Review of Launch Vehicle Related Aeroelastic Instability Studies at NAL

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1.Introduction

Modern launch vehicles are long slender bodies with high flexibility and hence are prone to aeroelastic instabilities during their flight. These instabilities may adversely affect the performance of the vehicle or may even cause its failure. It is therefore necessary that a rigourous investigation of the aeroelastic behaviour of the vehicle is done at the design stage itself to ensure that the vehicle is free from such instabilities during its atmospheric flight.

Important among the instabilities that a launch vehicle may experience are response to ground wind loads, divergence,flutter of control surfaces and panels, buffeting, coupled oscillations and fuel sloshing. Because of the complex nature of the aerodynamic input forces and aerodynamic-elastic-inertial interactions involved in most of these phenomena, it is often difficult and at times almost impossible to predict accurately the behaviour of the flight vehicle through theoretical means. Hence the designer has to take recourse to experimental means involving design and testing of aeroelastically scaled models. In this technique an aeroelastic model in a suitable wind tunnel is used as a mechanical analog of the mathematically complex problem requiring solution. The model in the wind tunnel first generates the correct aerodynamic input forces, and the measured response of the model to these input forces is then used to predict the response of the actual vehicle using appropriate scaling laws. The importance of scaled models in the study of aeroelastic problems of launch vehicles is amply demonstrated by the work done in this direction at the aerospace research laboratories of NASA and elsewhere.

With the importance of aeroelastic problems in the design of aerospace vehicles in mind, the Structures Division of the Laboratory, with active support from the Aerodynamic Division, initiated work on aeroelastic model studies in the early 1970's, mainly to understand the technique of aeroelastic model design and fabrication and to gain experience in aeroelastic testing. Early works in this direction were related to aircraft, involving design and testing of flutter models of typical aircraft wings (Ref.1&2).The know-how gained out of these studies was thus very useful while undertaking studies related to aeroelastic problems of launch vehicles for the ISRO in the early 1970's. This paper gives a brief review of the past and current aeroelastic studies at NAL on Satellite Launch Vehicles SLV3, ASLV and PSLV developed/being developed by the ISRO.

2. Wind tunnel Test Facility at NAL

The National Aeronautical Laboratory has two main blow-down wind tunnels located in the Wind Tunnel Centre at Belur; the 1.2m Trisonic Wind Tunnel and the 0.3m Trisonic Wind Tunnel. These blow-down tunnels are not best suited for conducting aeroelastic studies on flexible models because of some inherent deficiencies like large starting/stopping loads, smaller run time and higher starting stagnation pressures. Usually, aeroelastic studies are conducted in continuous tunnels in which these problems are eliminated. However, in the absence of such a facility in the country the blow-down tunnel itself is being used for aeroelastic studies with suitable modification to the system.

The 1.2 m Trisonic Blowdown Wind Tunnel (Fig.2.1)is used for most of the aeroelastic studies in the transonic and supersonic range. The tunnel provides Mach number variation from 0.2 to 4.0 with independent Reynolds Number variation. The test section used for subsonic and supersonic testing is a 1.2m square section. For transonic tests(M=0.5 to 1.4), a separate transonic insert with a 1.2m square test section with perforated walls is introduced between the nozzle and the model cart. The articulated sting support provides automatic attitude control of model in pitch (- 15degree to + 27 degree) and roll (+ 90degree). The flexible nozzle contour can be adjusted to obtain any required supersonic Mach number in the range $1.4 < M < 4.0$ at intervals of M= 0.1, whereas the transonic insert yields continuous Mach number variation between $0.5 < M < 1.4$. At any given Mach number,the required dynamic pressure variation is obtained by varying the blowing pressure.

Fig 2.2 shows available dynamic pressure ranges at different Mach numbers and Fig 2.3 gives Reynolds Number and total run time available at different Mach Numbers and blowing pressures.

At supersonic speeds, models are subjected to transient loads of very high magnitude during tunnel starting and stopping operations. The intensity of these loads increases with Mach Number and tunnel stagnation pressure. It is quite essential to protect the flexible aeroelastic models from these severe shock loads. The proximity plates that exist as a standard feature of the tunnel are usually inadequate for this purpose. Specially designed model protection devices are used for aeroelastic models. These devices are usually a pair of plates or channels depending on the shape of the model being tested (See section 3,4 & 5 for details). They lie close to the model covering a major portion of the model during tunnel starting and stopping and are retracted to the top & bottom walls during steady flow.

In the 0.3m Trisonic Wind Tunnel, fixed nozzle blocks are used to generate different supersonic Mach numbers.

3. Flutter Test of a Typical Rocket Fin

Flutter is one of the most important and complex problems in aeroelasticity. It is a dynamic aeroelastic phenomenon where structural oscillations are maintained by unsteady aerodynamic forces, and these oscillations become divergent above the flutter speed. In the design of lifting surfaces such as aircraft wings, tailplane, control surfaces and rocket fins, it is to be ensured that flutter does not occur in the design speed range. Flutter models are extensively used in such studies in wind tunnels to evaluate a particular design. Sometimes, if the size of the component and the flight condition to be simulated permit, the full scale component of the prototype itself can be tested in the wind-tunnel for aeroelastic studies.

Flutter testing of ROHINI 300 Rocket fin was the first task undertaken by the Laboratory in 1974 for ISRO in the field of aeroelastic model testing (Ref.3). For the type of flight conditions to be investigated, it was possible to test the full scale fin itself in the NAL 1.2m Trisonic Tunnel. The aim of the study was to determine the flutter susceptibility of the fin in flight conditions corresponding to the tunnel range of supersonic flow.

Figure 3.1 shows the RH 300 fin configuration. The fin has a sandwich form of construction consisting of thin stainless steel cover plates with a core of perforated aluminium sheet joined through rivets. It was instrumented with straingages, mounted externally on it near the root to monitor the bending and torsion signals which would give the frequency of model oscillations and also provide an indication of start of flutter. Before taking the model to the tunnel, a detailed investigation on the vibration characteristics of the fin was made using the Kennedy and Pancu Vector technique, the results of which would be useful in analysing wind tunnel test data. Fig 3.2 shows the ground vibration test results.

The fin was mounted on the sidewall of the 1.2m Trisonic Wind Tunnel at zero angle of attack using two M.S. angles in a manner similar to the way it was attached to the rocket body (Fig.3.3).

In order to protect the model from tunnel starting/stopping loads, it was partially covered by a pair of proximity plates located on either side of the model during the tunnel starting and stopping operations. Also, the tunnel was started and stopped at a lower stagnation pressure to reduce the intensity of this loading.

The tests were conducted at constant Mach numbers of 2.0, 2.5, 2.8 and 3.0, with the stagnation pressure being increased continuously at each Mach number (approximately within the range 40-65 Psi). During each test run, the bending and torsion signals and also the total pressure head were continiously recorded on a visicorder, and also on a magnetic tape for frequency analysis. Generally near flutter, the bending and torsion frequencies start approaching each other and the overall damping approaches zero.

From the analysis of the recorded signals, it was found that the model was being excited by the heavy starting loads initially, and later by the tunnel turbulance. It was also observed that there was very little variation of bending and torsion frequencies of the fin from those of its free vibration values. Testing of the fin could not be continued beyond M=3 as the model started failing due to inadequate protection from high starting loads. However, the test results showed that the fin was flutter free for the tested Mach number and dynamic pressure ranges.

4. Divergence Studies of SLV-3 Aeroelastic Models

Divergence is a static aeroelastic phenomenon involving interaction of aerodynamic and elastic forces. It assumes importance for slender launch vehicles with length to diameter ratio greater than about 20 and hence needs to be considered in the design process. For guided launch vehicles divergence can occur in one of the following two ways;

1) Structural body divergence-Here the deformation of the flexible vehicle due to aerodynamic load inputs gives rise to changes in local angle of attack which in turn induces additional aerodynamic loads. This process converges to a stable equilbrium deflected shape below the divergence speed. However, above this speed, bending deformations become divergent and unstable due to the aerodynamic stiffness exceeding the elastic stiffness which results in the failure of the structure. 2) Divergence due to reduced static margin-The vehicle structural deformation and subsequent change in aerodynamic load distribution tends to move the centre of pressure forward towards the nose end, thus reducing the static margin. Available control force near the nozzle end of the vehicle imposes a restriction on the maximum forward 'CP' shift due to flexibility. That is, static instability occurs when the available control force is insufficient to maintain positive static margin.

Divergence type of instability is known to have been encountered in launch vehicle like Bulbous Nike-Apache, Nike Tomahawk, First NASA Black Brant V.C.etc.

Figure 4.1 shows SLV-3 configuration. The slenderness ratio of the vehicle was more than 20, and hence it was important that its divergence behaviour was investigated. This task was undertaken at NAL through aeroelastic modelling and testing (Ref.4)
Intially a 1/45th scale aeroelastic model of SLV -3 was designed to match the characteristics of the 0.3m Trisonic Wind Tunnel of NAL. The model simulated the flight condition at M=2.5, the ratio of the design dynamic pressure to flight dynamic pressure being 0.825. The similarity parameters used in the design of divergence model were Mach number M, and stiffness parameter EI/ql, where (EI) is the flexural rigidity , q is the dynamic pressure & l is the characteristic length. Equivalant form of contruction was adopted in model design where a central aluminium spar with variable cross-section simulated the required scaled stiffnes distribution. The model was covered with balsa-wood segments (with flimsy foam inserts between segments, a silk cloth cover and a coating of araldite) to simulate the aerodynmaic shape. The model spar was instrumented with strain gages at different stations along the length. These gages were calibrated to read bending moments at each station.

