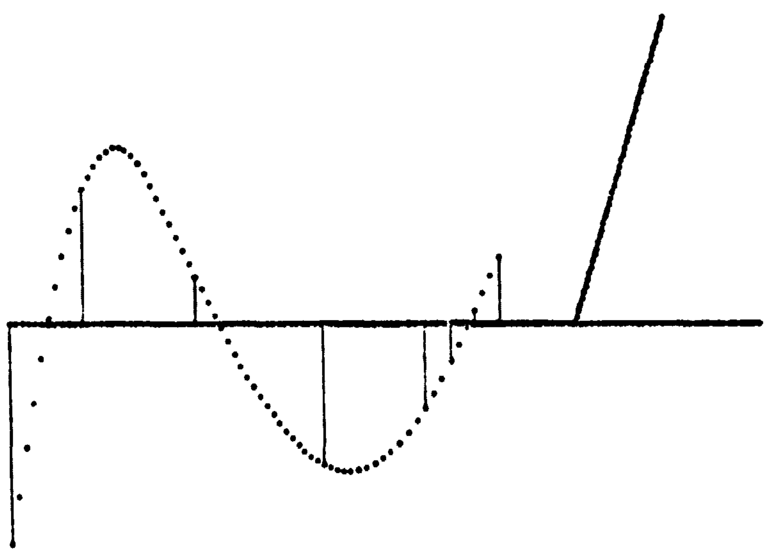


Figure 13. HPOTP rotor, mode 10.

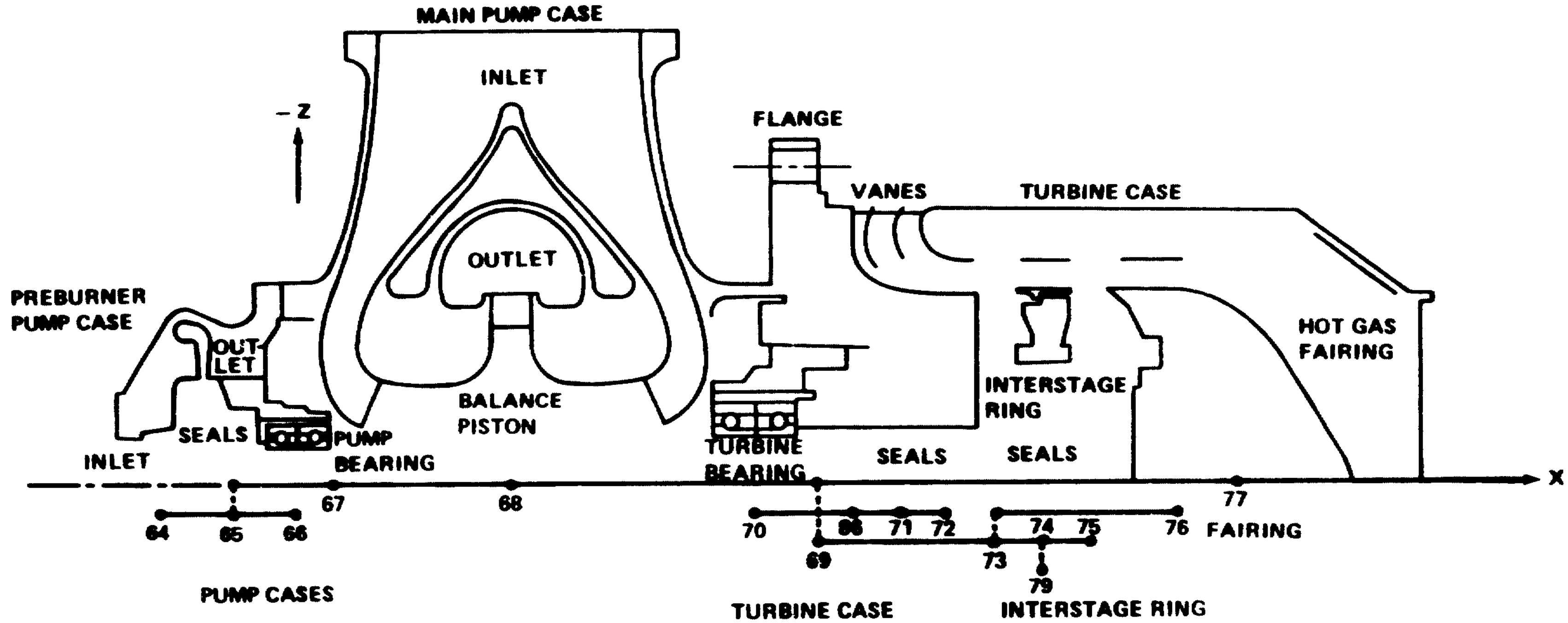
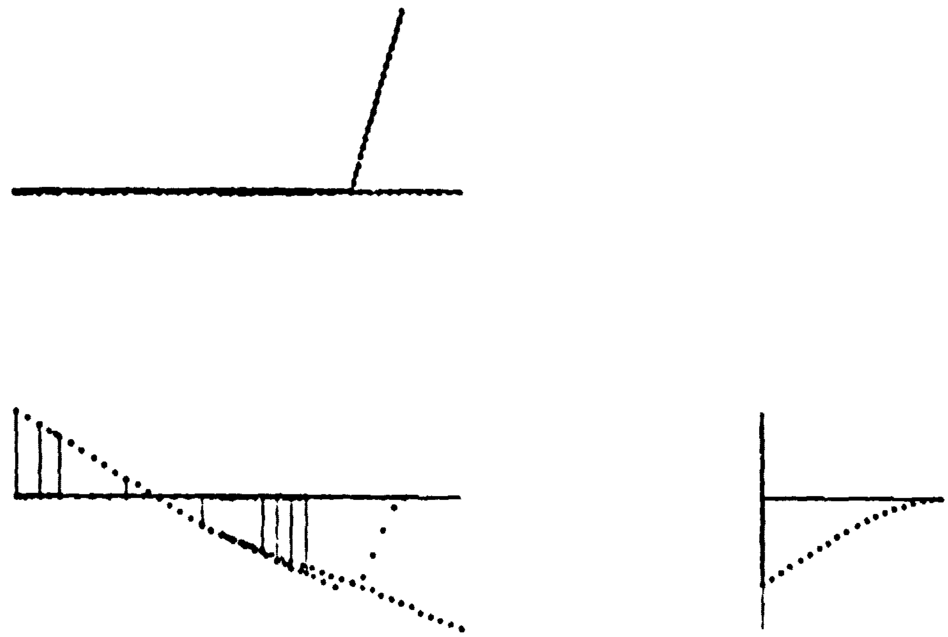
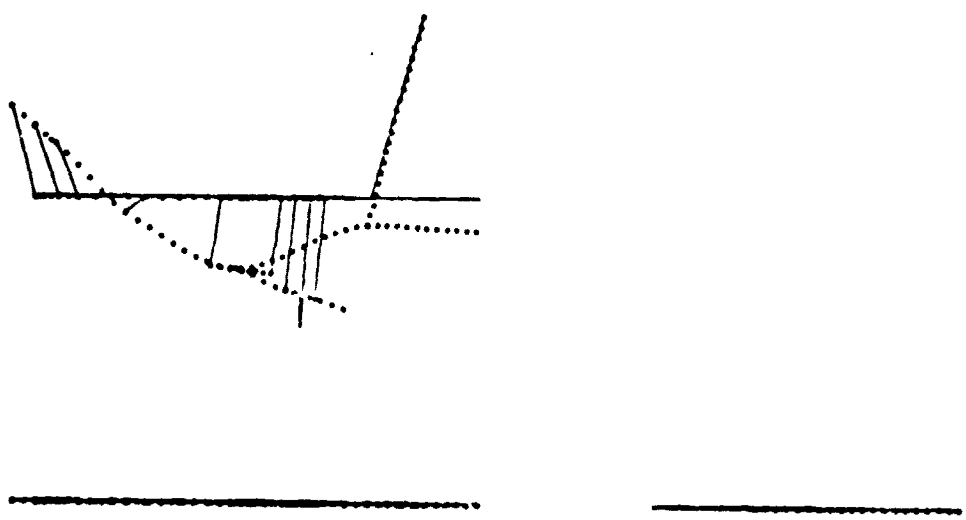


Figure 14. HPOTP case model.



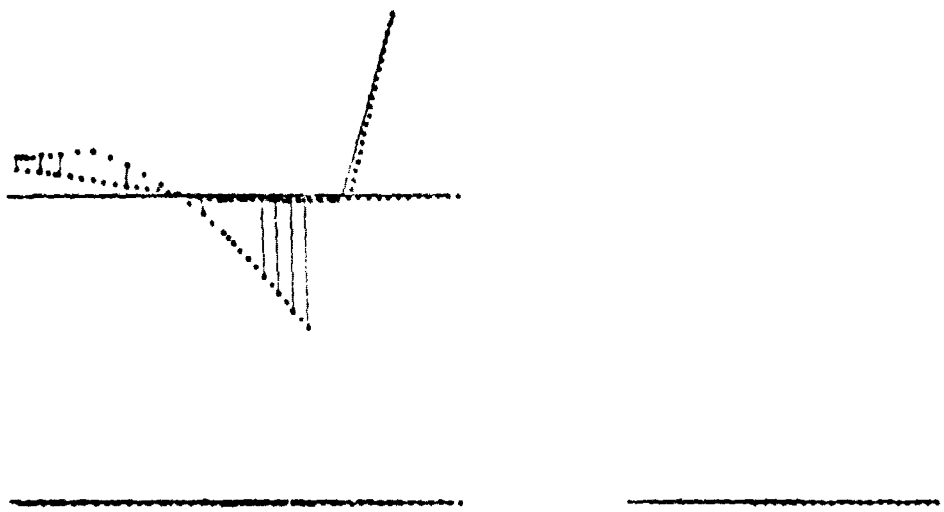
FREQUENCY (Hz) 0.262734 × 10^{+03}

Figure 15. HPOTP case, mode 3.