Figure 4.2 shows the aluminium spar and the balsa covered 1/45th scale model. The stiffness simulation in the model was checked by comparing the theoritcal and experimental slope distributions for an unit tip load. Fig 4.3 shows the extent of simulation achieved.

The model was tested in the 0.3m Trisonic wind-tunnel by supporting it rigidly at its nozzle end on the sting mount. This form of support is satisfactory since the deformed shape of the structure in flight is somewhat similar to the first bending mode of a cantiliver beam because of the comparatively high stiffness of the first stage of the vehicle. Fig 4.4 shows the model in the 0.3m tunnel.

The model was tested at a Mach number of 2.5 and an angle of attack of 53' with the test dynamic pressure range corresponding to 0.84 to 1.59 times the flight value. A protection device covering the model on 3 sides was used during the starting/stopping operations.

More elaborate tests were planned, first with 1/15th and then with 1/20th scale models, designed and fabricated to match the characteristics of the 1.2m Trisonic Wind Tunnel. However, these models failed due to severe stopping loads inspite of using protection devices. Hence, the 1/45th scale model itself was tested in this tunnel at Mach numbers 2,2.5 and 3.3 and an angle of attack of 1 degree, the dynamic pressure at each Mach number being varied in steps in the range available for that Mach number. These tests showed that the vehicle was free from structural body divergence at the Mach numbers and the range of dynamic pressures simulated in the tunnel.

The model strain gage outputs recorded on strip-chart recorders during each test run were analysed to get the bending moment variation along the model at different dynamic pressures at a constant Mach number. It was then possible to obtain from these plots the variations of modified centre of pressure location with dynamic pressure at each test Mach number. This is indicated in Fig 4.5 which shows the CP shift due to flexibility effects as compared to the rigid vehicle. It is seen that the CP moves forward by 2.5 to 4.5 times the diameter of the vehicle as the Mach number changes from 2.0 to 3.3. Also, all the three curves tend asymptotically towards a value of about 22 which is the CP location when nearly all the aerodynamic load contribution comes from the nose cone only.

The estimate of CP shift obtained from these tests could be used in the vehicle static stability calculations and in estimating control force requirements.

5.Flutter Studies of SLV-3 Fin Aeroelastic Model

Flutter studies on aeroelastic models of SLV-3 fin were undertaken at NAL with the object of determining the instability behaviour due to flutter at the most critical flight condition (that is, maximum dynamic pressure condition) in the vehicle trajectory, occuring at M= 3.3, and for possible angles of fin-tip control surface (Ref.5).

As flutter is a dynamic aeroelastic phenomenon, a flutter model must adequately represent the aerodynamic, elastic and inertial characteristics of the component under consideration. This is achieved if the model is designed to have the same values as the prototype for the following similarity parameters, in addition to simulating the aerodynamic shape and elastic stiffness and inertia distributions. These similarity parameters are Mach number M, stiffness parameter EI/ql^4 (Et/ql for replica model, where t is the material thickness), and density ratio σ/ρ where ρ is the air density and σ is the structural density.

The SLV-3 fin flutter model was designed to be a full scale model as this could be accommodated in the 1.2m Trisonic Tunnel test section without blockage. Consequently, it was possible to adopt the favoured replica form of construction for the model. The model was designed to have a stiffness ratio of 0.373 and a density ratio of 0.857 as compared to the prototype.

The flutter model was built out of aluminium alloy sheets and solid aluminium blocks. Inertial simulation was obtained by gluing small flat lead pieces of suitable weights at different stations inside the model. The model instrumentation consisted of strain rosettes fixed near the fin root and on the control shaft, and an accelerometer placed inside the fin tip. Provision was made within the model to pre-set fin tip deflections to 0, 2.5, 5, 7.5 and 10 degrees as desird, before starting the tunnel. Fig 5.1 shows details of the fin flutter model.

Before taking the model to the tunnel, it was subjected to extensive ground vibration studies, using the Kennedy-Pancu vector technique to determine its dynamic characteristics. Fig.5.2 shows a typical Kennedy- Pancu plot obtained during vibration testing and Fig 5.3 shows some vibration test results.

It is seen that the first mode is a pure bending mode, while in the subsequent three modes, combined bending and torsion occurs in the fin tip.

For wind tunnel testing,the model was mounted on the side wall of the test section in the 1.2m Trisonic Tunnel. Specially designed protection devices consisting of rectangular steel plates covering about 70% of the model on either side were used to protect the model from starting/stopping loads. Fig.5.4 shows the model mounted in the 1.2m Trisonic Tunnel along with protection devices. The model was tested at M= 3.3 and at the required dynamic pressure with fin tip angles of 0 and 2.5 degree, with the tunnel turbulence acting as the source of excitation. The tests showed that the model was flutter free for these configurations of the fin tip at the tested critical dynamic pressure and Mach number conditions.

The fin aeroelastic model was also tested for servo-aeroelastic instability at M=3.3 and design dynamic pressure, by using an externally mounted prototype servoactuator system for controlling fin-tip deflections during the test run. The model was found to be flutter free at the specified test conditions.

6. Transonic Flutter Tests on SLV-3 Fin Prototype

The transonic speed range is also a dynamic instability area since at these speeds, a complex interaction between moving shocks and boundary layer takes place resulting in unsteady aerodynamic loads. In the SLV-3 fin, the fin tip control surface motion was automatically controlled by an electro-hydraulic servo-actuation system. Thus, in addition to aerodynamic, inertial and elastic forces, the servo-control forces also come into play, and an adverse coupling between these forces could lead to instability. Hence, an experimental study was undertaken at NAL to establish the flutter behaviour and performance characteristics of the SLV-3 fin in unsteady transonic flight range, and to assess the adequacy of the fin and servo-actuator combination at all the modes of fin control surface actuation (Ref.6).

The prototype fin itself was used for aeroelastic studies since a study of the scaling parameters indicated that a transonic flutter model would not differ significantly from its prototype, and hence using the prototype itself would save enormous cost and time while still providing acceptable results. Testing the prototype itself at the lowest available dynamic pressure in the wind tunnel at the required Mach number of 0.95 meant that the simulated dynamic pressure was about 30 percent higher than that required, and hence if no instability occured at the test condition, it could be safely assumed that the fin would be free from instability at the critical flight condition.

The fin was instrumented with straingages on the control shaft, servo-actuator rods, and on the skin near the root, and with an accelerometer in the fin tip. An initial ground vibration study showed the first two natural frequencies to be 39 Hz and 71Hz respectively.

A special structure was built to side-mount the fin in the transonic test section of the tunnel such that the aerodynamic loads were not transferred to the delicate perforated wall structure of the tunnel from the fin. Fig 6.1 brings out schematically the wind tunnel test set-up and Fig 6.2 shows the fin mounted in the transonic test section. In the control system appropriate signal generator was brought in to feed in the signal to the actuator for controlling the fin-tip motion during the test run.

The fin was tested in the Mach Number range 0.93 to 1.10 with the dyanamic pressure being held constant, or varied in a ramp or stepped mode. The fin tip angle was either held constant at 0,5 and 10 degrees, or varied harmonically with an amplitude of 10 degrees and a frequency of 0.5, 1.0 or 1.5 Hz. The tunnel turbulance served as the forcing input for the test. Test signals were displayed on CRO's and visicorders for on the spot studies and recorded on an instrumentation tape recorder. These recorded signals were analysed later using an F.F.T analyzer by ensemble averaging of the autocorrelation functions of the output response for minimizing noise contamination and then obtaining the Fourier transforms of the auto-correlation functions. Fig 6.3 shows the effect of flow dynamic pressure on the fin response as obtained from a typical strain gage mounted on the actuator shaft during a typical run, and Figure 6.4 shows the variation of the first two modal frequencies with dynamic pressure.

It was also observed that the fin tip actuation mode had hardly any influence on the frequency shifts. The overall damping was also observed to be more or less constant over the test dynamic pressure range.

The studies on the prototype fin established that it was flutter free in the transonic flight range. It also showed that no coupling between the electro-hydraulic actuation system and the fin-tip structure took place over the fin tip actuation modes covered.

7. ASLV Transonic Buffet Studies

Transonic buffeting of launch vehicles is a phenomenon where the vehicle is subjected to severe fluctuating pressures caused by separated flows and shock oscillations during the transonic phase of its trajectory. It is a serious problem that needs careful study since it has been known to lead to failure of the vehicle.

Buffet pressures are highly configuration dependant, and are found to be significant in launch vehicles with bulbous nose configuration. Two main types of buffeting are observed in launch vehicles; 1) the high frequency shell mode response caused by separated wake type of flow which may affect the performance of equipment housed inside, and 2) low frequency overall bending mode response of the vehicle caused by unsteady pressures due to shock-boundary layer interactions at cone-cylinder junctions. This type of buffeting causes additional dynamic bending moments along the vehicle length which needs to be considered in the vehicle structural design.

Fig. 7.1 shows the ASLV configuration. It employs a bulbous-nose configuration which is known to be buffet prone. Hence it was proposed to design and test its scaled aeroelastic models at NAL to determine its buffet response characteristics (Ref.7). The buffet model's geometric scale was chosen to be 1/20th of the prototype size so that the model could be fully accommodated inside the transonic test section of 1.2m Trisonic Tunnel. The model was designed to simulate full-scale vehicle stiffness ratio EI/qL^4, mass ratio (σ/ρ) and reduced frequency wL/V (where w is the frequency parameter and V is the flow speed) corresponding to Mach one flight condition. Also, the model and protype structural damping should be as close as possible.

An aluminium alloy spar-ring-skin type of construction was adopted in model design. The spar-skin combination simulated the required stiffness distribution, with the rings stablilizing the structure along its length. The heat sheild portion and the strap-on nose cones were fabricated separately as filament wound GFRP shells. Mass simulation was achieved using lead weight pieces attached to the interior of the model. Figs. 7.2 & 7.3 show stiffness and mass simulations attempted in the model as compared to the actual distributions (Ref.8).

The buffet model in the wind tunnel must simulate the free-free dynamic beam bending modes of the prototype vehicle. This was achieved by supporting the model on a relatively rigid sting on sufficiently flexible springs at points corresponding to the node points of the first free-free bending mode. Such a system was known to provide negligible restraint in the second and third modes of vibration. Fig 7.4 shows the spring support system used which comprises of a linear motion bearing housed in the sting, a rod freely moving in the L.M bearing but attached rigidly to the model, and a pair of leaf springs supporting the model on either side of the spring.

The model was instrumented with several strain gage bridges along its length which were then calibrated to read bending moments at their respective locations. Fig. 7.5 shows a sectional view of the model and Fig. 7.6 shows the model undergoing ground vibration studies for verifying the degree of simulation achieved.

The model vibration characteristics were determined using a conventional sinusoidal excitation-response study, as well as from transient force-response and random force-response studies using a Fourier Analyser for spectral analysis.Fig 7.7 shows the comparison of theoretical and experimental frequencies and mode shapes for the first free-free mode of the model.

Figure 7.8 shows the ASLV buffet model mounted in the 1.2m Trisonic Wind Tunnel and Figures 7.9 shows the instrumentation used for recording the strainguage, accelerometer and pressure signals during a test run. The model would be tested in the tunnel in the transonic Mach number range, at angles of attack of 0,1 & 2 degrees and within a dynamic pressure range which includes the design dynamic pressure. The dynamic strain guage signals would be recorded on a tape recorder and later subjected to a spectral analysis using a Fourier analyser to get the individual modal bending moment responses in the first three modes at the strain gage locations. These modal responses are then scaled up to full scale values using the appropriate scaling parameters.

The vehicle structural designer needs to know the bending moment distribution along the length of the vehicle due to buffeting. This can be calculated by extrapolating individual modal response at a strain gage location to other locations using normalized inertial bending moment distribution plots for each mode. However, it must be ensured that the strain gage selected is sensitive to bending moments in all the important modes of interest. The total mean square bending moment at any location for the full scale vehicle is obtained as the sum of the individual mean square modal bending moments at that location.

The relation used for relating modal responses to full-scale values includes a parameter representing modal aerodynamic damping of the model. This can be obtained by measuring total modal damping of the model in the wind-on condition and subtracting modal structural damping already obtained during ground vibration tests. However, measurement of total modal damping with wind-on in the tunnel requires incorporation of a built in shaker inside the model which is rather difficult in a model of the size being tested. Since it has been shown in literature that for launch vehicle like structures aerodynamic damping is usually small, no attempt has been made in the present study to measure aerodynamic damping.

8. PSLV Aeroelastic Studies

The Polar Satellite launch Vehicle (PSLV) designed to carry a payload of 1000 Kgs., also has a bulbous nose portion and six strap-on boosters as shown in Fig 8.1 which may induce unsteady buffet flows. It is thus necessary to carry out a detailed experimental investigation to determine its transonic buffet characteristics.

A 2.5 percent scale aeroelastic model is planned for PSLV buffet studies as this is the maximum length that can be accommodated in the transonic test section. The model design philosophy and manner of support are similar to that of ASLV model. The model will use both aluminium alloy sheets and GFRP in its construction depending on the thickness requirements. An attempt will be made to simulate the payload system as a seperate branch beam so that the interaction between the main body and the payload could be studied. It is also planned to excite the model during a wind tunnel test run in its first three free-free natural modes using a sting mounted mini-shaker to obtained aerodynamic damping measurements in these modes.

It is also proposed to study the effects of vehicle flexibility on the aerodynamic load distribution and divergence stability of PSLV in the maximum dynamic pressure condition which occurs in the supersonic flight regime. The model will have to be protected against starting and stopping loads in the tunnel. Since the 1/40th scale model length is too large to provide such protection, a 1/80th scale modal is planned. As this is a static aeroelastic phenomenon, only the stiffness distribution needs to be simulated. It is planned to support the model externally at the point corresponding to the zero slope location in its theoretically determined free-free deflected shape as this is a better simulation than supporting it at its root end as a cantilever. The model design, instrumentation and testing procedures would be similar to that of SLV-3 divergence model discussed in Section 4.

The model would be tested in the 1.2m Trisonic wind tunnel at the required Mach number and dynamic pressures. The bending moment distribution along the length of the model would be measured from which the total normal load and the forward movement of CP due to flexibility effects could be determined.

9. Conclusions.

Aeroelastic instabilities of a launch vehicle is an important phenomenon that needs to be thoroughly investigated during its design process. Experimental method involving aeroelastic model testing is a useful and reliable technique for such studies. The aeroelastic model studies undertaken at NAL to investigate instability characteristics such as flutter, divergence, buffeting and flexibility effects of launch vehicles and their components designed and developed by the ISRO are reviewed. Details of model design, instrumentation, testing procedures and test results are presented for each case. The review clearly brings out the importance and usefulness of aeroelastic model studies in launch vehicle design.

10. Acknowledgement.

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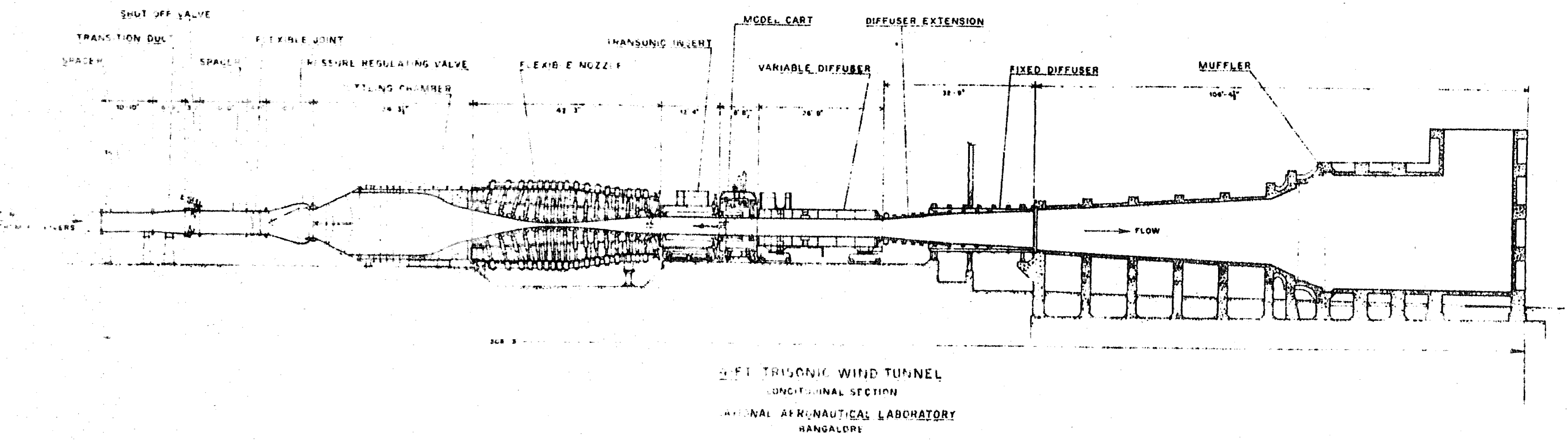


FIG. 2.1. 1.2 m. TRISONIC BLOW DOWN WIND TUNNEL (N.A.L)