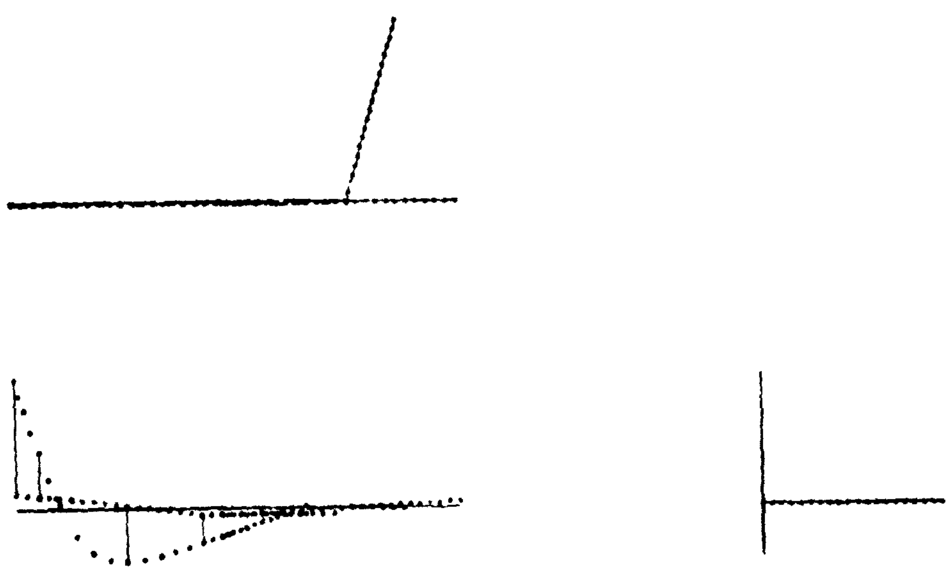
FREQUENCY (Hz) 0.592951 × 10^{+03}

Figure 16. HPOTP case, mode 5.



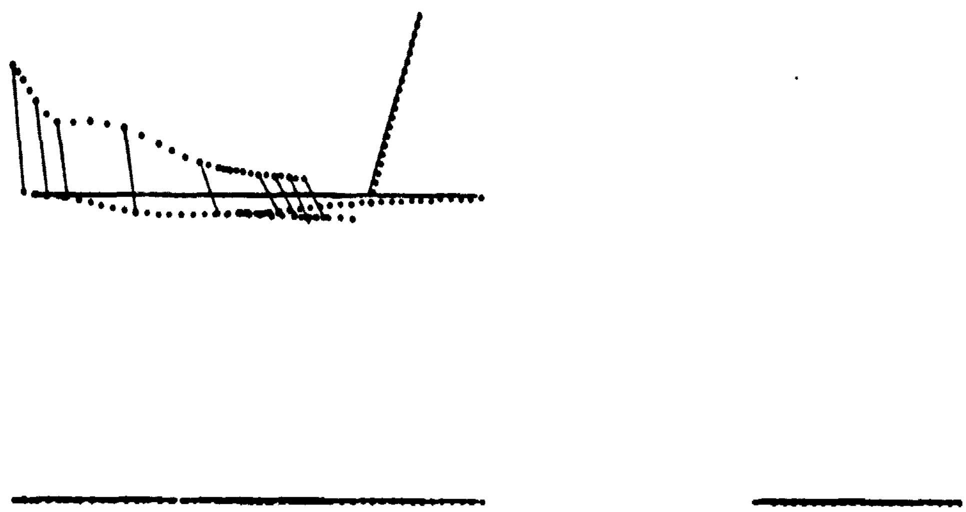
FREQUENCY (Hz) 0.257877 × 10^{+03}

Figure 17. Coupled HPOTP rotor and case (RPL), mode 5.



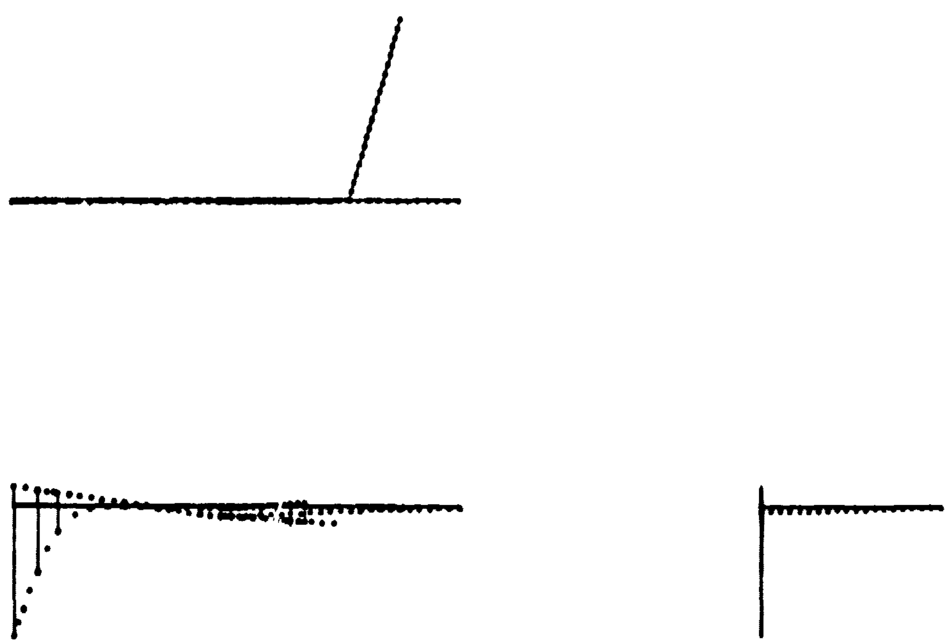
FREQUENCY (Hz) 0.536451 × 10^{+03}

Figure 18. Coupled HPOTP rotor and case (RPL), mode 9.



FREQUENCY (Hz) 0.599[illegible] $\times 10^{+03}$

Figure 19. Coupled HPOTP rotor and case (RPL), mode 11.



FREQUENCY (Hz) 0.643812 $\times 10^{+03}$

Figure 20. Coupled HPOTP rotor and case (RPL), mode 13.

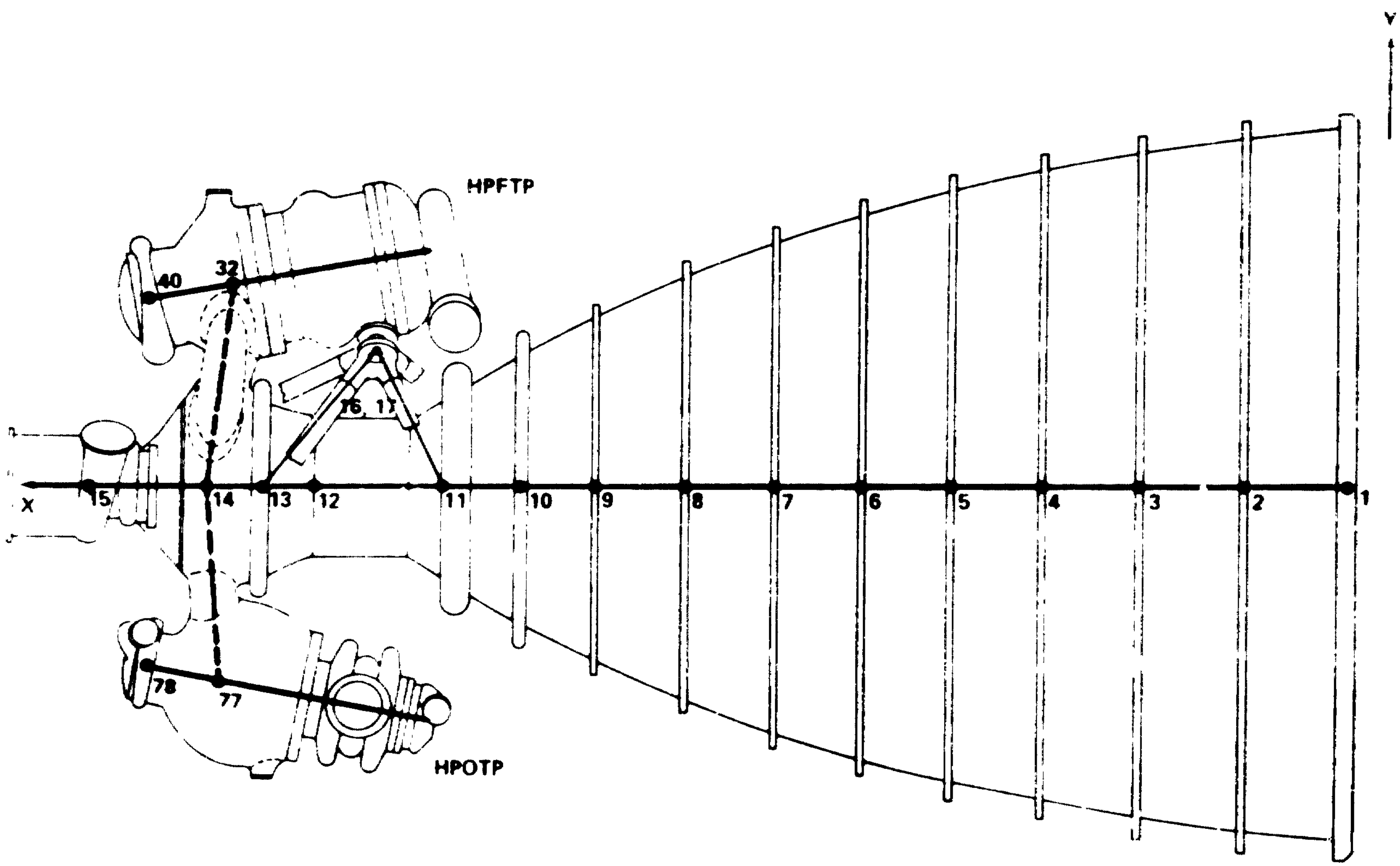
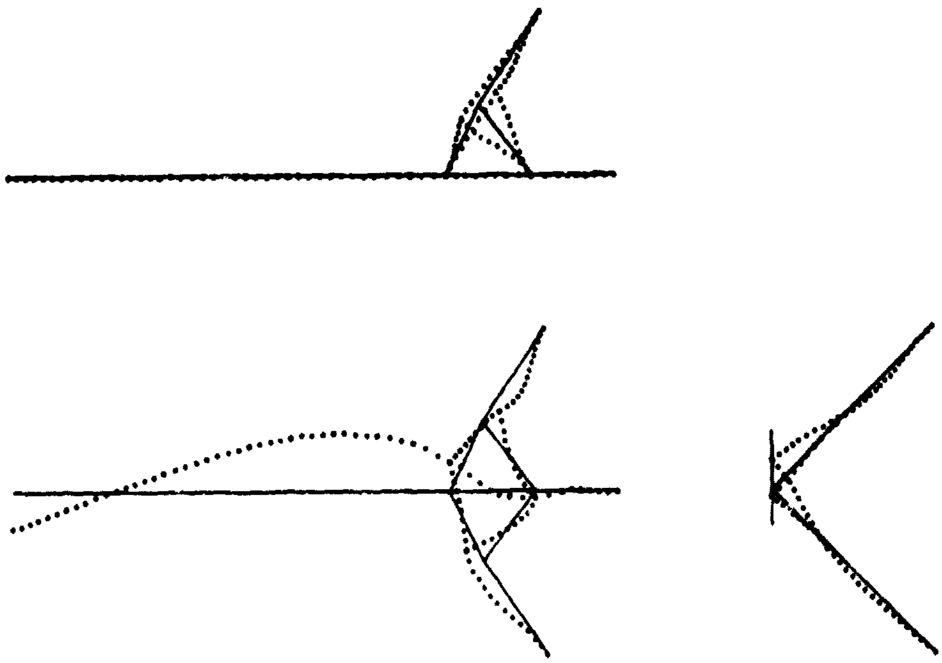
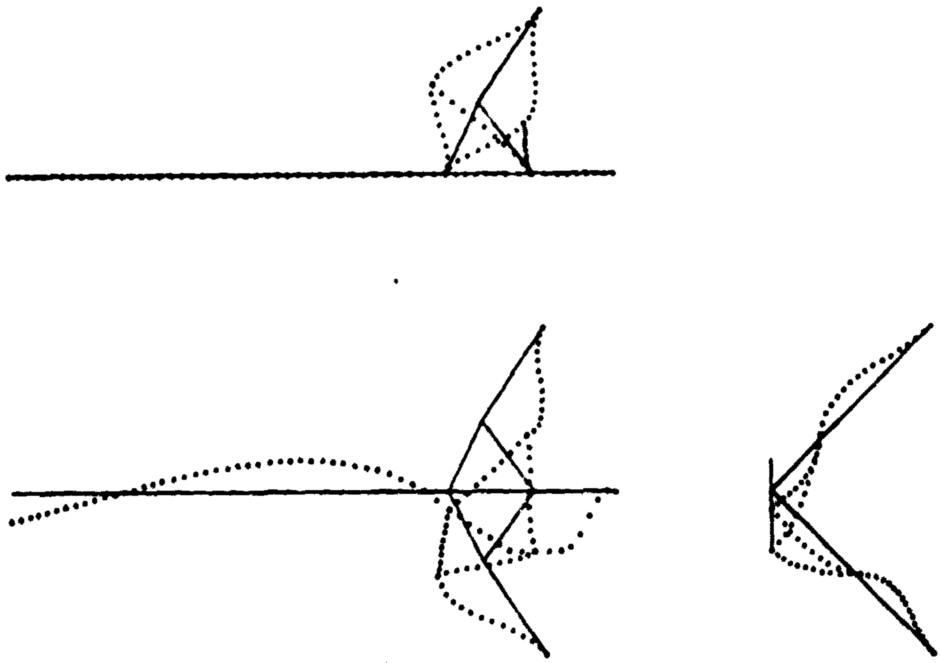


Figure 21. SSME model.



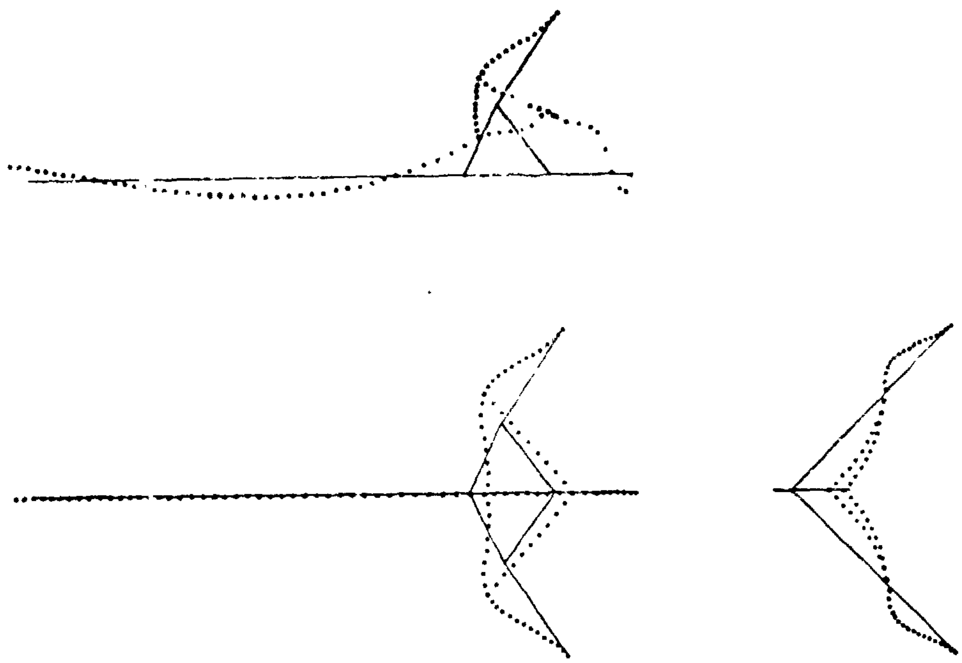
FREQUENCY (Hz) 0.240914 × 10^+03

Figure 22. SSME (excluding turbopumps), mode 12.



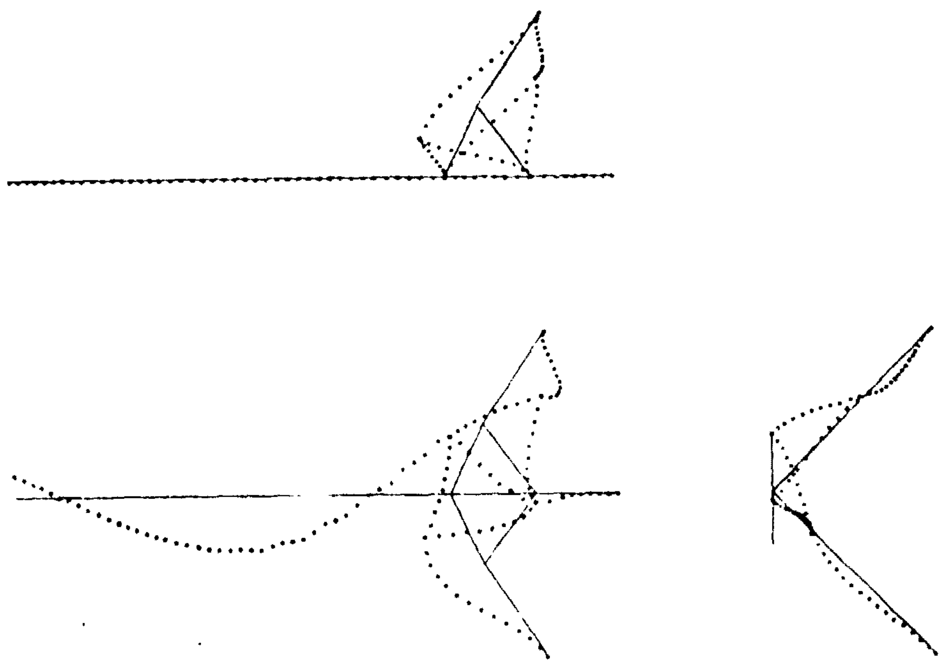
FREQUENCY (Hz) 0.311088 × 10^+03

Figure 23. SSME (excluding turbopumps), mode 15.



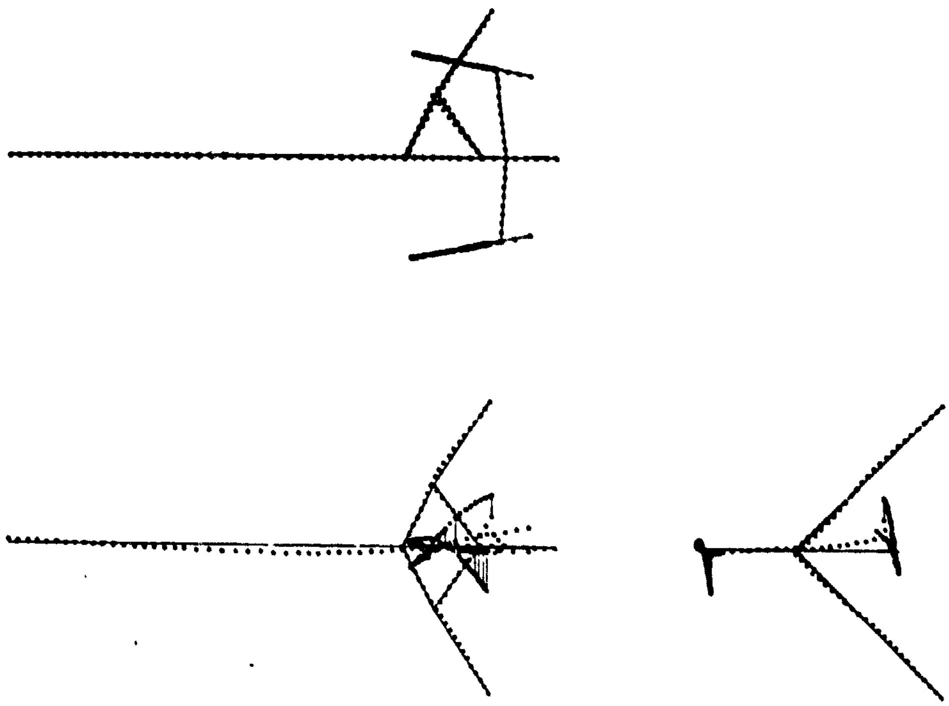
FREQUENCY (Hz) 0.411693 · 10^{+03}

Figure 24. SSME (excluding turbopumps), mode 18.



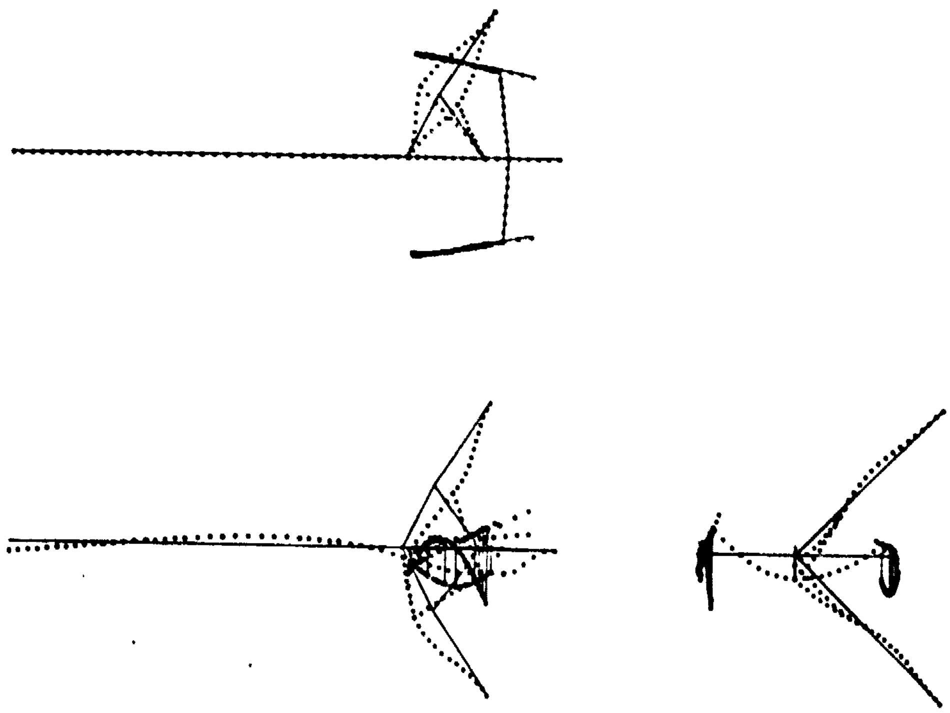
FREQUENCY (Hz) 0.415275 · 10^{+03}

Figure 25. SSME (excluding turbopumps), mode 19.