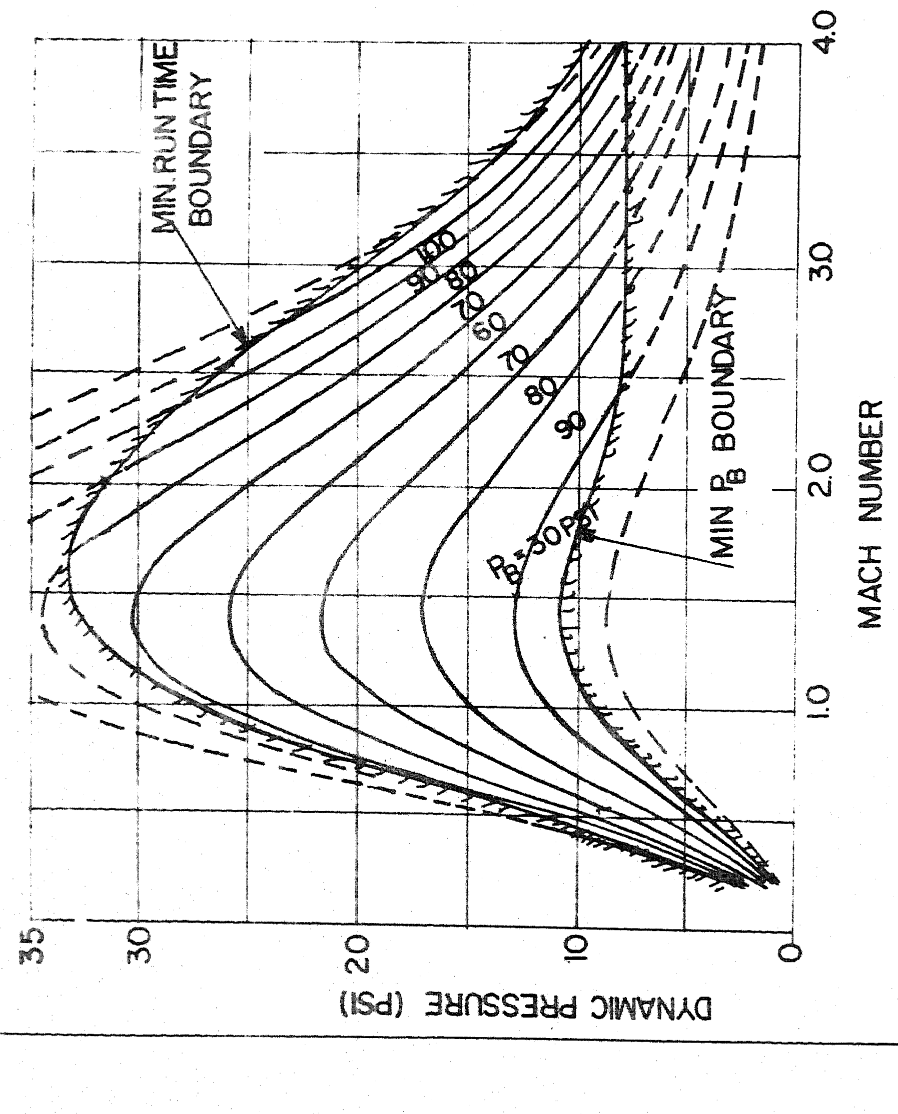


FIG.2.2. DYNAMIC PRESSURE Vs MACH NUMBER

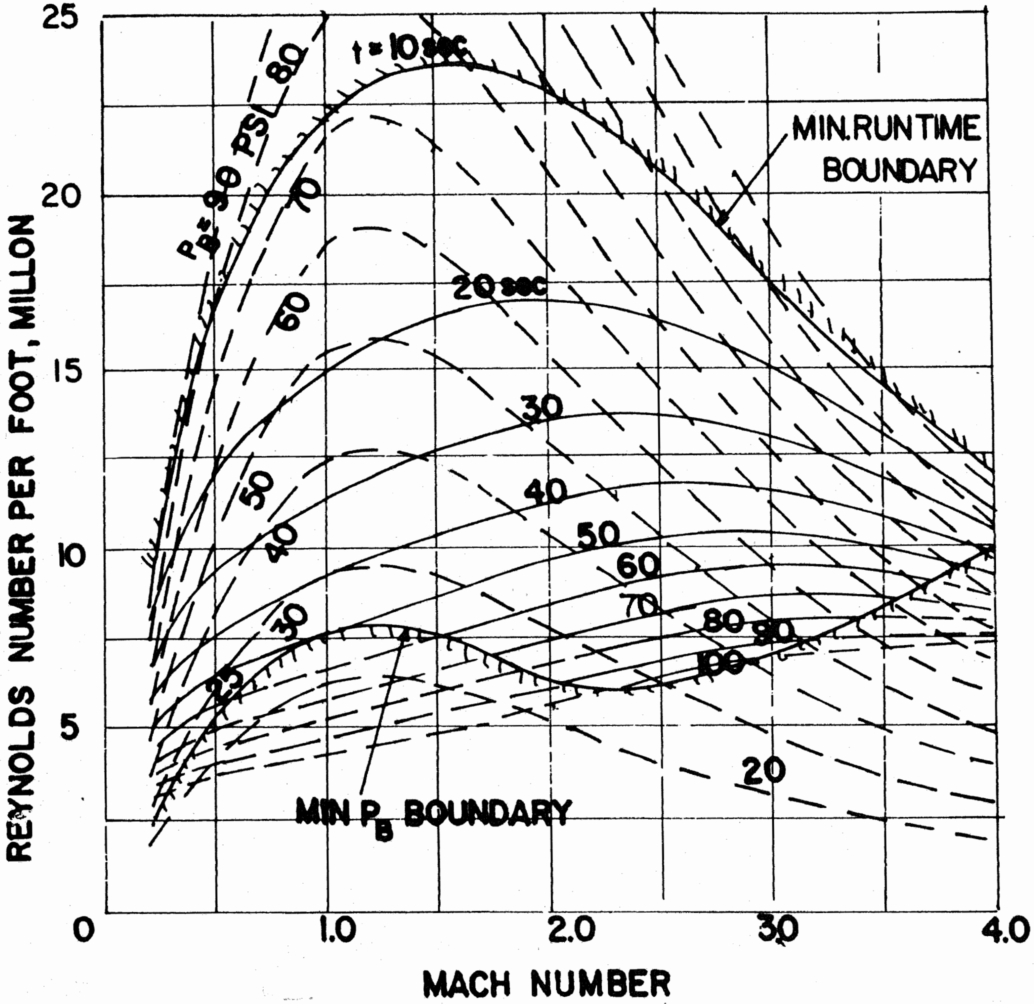


FIG .2.3. REYNOLDS NUMBER Vs MACH NUMBER

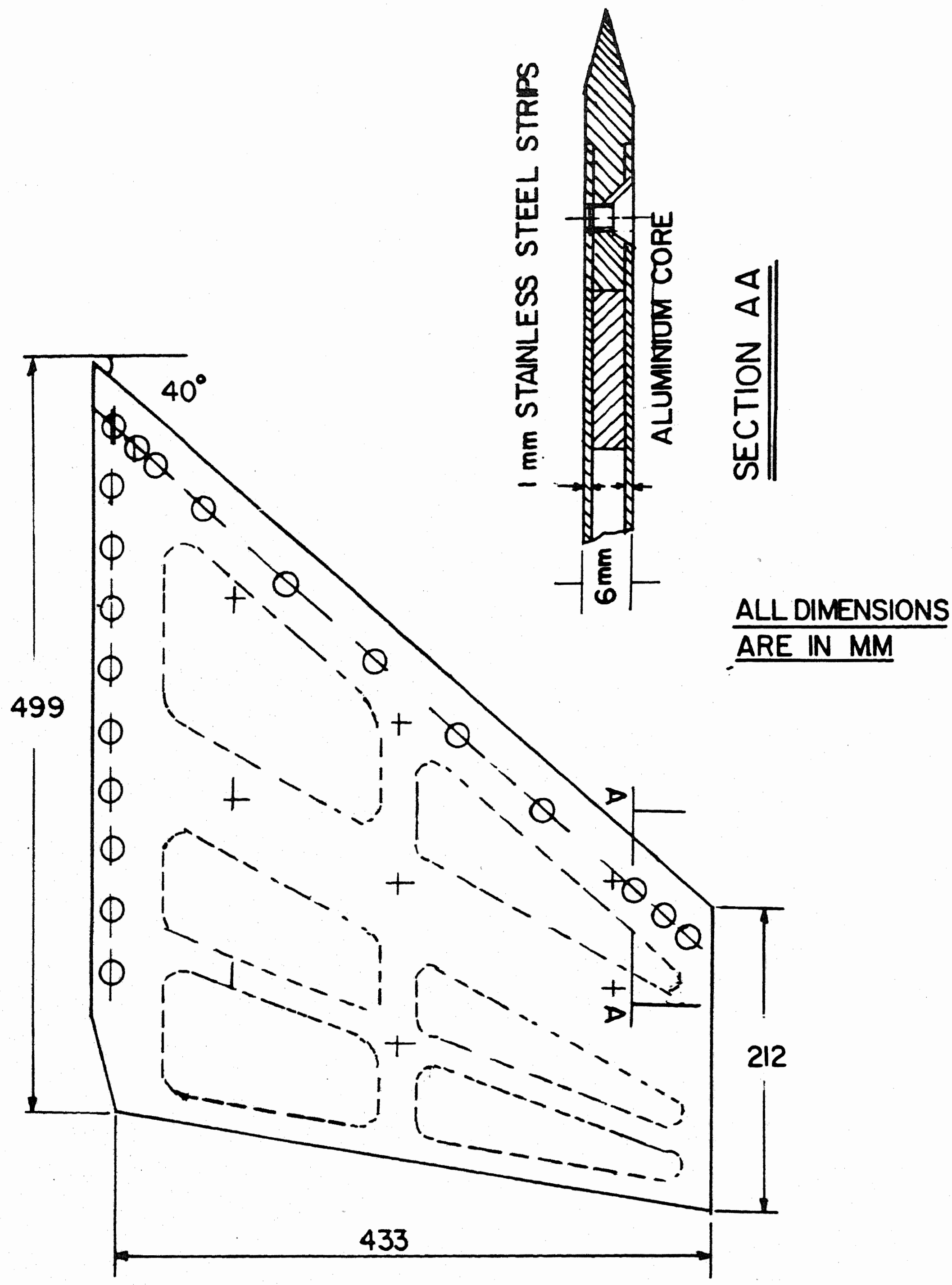


FIG.3.1. TYPICAL ROCKET FIN

MODE NO.	NATURE	FREQUENCY Cps	NODAL LINE
FUNDAMENTAL	BENDING	37.4	
SECOND	TORSION	106.0	———
THIRD	BENDING	170.0	- - - -