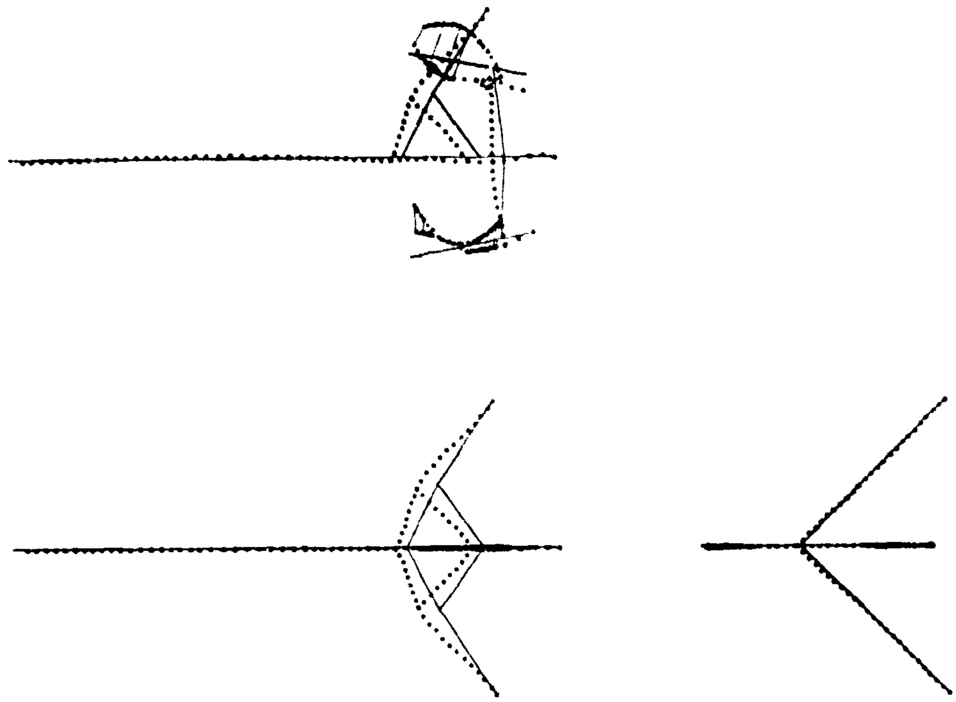
FREQUENCY (Hz) 0.256210 · 10⁺⁰³

Figure 26. SSME (including turbopumps), mode 23.



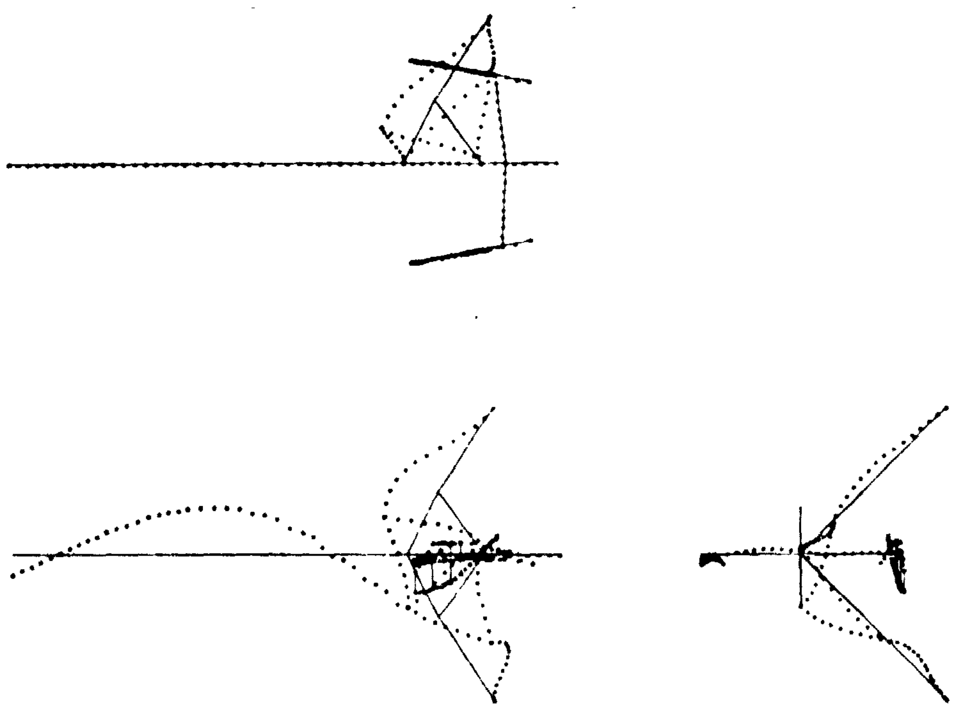
FREQUENCY (Hz) 0.331022 · 10⁺⁰³

Figure 27. SSME (including turbopumps), mode 30.



FREQUENCY (Hz) 0.406570 × 10^{+03}

Figure 28. SSME (including turbopumps), mode 33.



FREQUENCY (Hz) 0.415549 · 10^{+03}

Figure 29. SSME (including turbopumps), mode 34.

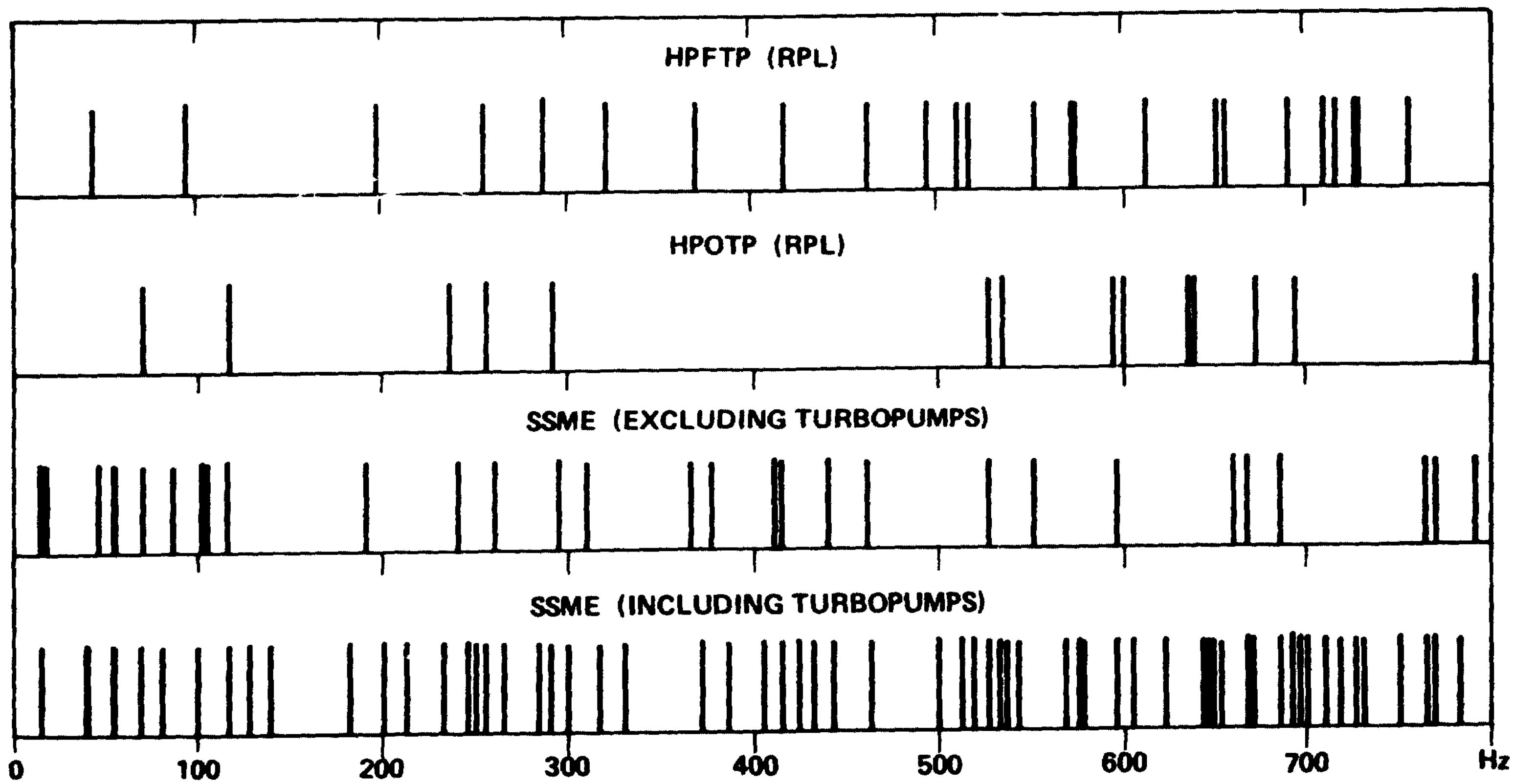
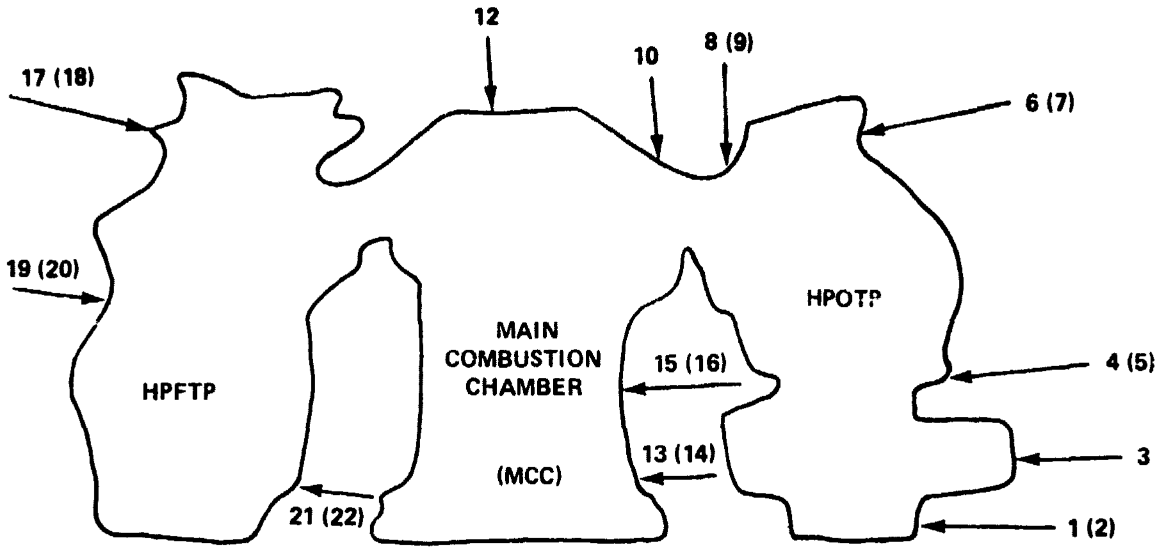


Figure 30. SSME and major component spectra.



MEASUREMENT POINT	DESCRIPTION
1 (2)	HPOTP PUMP FLANGE
3	HPOTP DISCHARGE VOLUTE
4 (5)	HPOTP TURBINE FLANGE
6 (7)	HPOTP PREBURNER TOP
8 (9)	BASE OF HPOTP MANIFOLD
10	MAIN INJECTOR BASE
15 (16)	MCC INLET
13 (14)	MCC NOZZLE MANIFOLD
12	MCC TOP
17 (18)	HPFTP PREBURNER TOP
19 (20)	HPFTP TURBINE FLANGE
21 (22)	HPFTP PUMP FLANGE

NOTE: POINTS IN PARENTHESIS ARE ON THE "BACK" OF THE STRUCTURE

Figure 31. SSME measurement points.

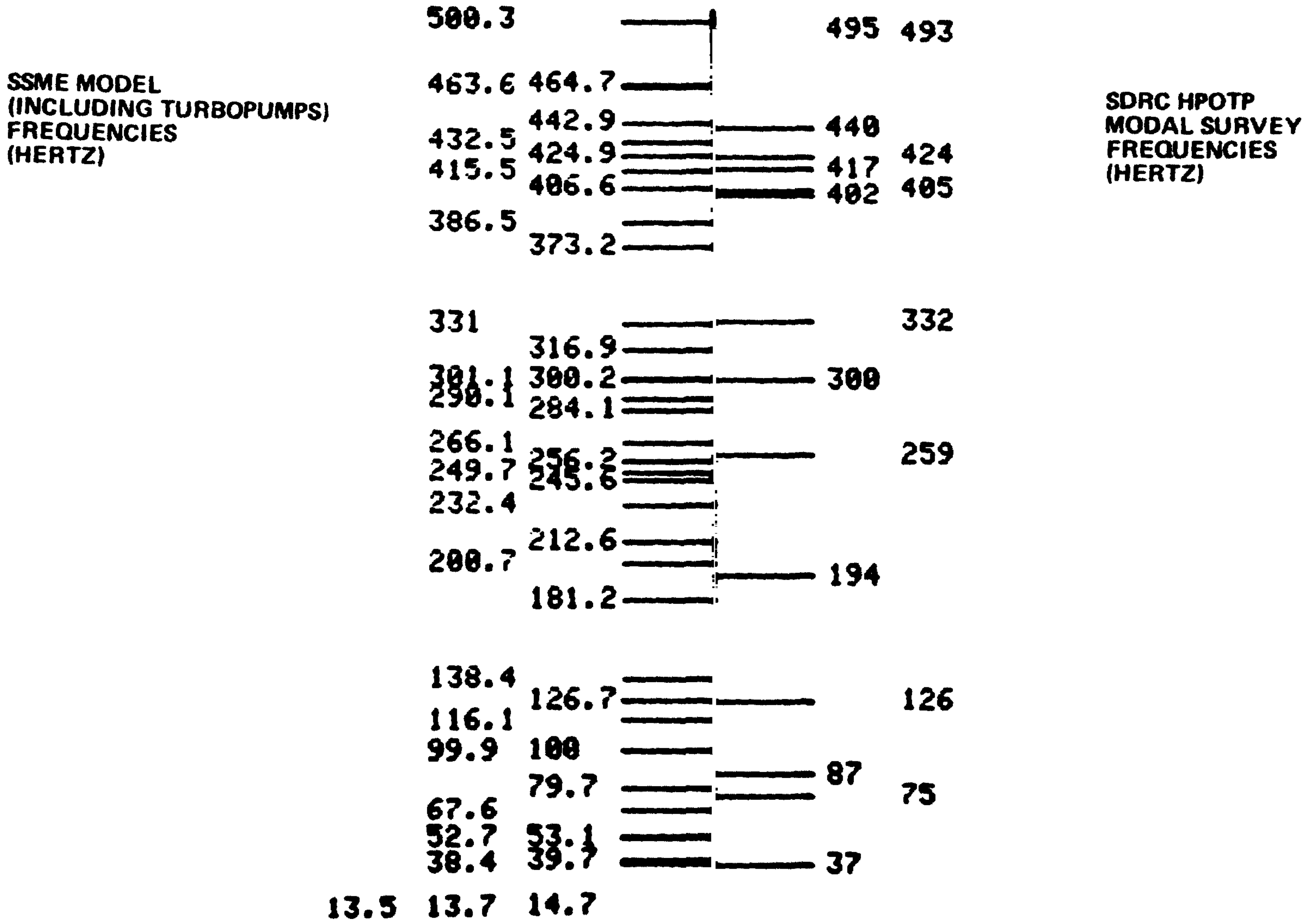


Figure 32. Comparison of SSME model and HPOTP modal survey frequencies.

TABLE 1a. HPFTP ROTOR MODEL DATA

Joint No.	x (m)	y (m)	z (m)	Mass (kg)	J_x (kg-$m^2 \times 10^{-2}$)	I_y (kg-$m^2 \times 10^{-2}$)	I_z (kg-$m^2 \times 10^{-2}$)	Description
20	0	0	0	2.688	—	—	—	Pump Bearing
21	0.076	0	0	8.038	6.889	3.643	3.643	First Impeller
22	0.127	0	0	1.781	—	—	—	Seal
23	0.203	0	0	8.038	6.889	3.643	3.643	Second Impeller
24	0.254	0	0	1.781	—	—	—	Seal
25	0.330	0	0	7.879	6.696	3.535	3.535	Third Impeller
26	0.406	0	0	5.078	0.293	0.293	0.293	Impeller/Turbine
27	0.476	0	0	8.042	6.350	3.161	3.161	Second Turbine
28	0.540	0	0	9.775	6.438	3.307	3.307	First Turbine
29	0.597	0	0	3.175	0.293	0.293	0.293	Turbine Bearing
45	-0.051	0	0	—	—	—	—	Radial Bentlies[a]
47	-0.042	0.038	0	—	—	—	—	Axial Bently[b]
				56.275				

a. Relative to a rectangular coordinate frame which shares a common origin and x-axis with joints 20 through 29 but rotated -110 deg about the x-axis.

b. Same as a. but rotated 130 deg about the x-axis.

TABLE 1b. HPFTP ROTOR MODEL DATA

Beam No.	Joint No. 1	Joint No. 2	J_x ($m^4 \times 10^{-7}$)	I_y ($m^4 \times 10^{-7}$)	I_z ($m^4 \times 10^{-7}$)	Area ($m^2 \times 10^{-3}$)	Material	Description
3	20	21	54.926	27.463	27.463	5.190	Inconel	Pump shaft
4	20	22	0.409	0.204	0.204	0.507	Inconel	Tie-bolt
5	20	45	—	—	—	—	—	Radial Bently Arm
6	20	47	—	—	—	—	—	Axial Bently Arm
7	21	22	54.926	27.463	27.463	5.190	Inconel	Pump shaft
8	22	23	54.926	27.463	27.463	5.190	Inconel	Pump shaft
9	22	24	0.409	0.204	0.204	0.507	Inconel	Tie-bolt
10	23	24	54.926	27.463	27.463	5.190	Inconel	Pump shaft
11	24	25	54.926	27.463	27.463	5.190	Inconel	Pump shaft
12	24	26	0.409	0.204	0.204	0.507	Inconel	Tie-bolt
13	25	26	54.926	27.463	27.463	5.190	Inconel	Pump shaft
14	26	27	68.514	34.257	34.257	4.552	Inconel	Turbine shaft
15	27	28	68.514	34.257	34.257	4.552	Inconel	Turbine shaft
16	28	29	68.514	34.257	34.257	4.552	Inconel	Turbine shaft

TABLE 2. HPFTP ROTOR MODES

Mode	"500 Hz" Rotor Frequency (Hz)	"637 Hz" Rotor Frequency (Hz)	Description
1-6	—	—	Rigid Body
7-8	498.1	637.5[a]	First Bending, Y, Z
9	561.5	724.5	First Torsion, X
10	1117.1	1446.1	Second Torsion, X
11-12	1150.8	1507.1[a]	Second Bending, Y, Z
13	1588.8	2019.4	Third Torsion, X
14-15	1936.5	2526.3	Third Bending, Y, Z
16	2104.5	2728.1	Axial, X

a. Refer to Figures 2 and 3.