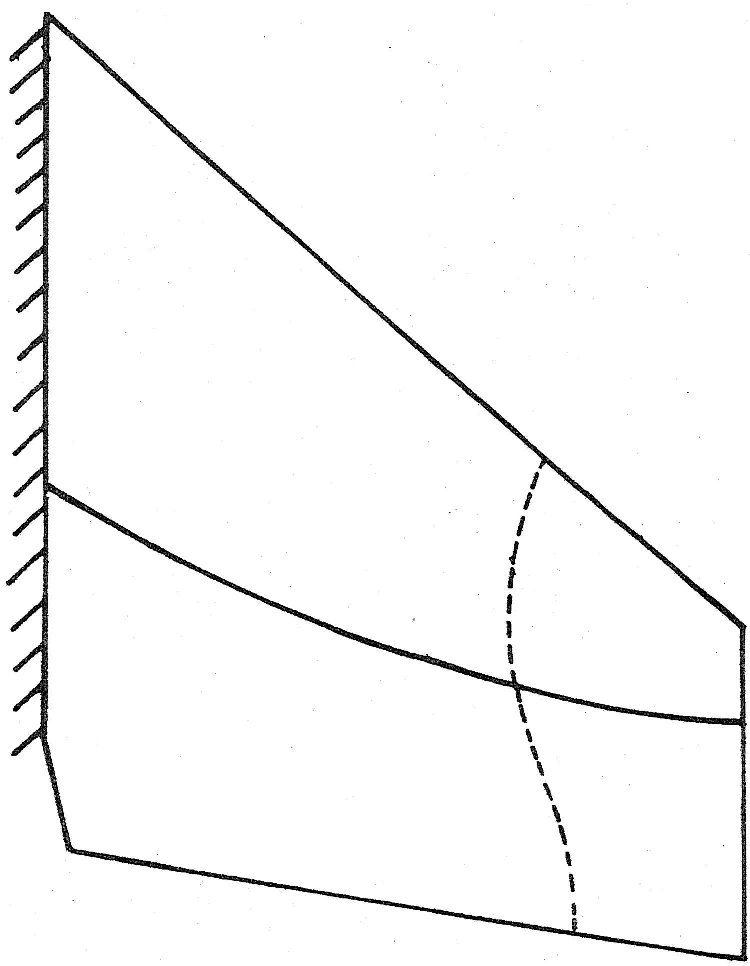


FIG. 3.2. NODAL LINES FOR DIFFERENT MODES

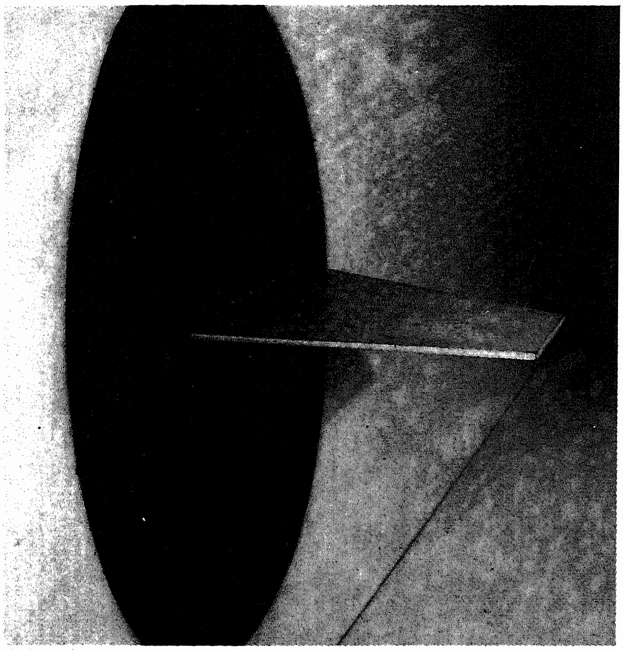


FIG.3.3. RH 300 PROTO TYPE FIN MOUNTED ON THE SIDE WALL OF 1.2 m TRANSONIC WIND TUNNEL

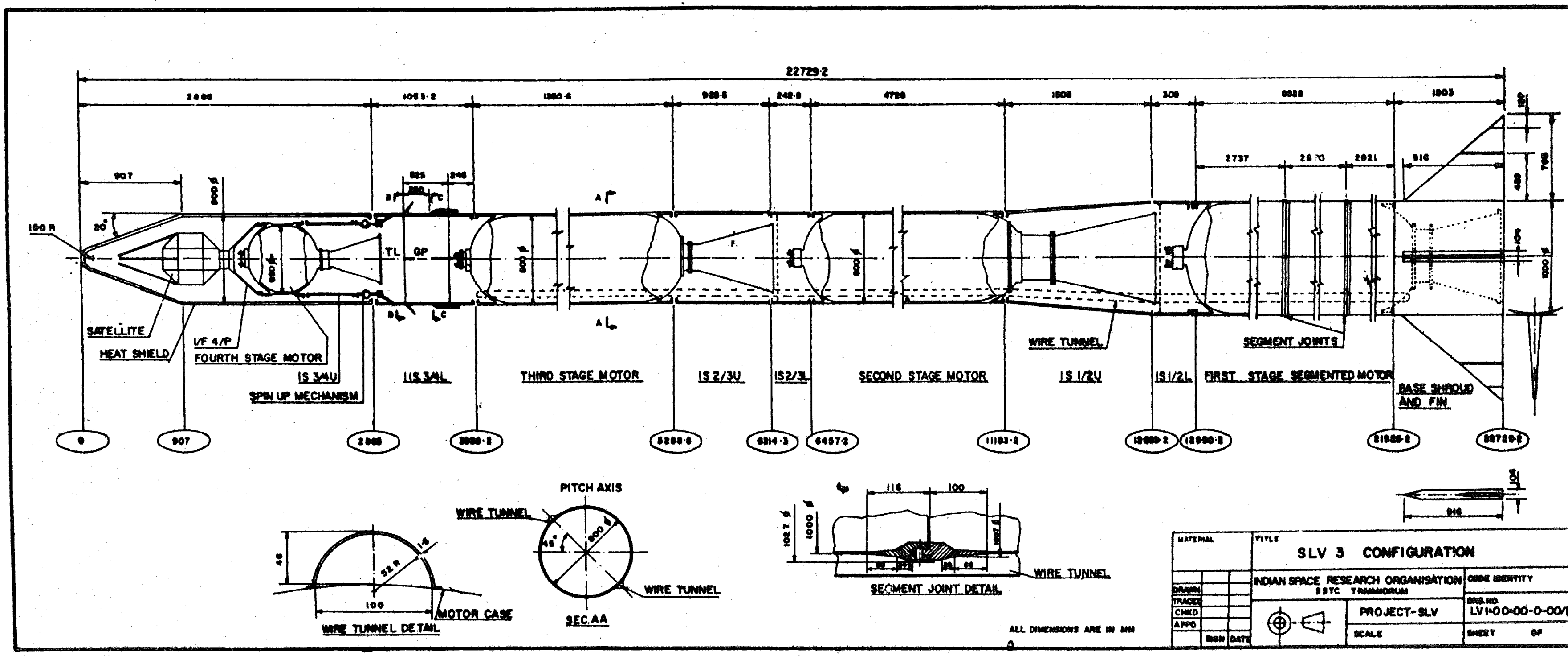
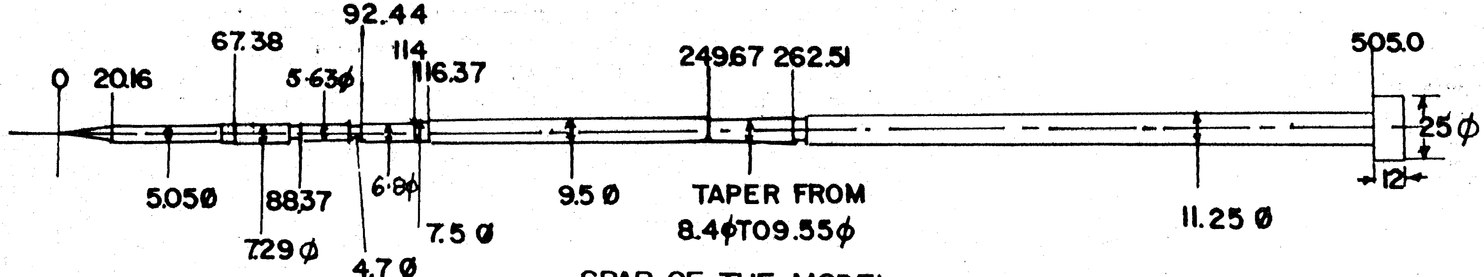
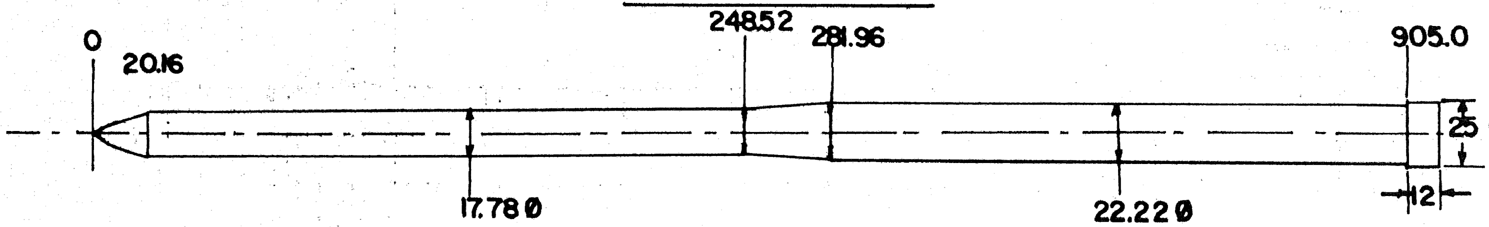