TABLE 3a. HPFTP CASE MODEL DATA

Joint No.	x (m)	y (m)	z (m)	Mass (kg)	J_x (kg-m²)	I_y (kg-m²)	I_z (kg-m²)	Description
30	0.597	0	0	25.401	0.585	0.293	0.293	Turbine Bearing
31	0.508	0	0	82.100	2.634	1.317	1.317	Turbine Case
32	0.610	0	0	37.195	1.536	0.768	0.768	Pump Case
14	0.671	0.351	0	—	—	—	—	Powerhead
33	0.330	0	0	63.503	2.561	1.280	1.280	Pump Case
34	0.254	0	0	36.287	0.585	0.293	0.293	Diffuser
35	0.127	0	0	36.287	0.585	0.293	0.293	Diffuser
36	0.203	0	0	36.287	1.492	0.746	0.746	Pump Case
37	0	0	0	20.865	0.351	0.176	0.176	Pump Bearing
38	0.540	0	0.222	—	—	—	—	Axial Accelerometer[a]
39	-0.101	0.074	0	—	—	—	—	Axial Accelerometer[a]
40	0.864	0	0	27.216	0.176	0.088	0.088	Preburner
41	0.064	0	0	40.823	1.171	0.585	0.585	Pump Case
42	0.135	0	0	—	—	—	—	Radial Accelerometers[a]
43	0.540	0	0	—	—	—	—	Radial Accelerometers[a]
44	0.135	0	0	—	—	—	—	Radial Accelerometer[b]
46	-0.051	0	0	—	—	—	—	Radial Bently[c]
48	-0.042	0.038	0	—	—	—	—	Axial Bently[d]
49	0.140	0	0	—	—	—	—	Pump Case
				405.964				

a. Relative to a rectangular coordinate frame which shares a common origin and X-axis with joints 14, 30 through 37, 40, 41, and 49 but rotated -45° about the X-axis.

b. Same as a. but rotated 100° about the X-axis.

c. Same as a. but rotated -110° about the X-axis.

d. Same as a. but rotated 130° about the X-axis.

TABLE 3b. HPFTP CASE MODEL DATA

Beam No.	Joint No. 1	Joint No. 2	J_x $(m^4 \times 10^{-5})$	I_y $(m^4 \times 10^{-5})$	I_z $(m^2 \times 10^{-5})$	Area $(m^2 \times 10^{-3})$	Material	Description
17	30	31	0.882	0.441	0.441	0.381	Inconel	Turbine Case
18	31	32	19.147	9.573	9.573	4.645	Inconel	Pump Case
19	31	33	19.147	9.573	9.573	4.645	Inconel	Pump Case
20	31	38	—	—	—	—	—	Accelerometer Arm
21	31	43	—	—	—	—	—	Accelerometer Arm
22	32	14	9.240	8.533	0.701	2.476	Inconel	Hot Gas Manifold
23	32	40	19.147	9.573	9.573	4.645	Inconel	Preburner
24	33	34	—	1.432	1.432	0.903	Aluminum	Diffuser
25	33	36	19.147	9.573	9.573	4.645	Inconel	Pump Case
26	34	35	—	1.432	1.432	0.903	Aluminum	Diffuser
27	35	41	—	1.432	1.432	0.903	Aluminum	Diffuser
28	36	42	—	—	—	—	—	Accelerometer Arm
29	36	44	—	—	—	—	—	Accelerometer Arm
30	36	49	19.147	9.573	9.573	4.645	Inconel	Pump Case
31	37	39	—	—	—	—	—	Accelerometer Arm
32	37	41	2.514	1.257	1.257	0.839	Titanium	Pump Case
33	37	46	—	—	—	—	—	Radial Bently Arm
34	37	48	—	—	—	—	—	Axial Bently Arm
35	41	49	2.514	1.257	1.257	0.839	Titanium	Pump Case

TABLE 3c. HPFTP CASE MODEL DATA

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^9$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
19	34	35	0						Diffuser to
			0	0			Symmetric		Diffuser
			0	0	0				Contacts
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	7.846	
20	34	36	0						Case to
			0	0			Symmetric		Diffuser
			0	0	0				Contacts
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	3.503	

TABLE 4. HPFTP CASE MODES

Mode	Frequency (Hz)	Description
1	50.1	Case rocking, Y
2	108.6	Case rocking, Z
3	197.8	First diffuser torsion, X
4	214.4[a]	Case rocking + bending, Y
5	275.5[a]	Case rocking + bending, Z
6	367.8	First case torsion, X
7	428.1	First case translation + bending, Y
8	493.8	First case bending, Z
9	511.2	Turbine case bending, Y
10	535.5	Turbine case torsion
11	560.9	First diffuser bending, Z
12	562.1	First diffuser bending, Y
13	594.7	Turbine case bending, Z
14	634.9	Case axial, X
15	658.5	Second case torsion, X
16	691.3	Hot gas manifold bending, Y
17	706.1	Second diffuser torsion, X
18	708.2	Second diffuser bending, Z
19	718.2	Second diffuser bending, Y
20	812.8	Second case bending, Z
21	818.1	Second case translation + bending, Y

a. Refer to Figures 6 and 7.

TABLE 5. HPFTP PARAMETRIC CONFIGURATIONS

Configuration Number:	1	2	3	4	5	6	7[a]	8	9	10
500 Hz Rotor								X	X	
637 Hz Rotor	X	X	X	X	X	X	X			X
No Seals				X						
Nominal Seals		X			X			X		
3-Step Seals			X			X			X	X
Smooth Seals	X						X			
$1.62/7.27 \times 10^7$ Carrier		X	X							
3.00×10^7 Carrier								X		
5.25×10^8 Carrier	X			X	X	X	X		X	X
Inboard Bearing	X									X

a. Baseline as herein documented.

TABLE 6. HPFTP CASE AND ROTOR COUPLING ELEMENTS

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^8$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	[illegible]	
21	20	37	0						Bearings and Carriers
22	29	30	0	1.313			Symmetric		
			0	0	1.313				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	
23	25	33	4.553						Balance Piston
			0	0			Symmetric		
			0	0	0				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	
24	22	35	0						Smooth Seals (RPL)
25	24	34	0	0.439					
			0	0	0.439				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	

TABLE 7. COUPLED HPFTP ROTOR AND CASE MODES (RPL)

Mode	Frequency (Hz)	Description
1	—	Rotor free spin, X
2	47.0	Case rocking, Y
3	100.8	Case rocking, Z
4	196.4	Case rocking + bending, Y
5	197.5	Diffuser torsion
6	249.8	Case rocking + bending, Z
7	287.6	Rotor translation, Y
8	321.0[a]	Rotor translation, Z
9	375.1	Rotor rocking, Z
10	424.0[a]	Rotor rocking, Y
11	463.7	Rotor axial, X
12	488.7	Case + rotor rocking, Z
13	513.6	Rotor bending, Y
14	515.0[a]	Rotor bending, Z
15	554.3	Turbine case torsion, X
16	574.7	Diffuser bending, Y
17	577.4	Diffuser bending, Z
18	599.4	Case+ rotor rocking, Y
19	650.4	Case torsion, X
20	657.3	Case axial, X
21	694.9	Turbine case bending, Z

a. Refer to Figures 8 through 10 and Figure 30.

TABLE 8a. HPOTP ROTOR MODEL DATA

Joint No.	x (m)	y (m)	z (m)	Mass (kg)	J_x ($kg\text{-}m^2 \times 10^{-3}$)	I_y ($kg\text{-}m^2 \times 10^{-3}$)	I_z ($kg\text{-}m^2 \times 10^{-3}$)	Description
50	-0.067	0	0	1.078	1.138	1.015	1.015	Preburner Impeller
51	-0.040	0	0	1.380	0.909	0.714	0.714	Seal
52	0	0	0	0.585	0.098	0.118	0.118	Pump Bearing
53	0.066	0	0	3.518	4.570	3.145	3.145	Main Impeller
54	0.133	0	0	6.074	20.399	10.714	10.714	Main Impeller
55	0.200	0	0	3.903	4.178	3.638	3.638	Main Impeller
56	0.280	0	0	1.543	0.040	0.436	0.436	Turbine Bearing
57	0.320	0	0	1.903	1.129	0.317	0.317	Seal
58	0.399	0	0	0.851	-	-	-	Seal
59	0.429	0	0	5.676	45.731	23.183	23.183	Second Turbine
60	0.457	0	0	1.549	4.019	2.401	2.401	Seal
61	0.486	0	0	6.271	45.825	23.212	23.212	First Turbine
62	-0.086	0	0	0.303	-	-	-	Seal
63	0.369	0	0	1.121	-	-	-	Seal
87	0.340	0	0	-	-	-	-	Seal
				35.755				

TABLE 8b. HPOTP ROTOR MODEL DATA

Beam No.	Joint No. 1	Joint No. 2	J_x ($m^4 \times 10^{-7}$)	I_y ($m^4 \times 10^{-7}$)	I_z ($m^4 \times 10^{-7}$)	Area ($m^2 \times 10^{-3}$)	Material	Description
36	50	51	1.314	0.657	0.657	0.639	Steel	Preburner Shaft
37	50	62	25.034	12.532	12.532	3.790	Steel	Preburner Shaft
38	51	52	1.347	0.674	0.674	0.744	Steel	Interpump Shaft
39	52	53	2.170	1.085	1.085	1.199	Steel	Main Pump Shaft
40	53	54	10.886	5.443	5.443	2.221	Steel	Main Impeller Shaft
41	54	55	31.999	16.000	16.000	2.456	Steel	Main Impeller Shaft
42	55	56	37.998	18.939	18.999	2.807	Steel	Pump Shaft
43	56	57	30.149	15.074	15.074	3.132	Steel	Pump Shaft
44	57	87	37.827	18.913	18.913	3.638	Steel	Pump Shaft
45	58	59	37.815	18.907	18.907	3.838	Steel	Turbine Shaft
46	58	63	35.353	17.677	17.677	3.719	Steel	Pump Shaft
47	59	60	78.559	39.280	39.280	11.338	Steel	Turbine Shaft
48	60	61	37.317	18.659	18.659	14.[illegible]	Steel	Turbine Shaft
49	63	87	37.827	18.913	18.913	3.[illegible]	Steel	Pump Shaft

TABLE 9. HPOTP ROTOR MODES

Mode	Frequency (Hz)	Description
1-6	—	Rigid Body
7-8	470.4[a]	First Bending, Y, Z
9	936.4	First Torsion, X
10-11	1040.5[a]	Second Bending, Y, Z
12	1289.0	Second Torsion, X
13-14	1856.8	Third Bending, Y, Z
15	2484.2	Axial, X

a. Refer to Figures 12 and 13.