FIG. 4.1. SLV-3 CONFIGURATION DETAILS



SPAR OF THE MODEL



BALSA COVERED MODEL

ALL DIMENSIONS ARE IN MM

FIG.4.2. AERO ELASTIC BODY DIVERGENCE MODEL DETAILS

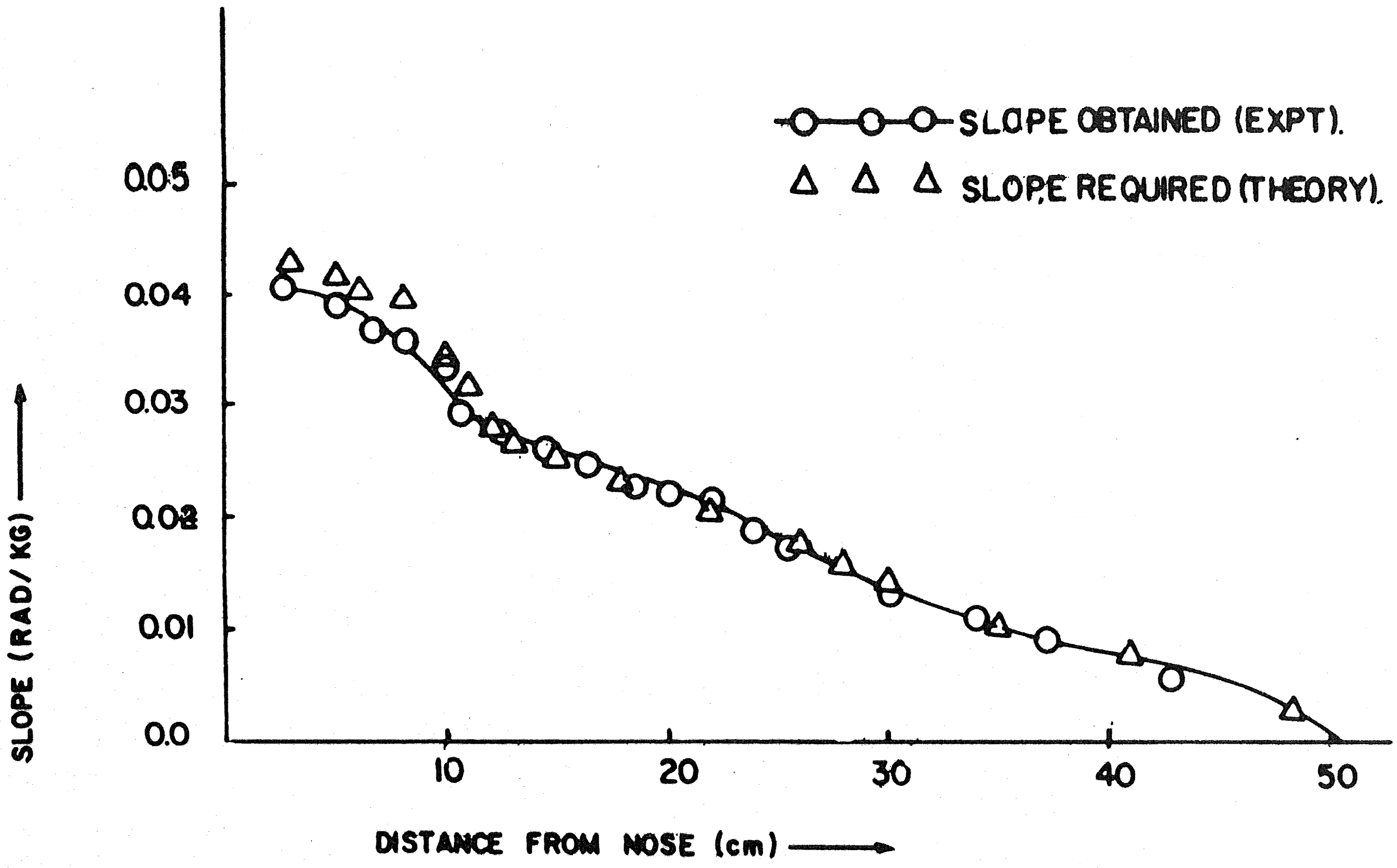


FIG.4.3 COMPARISON OF THEORITICAL SLOPE DISTRIBUTION (UNIT LOAD AT NOSE END) REQUIRED WITH THE SLOPE DISTRIBUTION OBTAINED FROM EXPERIMENT ON THE 1/45 SCALE BODY DIVERGENCE AEROELASTIC MODEL OF SLV-3.

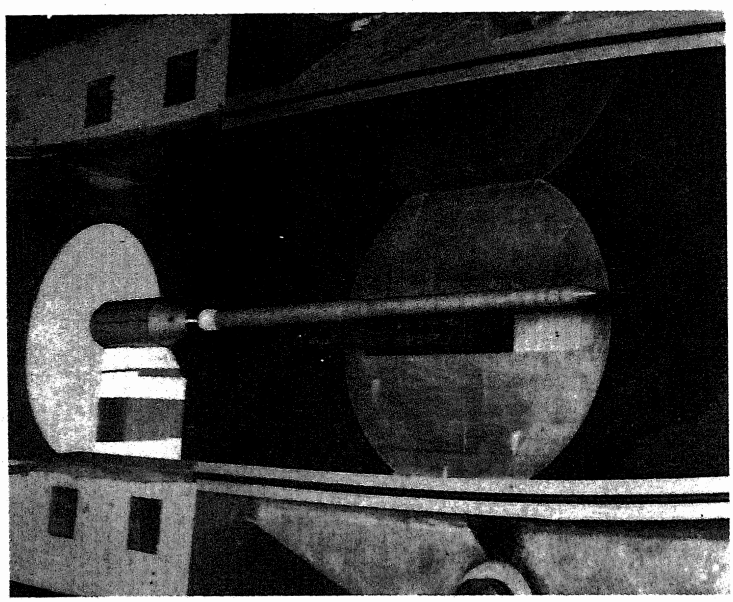


FIG. 4.4. 1/45th SCALE SLV-3 BODY DIVERGENCE MODEL MOUNTED IN 0.3 m WIND TUNNEL

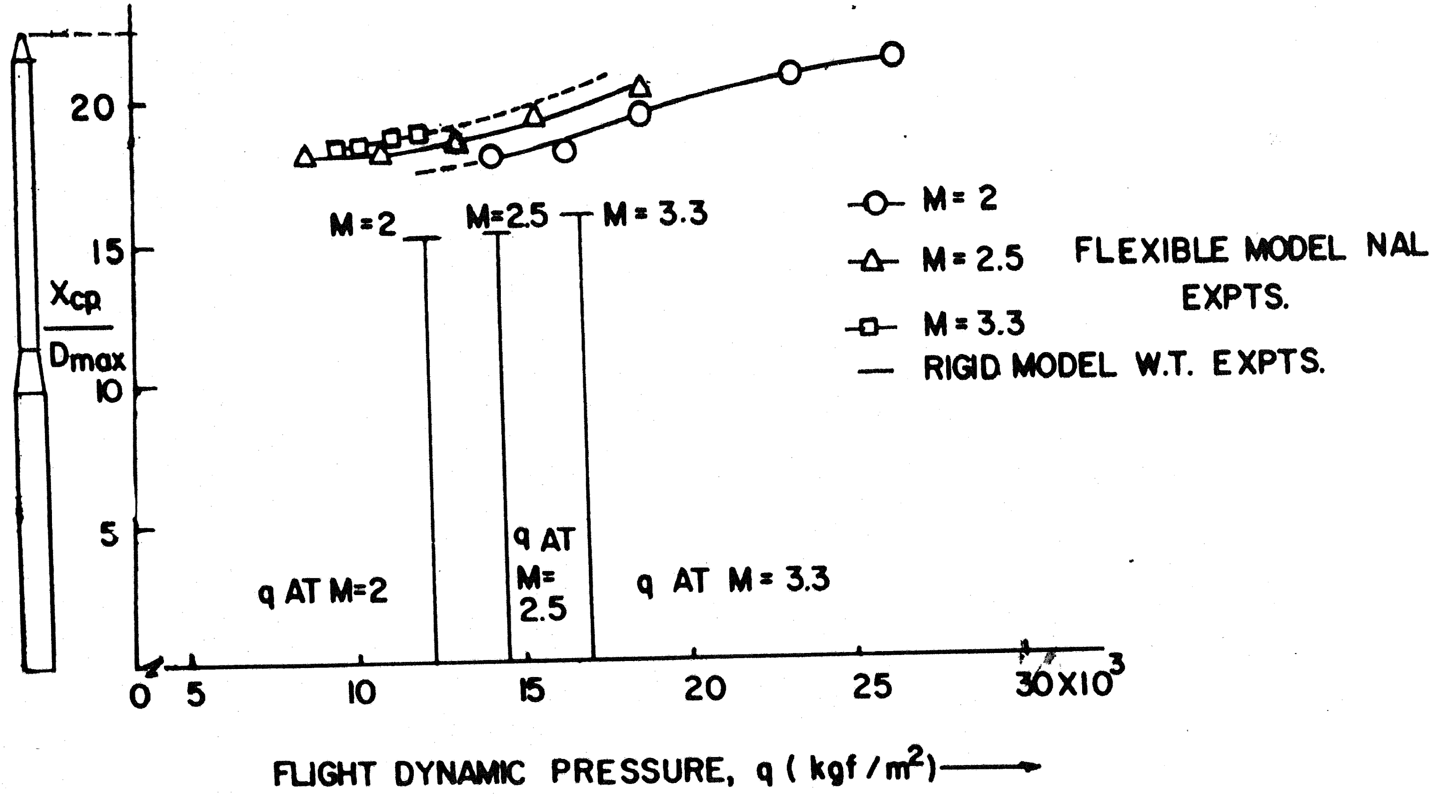


FIG. 4.5 CENTRE OF PRESSURE SHIFT WITH DYNAMIC PRESSURE AT $\alpha = 0°$

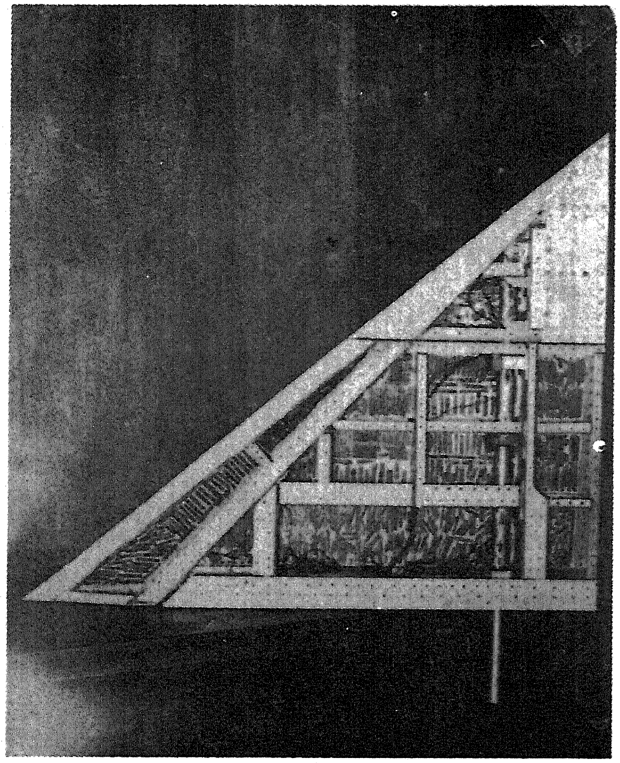


FIG. 5.1. INTERNAL CONSTRUCTIONAL DETAILS OF SLV-3 FIN FLUTTER MODEL

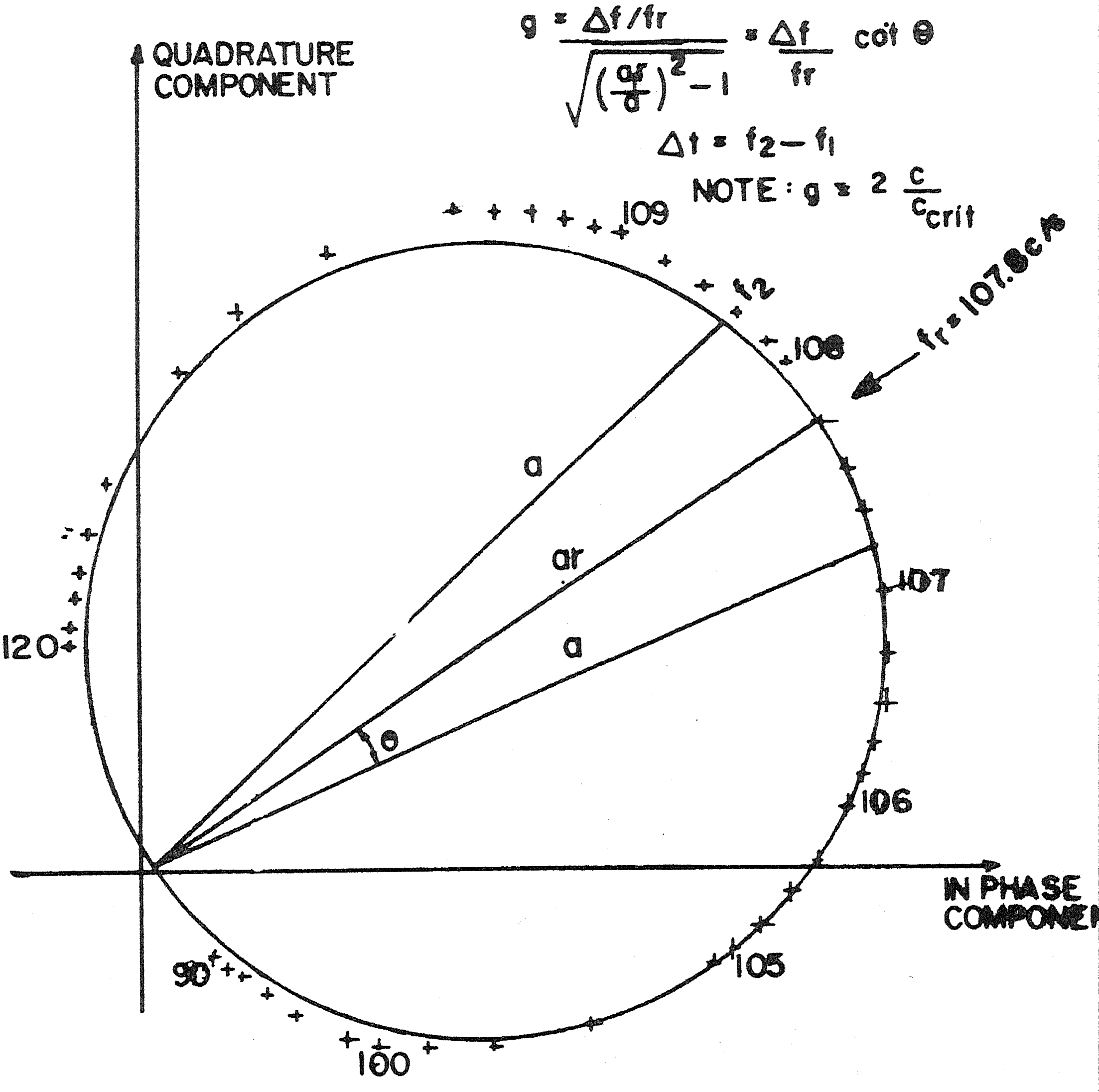


FIG.5.2. TYPICAL KENNEDY-PANCU POLAR RESPONSE PLOT OBTAINED DURING GROUND VIBRATION TESTING

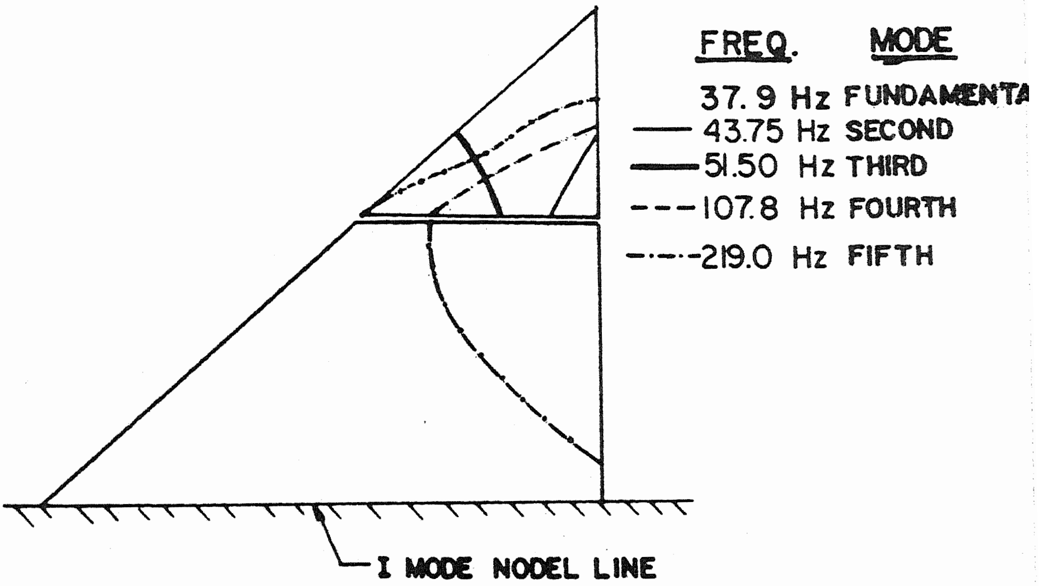