TABLE 10a. HPOTP CASE MODEL DATA

Joint No.	x (m)	y (m)	z (m)	Mass (kg)	J_x (kg-m^2 × 10^{-1})	I_y (kg-m^2 × 10^{-1})	I_z (kg-m^2 × 10^{-1})	Description
64	-0.086	0	0	8.963	0.205	0.102	0.102	Seal
65	-0.040	0	0	8.963	0.644	0.322	0.322	Seal
66	0	0	0	4.354	0.088	0.044	0.044	Pump Bearing
67	0.022	0	0	6.804	0.878	0.439	0.439	Pump Case
68	0.133	0	0	55.338	7.901	3.951	3.951	Balance Piston
69	0.320	0	0	29.484	3.219	1.610	1.610	Seal
70	0.280	0	0	7.620	0.322	0.161	0.161	Turbine Bearing
71	0.369	0	0	9.525	0.585	0.293	0.293	Seal
72	0.399	0	0	9.525	0.585	0.293	0.293	Seal
73	0.429	0	0	11.975	2.780	1.390	1.390	Second Turbine Stage
74	0.457	0	0	5.352	0.819	0.410	0.410	Seal
75	0.486	0	0	3.992	0.790	0.395	0.395	First Turbine Stage
76	0.542	0	0	11.975	0.585	0.293	0.293	Inlet Fairing
77	0.574	0	0	105.687	35.117	17.558	17.558	Turbine Case
78	0.788	0	0	38.102	1.171	0.585	0.585	Preburner
79	0.457	0	0	2.631	0.205	0.102	0.102	Interstage Ring
80	-0.029	0	0.127	-	-	-	-	PB45 Accelerometer[a]
81	-0.029	0.127	0	-	-	-	-	PB135 Accelerometer[a]
82	-0.029	0	0.127	-	-	-	-	PB180 Accelerometer
83	0.305	0	0.216	-	-	-	-	RAD1 Accelerometer[a]
84	0.305	-0.216	0	-	-	-	-	RAD2 Accelerometer
85	0.305	0.216	0	-	-	-	-	RAD3 Accelerometer[a]
86	0.340	0	0	-	-	-	-	Seal
				320.290				

a. Relative to a rectangular coordinate frame which shares a common origin and x-axis with joints 64 through 79, 82, 84, and 86 but rotated 135 deg about the x-axis.

TABLE 10b. HPOTP CASE MODEL DATA

Beam No.	Joint No. 1	Joint No. 2	J_x ($m^4 \times 10^{-5}$)	I_y ($m^4 \times 10^{-5}$)	I_z ($m^4 \times 10^{-5}$)	Area ($m^2 \times 10^{-3}$)	Material	Description
50	64	65	5.262	2.631	2.631	8.655	Inconel	Preburner Pump Case
51	65	66	5.262	2.631	2.631	8.655	Inconel	Pump Bearing Support
52	65	67	21.775	10.887	10.887	17.041	Inconel	Pump Case Partition
53	65	80	—	—	—	—	—	Accelerometer Arm
54	65	81	—	—	—	—	—	Accelerometer Arm
55	65	82	—	—	—	—	—	Accelerometer Arm
56	67	68	5.675	2.942	2.733	2.205	Inconel	Pump Case
57	68	69	5.675	2.942	2.733	2.205	Inconel	Pump Case
58	69	70	16.025	7.908	7.908	18.065	Inconel	Turbine Bearing Support
59	69	73	12.487	6.181	6.181	5.290	Inconel	Vanes
60	69	77	26.785	13.392	13.392	6.486	Inconel	Turbine Case
61	69	83	—	—	—	—	—	Accelerometer Arm
62	69	84	—	—	—	—	—	Accelerometer Arm
63	69	85	—	—	—	—	—	Accelerometer Arm
64	69	86	16.025	7.908	7.908	18.065	Inconel	Pump Seals Support
65	71	72	16.025	7.908	7.908	18.065	Inconel	Pump Seals Support
66	71	86	16.025	7.908	7.908	18.065	Inconel	Pump Seals Support
67	73	74	7.986	3.993	3.993	3.964	Inconel	Turbine Seals Support
68	73	76	11.528	5.764	5.764	4.897	Inconel	Fairing
69	74	75	7.986	3.993	3.993	3.964	Inconel	Turbine Seals Support
70	77	14	6.638	5.363	1.271	4.968	Inconel	Hot Gas Manifold
71	77	78	26.785	13.392	13.392	6.486	Inconel	Preburner

TABLE 10c. HPOTP CASE MODEL DATA

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^9$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
26	74	79	1.016						Interstage Ring
			0	0.140			Symmetric		
			0	0	0.140				
			0	0	0	4.553			
			0	0	0	0	2.277		
			0	0	0	0	0	2.277	

TABLE 11. HPOTP CASE MODES

Mode	Frequency (Hz)	Description
1	74.8	Case rocking, Y
2	124.4	First case rocking, Z
3	262.7[a]	Second case rocking, Z
4	310.3	Case axial + bending, Y
5	593.0[a]	Case rocking + bending, Y
6	601.0	First case bending, Z
7	678.6	First case bending, Z
8	773.5	Case bending, Y
9	896.1	Case axial, X
10	1007.5	Turbine seal support, Z
11	1009.8	Turbine seal support, Y
12	1048.5	Second case bending, Z
13	1172.2	Case torsion, X
14	1184.4	Turbine seal support, Y
15	1238.1	Turbine seal support, Z
16	1296.9	Case rocking + bending, Z

a. Refer to Figures 15 and 16.

TABLE 12. HPOTP ROTOR AND CASE COUPLING ELEMENTS

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^6$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
27	52	66	0						Pump
			0	140.101			Symmetric		Bearing
			0	0	140.101				and Carrier
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	
28	56	70	0						Turbine
			0	210.152			Symmetric		Bearing
			0	0	210.152				and Carrier
			0	0	0	0			
			0	0	0	0	0	0	
			0	0	0	0	0	0	
29	54	68	894.198						Balance
			0	0			Symmetric		Piston
			0	0	0				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	

TABLE 12. (Continued)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^6$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
30	51	65	0						Preburner
			0	2.721			Symmetric		Pump
			0	0	2.721				Seal
			0	0	0	0			(RPL)
			0	0	0	0	0		
			0	0	0	0	0	0	
31	62	64	0						Preburner
			0	0.413			Symmetric		Pump
			0	0	0.413				Seal
			0	0	0	0			(RPL)
			0	0	0	0	0		
			0	0	0	0	0	0	
32	58	72	0						Hot Gas
			0	34.168			Symmetric		Seal
			0	0	34.168				(RPL)
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	

TABLE 12. (Concluded)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^6$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
33	59	73	0						Second Turbine Seal (RPL)
			0	0.958			Symmetric		
			0	0	0.958				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	
34	60	79	0						Interstage Seal (RPL)
			0	0.129			Symmetric		
			0	0	0.129				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	
35	61	75	0						First Turbine Seal (RPL)
			0	0.885			Symmetric		
			0	0	0.885				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	

TABLE 13. COUPLED HPOTP ROTOR AND CASE MODES (RPL)

Mode	Frequency (Hz)	Description
1	—	Rotor Free Spin, X
2	69.9	Case Rocking, Y
3	115.1	Case Rocking, Z
4	237.9	Rotor Rocking, Z
5	257.9[a]	Rotor Rocking Y
6	293.0	Case Rocking + Rotor Bending, Z
7	293.8	Case Rocking + Rotor Bending, Y
8	528.8	Rotor Bending, Y
9	536.5[a]	Rotor Bending, Z
10	595.1	Rotor Translation, Z
11	599.3[a]	Rotor Translation, Y
12	637.0	Rotor Bending, Y
13	643.8[a]	Rotor Bending, Z
14	681.3	Rotor Axial, X
15	691.5	Case Torsion, X
16	803.5	Case + Rotor Rocking + Bending, Y
17	936.5	Rotor Torsion, X
18	1009.5	Turbine Interstage Ring, Z
19	1012.5	Turbine Interstage Ring, Y
20	1022.2	Case Axial, X
21	1051.7	Case + Rotor Rocking + Bending, Z

a. Refer to Figures 17 through 20 and Figure 30.

TABLE 14a. SSME MODEL DATA

Joint No.	x (m)	y (m)	z (m)	Mass (kg)	J_x (kg-m²)	I_y (kg-m²)	I_z (kg-m²)	Description
1	0	0	0	43.844	57.791	28.895	28.895	Nozzle Exit
2	0.351	0	0	82.817	102.503	51.251	51.251	Nozzle
3	0.683	0	0	74.221	84.067	42.033	42.033	Nozzle
4	0.991	0	0	64.641	64.412	32.206	32.206	Nozzle
5	1.278	0	0	57.216	50.535	25.267	25.267	Nozzle
6	1.554	0	0	51.945	38.356	19.257	19.257	Nozzle
7	1.831	0	0	47.042	28.604	14.302	14.302	Nozzle
8	2.108	0	0	41.694	19.033	9.516	9.516	Nozzle
9	2.398	0	0	30.985	9.240	4.620	4.620	Nozzle
10	2.628	0	0	44.956	13.507	9.786	4.088	Nozzle
11	2.860	0	0	217.457	57.610	43.780	33.084	Thrust Chamber
12	3.251	0	0	336.339	119.105	82.512	77.393	Thrust Chamber
13	3.419	0	0	243.126	64.042	50.713	48.963	Powerhead
14	3.586	0	0	531.157	129.774	192.392	80.545	Powerhead[a]
15	3.952	0	0	314.793	134.629	116.060	33.626	Gimbal
16	3.078	0.450	-0.450	52.844	—	—	—	Actuator Attachment
17	3.078	0.450	0.450	52.844	—	—	—	Actuator Attachment
18	3.485	1.053	-1.053	52.844	—	—	—	Actuator Attachment
19	3.485	1.053	1.053	52.844	—	—	—	Actuator Attachment
				2393.609				

a. Both turbopumps are inclined 10.5° to the SSME centerline with the HPFTP pump bearing at X = 2.914 m and Y = 0.743 m and the HPOTP pump bearing at X = 2.989 m and Y = -0.698 m. Refer to Figure 21.

TABLE 14b. SSME MODEL DATA

Beam No.	Joint No. 1	Joint No. 2	J_x ($m^4 \times 10^{-4}$)	I_y ($m^4 \times 10^{-4}$)	I_z ($m^4 \times 10^{-4}$)	Area ($m^2 \times 10^{-2}$)	Material	Description
1	12	13	8.919	4.460	4.460	1.473	Inconel	Combustion Chamber
2	13	14	33.951	16.976	16.976	4.181	Inconel	Powerhead

TABLE 14c. SSME MODEL DATA

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^8$ N/in)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
1	1	2	61.189						Nozzle
			0	61.189			Symmetric		
			0	0	161.274				
			0	-10.725	0	104.974			
			10.725	0	0	0	104.974		
			0	0	0	0	0	78.705	
2	2	3	58.370						Nozzle
			0	58.370			Symmetric		
			0	0	153.831				
			0	-9.710	0	92.874			
			9.710	0	0	0	92.874		
			0	0	0	0	0	69.666	
3	3	4	57.372						Nozzle
			0	57.372			Symmetric		
			0	0	151.134				
			0	-8.816	0	81.971			
			8.816	0	0	0	81.971		
			0	0	0	0	0	61.543	

TABLE 14c. (Continued)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^8$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
4	4	5	54.342						Nozzle
			0	54.342			Symmetric		
			0	0	143.131				
			0	-7.798	0	68.503			
			7.798	0	0	0	68.503		
			0	0	0	0	0	51.442	
5	5	6	48.633						Nozzle
			0	48.633			Symmetric		
			0	0	128.193				
			0	-6.735	0	53.193			
			6.735	0	0	0	53.193		
			0	0	0	0	0	39.895	
6	6	7	40.542						Nozzle
			0	40.542			Symmetric		
			0	0	106.932				
			0	-5.614	0	37.048			
			5.614	0	0	0	37.048		
			0	0	0	0	0	27.693	

TABLE 14c. (Continued)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^8$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
7	7	8	33.414						Nozzle
			0	33.414			Symmetric		
			0	0	88.789				
			0	-4.648	0	24.518			
			4.648	0	0	0	24.518		
			0	0	0	0	0	18.224	
8	8	9	28.143						Nozzle
			0	28.143			Symmetric		
			0	0	74.762				
			0	-4.075	0	15.016			
			4.075	0	0	0	15.016		
			0	0	0	0	0	11.009	
9	9	10	30.892						Nozzle
			0	30.892			Symmetric		
			0	0	82.029				
			0	-3.570	0	10.523			
			3.570	0	0	0	10.523		
			0	0	0	0	0	7.719	

TABLE 14c. (Continued)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^8$ N/m)						Description
			δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	
10	10	11	21.365						Nozzle
			0	21.365			Symmetric		
			0	0	57.250				
			0	-2.468	0	4.498			
			2.468	0	0	0	4.498		
			0	0	0	0	0	3.216	
11	11	12	14.255						Combustion Chamber
			0	14.255			Symmetric		
			0	0	39.176				
			0	-2.788	0	1.052			
			2.788	0	0	0	1.052		
			0	0	0	0	0	0.385	
12	14	15	26.374						Powerhead
			0	26.374			Symmetric		
			0	0	59.368				
			0	-3.446	0	0.600			
			3.446	0	0	0	0.600		
			0	0	0	0	0	0.115	

TABLE 14c. (Concluded)

Element No.	Joint No. 1	Joint No. 2	Stiffness Submatrix ($K_{11} \times 10^3$ N/m) δ_x	δ_y	δ_z	θ_x	θ_y	θ_z	Description
13	11	16	0.343						Lower
14	11	17	0	2.662			Symmetric		Actuator
			0	0	9.562				Bipods
			0	-0.061	0	0.019			
			0.061	0	0	0	0.016		
			0	0	0	0	0	0.0067	
15	13	16	0.182						Upper
16	13	17	0	1.517			Symmetric		Actuator
			0	0	8.196				Bipods
			0	-0.042	0	0.015			
			0.042	0	0	0	0.013		
			0	0	0	0	0	0.0047	
17	16	18	0						Actuators
18	17	19	0	0			Symmetric		
			0	0	0.473				
			0	0	0	0			
			0	0	0	0	0		
			0	0	0	0	0	0	

TABLE 15. SSME MODES (EXCLUDING TURBOPUMPS)

Mode	Frequency (Hz)	Description
1	14.1	Rocking, Z
2	14.1	Rocking, Y
3	16.9	First Torsion, X
4	45.0	First Bending, Z
5	54.1	First Bending, Y
6	70.1	Second Torsion, X
7	86.6	Second Bending, Z
8	102.1	Actuator Arms
9	104.6	Actuator Arms
10	115.1	Second Bending, Y
11	190.7	First Axial, X
12	240.9[a]	Third Bending, Z
13	261.5	Second Bending, Y
14	296.4	Third Torsion, X
15	311.1[a]	Second Bending, Z
16	367.3	Fourth Torsion, X
17	377.7	Second Axial, X
18	411.7[a]	Third Bending, Y
19	415.3[a]	Third Bending, Z
20	441.1	Third Bending, Y
21	462.4	Actuator Arms
22	527.6	Actuator Arms
23	552.4	Third Bending, Z
24	596.9	Third Bending, Y
25	661.4	Third Axial, X
26	668.7	Fifth Torsion, X
27	686.2	Actuator Arms
28	764.9	Fourth Axial, X
29	770.2	Fourth Bending, Z
30	791.9	Fourth Bending, Y

a. Refer to Figures 22 through 25 and Figure 30.

TABLE 16. SSME MODES (INCLUDING TURBOPUMPS)

Mode	Frequency (Hz)	Description
1	—	HPFTP Rotor Free Spin, X
2	—	HPOTP Rotor Free Spin, X
3	13.5	Engine Rocking, Y
4	13.7	Engine Rocking, Z
5	14.7	First Engine Torsion, X
6	38.4	First Engine Bending, Y
7	39.7	First Engine Bending, Z
8	52.7	Second Engine Torsion, X
9	53.1	HPFTP Rocking, Y
10	67.6	HPOTP Rocking, Y
11	79.7	Pumps Rocking in Phase, Z
12	99.9	Actuator Arms (HPFTP Rocking, Z)
13	100.0	Actuator Arms
14	116.1	Second Engine Bending, Y
15	126.7	First Engine Bending, Z (Pumps Rocking in Phase, Z)
16	138.4	Pumps Rocking Out of Phase, Z
17	181.2	First Engine Axial (Pumps Rocking, Y)
18	200.7	First HPFTP Diffuser Torsion, X
19	212.6	HPFTP Case Rocking + Bending, Y (Engine Axial)
20	232.4	HPOTP Rotor Rocking, Z
21	245.6	HPOTP Rotor Rocking, Z (Engine Bending)
22	249.7	HPOTP Rotor Rocking, Y
23	256.2[a]	Pump Rotors Rocking, Z
24	266.1	HPOTP Rotor Bending, Y (Engine Bending)
25	284.1	HPOTP Case + Rotor Bending, Z
26	290.1	HPFTP Rotor Translation, Y
27	300.2	HPFTP Rotor Translation, Z (HPOTP Bending)
28	301.1	HPOTP Case and Rotor Bending, Y
29	316.9	HPFTP Rotor Rocking, Z
30	331.0[a]	Pump Rotors Rocking, Z (Engine Bending)
31	373.2	HPFTP Rotor Rocking, Z (Engine Torsion)
32	386.5	HPFTP Rotor Rocking, Y (Engine Axial)
33	406.6[a]	Pump Cases and Rotors Bending, Y (Engine Axial)
34	415.5[a]	Third Engine Bending, Z (HPFTP Rocking)
35	424.9	HPFTP Rotor Rocking, Z (Engine Bending)
36	432.5	HPFTP Rotor Rocking, Y
37	442.9	Third Engine Bending, Y
38	463.6	Actuator Arms
39	464.7	HPFTP Rotor Axial, X
40	500.3	HPFTP Case and Rotor Rocking, Z

a. Refer to Figures 26 through 30.

TABLE 16. (Concluded)

Mode	Frequency (Hz)	Description
41	513.7	HPFTP Rotor Bending, Y
42	519.3	HPFTP Rotor Bending, Z
43	527.8	HPOTP Rotor Bending, Y
44	533.3	Actuator Arms (HPOTP Rotor Bending, Y)
45	536.1	HPOTP Rotor Bending, Z
46	543.4	HPFTP Turbine Case Torsion (Engine Bending, Z)
47	568.6	HPFTP Diffuser Bending, Y (HPOTP Rotor Bending)
48	568.8	HPFTP Turbine Case Torsion (Engine Bending, Z)
49	576.8	HPFTP Diffuser Bending, Z
50	578.0	First HPFTP Diffuser Bending, Y (HPOTP Rotor Bending)
51	596.6	HPOTP Rotor Translation, Z
52	605.8	HPOTP Rotor Translation, Y
53	623.3	HPOTP Rotor Bending, Y (HPFTP Rotor Rocking)
54	643.9	HPOTP Rotor Bending, Z
55	647.9	Third Engine Axial, X
56	650.7	HPOTP Rotor Axial, X
57	654.8	HPFTP Case Torsion, X
58	668.7	Fifth Engine Torsion, X
59	671.4	Pump Cases and Rotors Bending, Y
60	685.9	Actuator Arms
61	693.2	HPFTP Turbine Case Bending, Z
62	697.1	HPOTP Case Torsion, X
63	700.5	HPOTP Rotor Axial
64	710.9	Second HPFTP Diffuser Torsion, X
65	718.7	Second HPFTP Diffuser Bending, Y
66	728.3	First HPFTP Rotor Torsion, X
67	730.5	Second HPFTP Rotor Torsion, X
68	751.4	HPFTP Hot Gas Manifold Bending, Y
69	765.9	Fourth Engine Axial, X
70	770.3	Fourth Engine Bending, Z
71	784.0	HPOTP Rotor Axial, X (Engine Bending)
72	807.5	HPOTP Rotor Axial, X (Engine Bending)
73	811.8	HPFTP Rotor Bending, Z
74	816.0	HPFTP Rotor Bending, Y
75	828.4	Actuators (Engine Bending, Z)
76	873.1	Actuators (Engine Bending, Z)
77	882.2	Fifth Engine Axial (Actuators)
78	895.4	HPFTP Rotor Bending, Z
79	897.9	HPFTP Rotor Bending, Y
80	911.7	HPFTP Case Axial, X

TABLE 17. COMPARISON OF SSME MODEL AND HPOTP MODAL SURVEY FREQUENCIES

SSME Model (Including Turbopumps) Frequency (Hz)	Percent Difference	SDRC HPOTP Modal Survey Frequency (Hz)	SDRC Description
39.7	-6.8	37	Z Translations, HPOTP and HPFTP In-Phase
79.7	-5.9	75	HPOTP θ_y
—	—	87	Z Translations, HPOTP and HPFTP Out-of-Phase
138.4	-9.0	126	θ_y of HPOTP and HPFTP Out-of-Phase
200.7	-3.3	194	θ_y of HPOTP
256.2	+1.1	259	θ_y of HPOTP
300.2	-0.1	300	HPOTP Bending in XZ Plane
331.0	+0.3	332	HPOTP Bending in XY Plane
—	—	402	HPOTP and HPFTP θ_y Out-of-Phase
406.6	-0.4	405	(Complex Mode)
415.5	+0.4	417	(Complex Mode)
424.9	-0.2	424	HPOTP Bending in XY Plane
442.9	-0.7	440	HPOTP θ_x Torsion
—	—	493	(Complex Mode)
500.3	-1.1	495	(Complex Mode)

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APPROVAL

FINITE ELEMENT MODELS OF THE SPACE SHUTTLE MAIN ENGINE

By G. R. Muller

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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