FIG.5.3. NATURAL MODES OF VIBRATION OF FIN FLUTTER MODEL

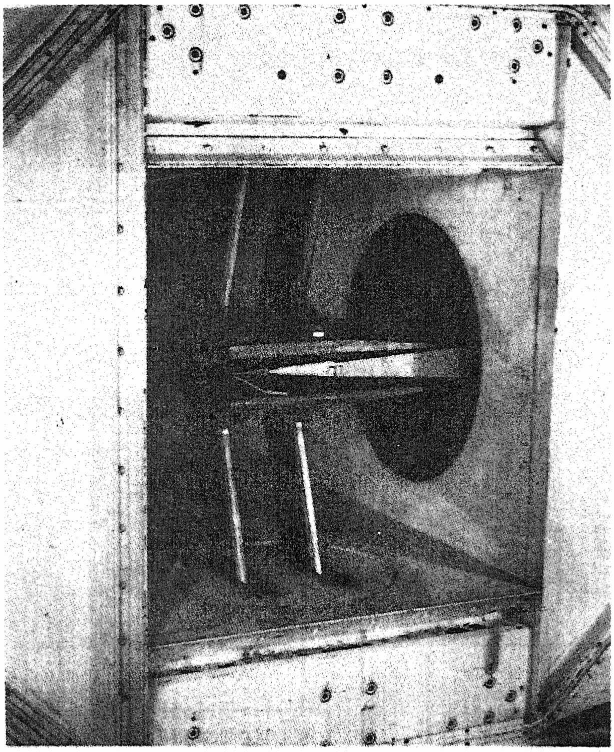


FIG. 5.4. SLV-3 FIN FLUTTER MODEL MOUNTED IN 1.2 M WIND TUNNEL WITH PROTECTION DEVICES

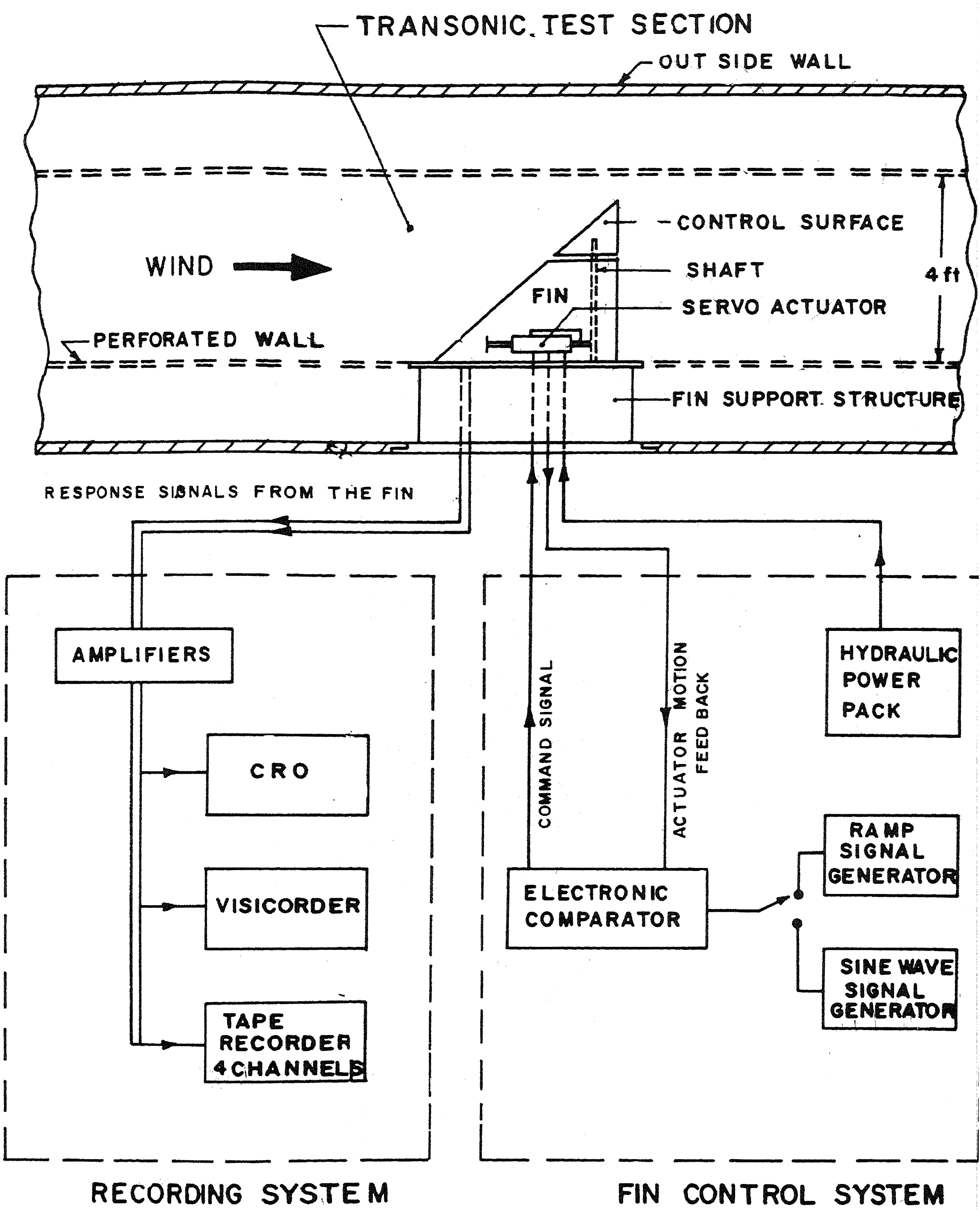


FIG. 6.1

LAYOUT FOR TRANSONIC FLUTTER TESTING ON SLV - 3 FIN

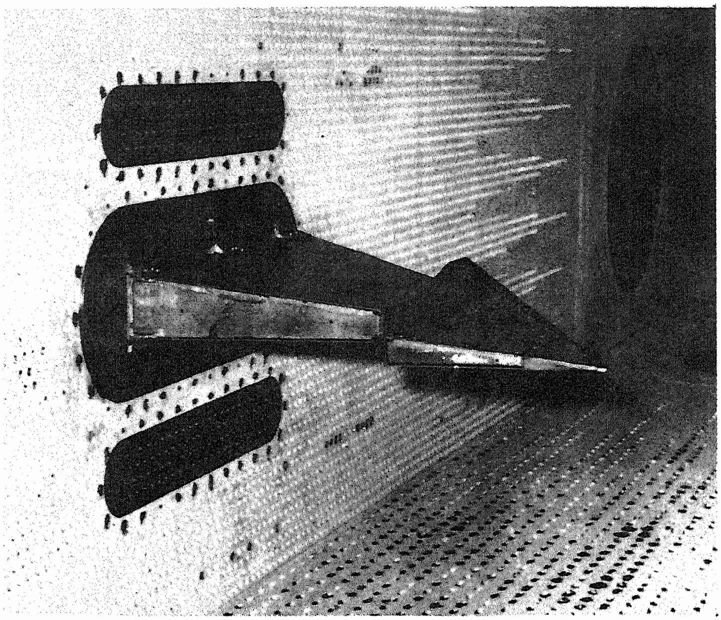
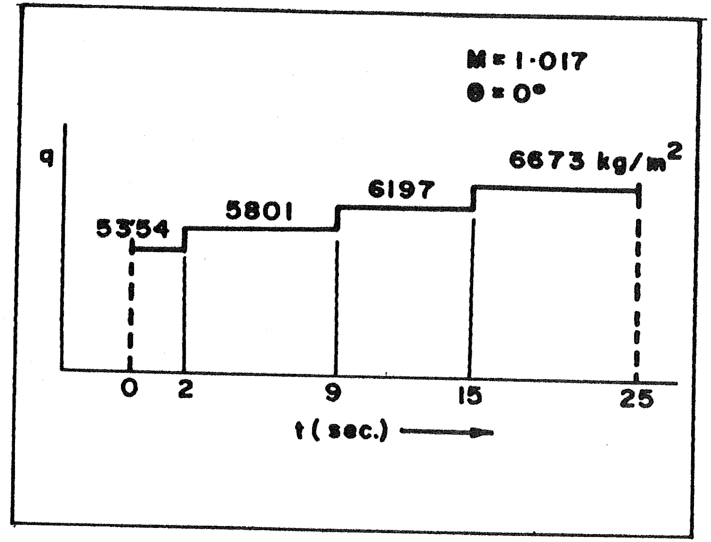


FIG. 6.2. SLV-3 PROTO FIN MOUNTED IN TRANSONIC TEST SECTION OF 1.2 m WIND TUNNEL.

EFFECT OF DYNAMIC PRESSURE ON PSD

FIG: 53

RUN No: 1
CHANNEL: 2
FREQ RANGE: 0–128 C.P.S.
FILTER BAND WIDTH: 31–80 C.P.S.



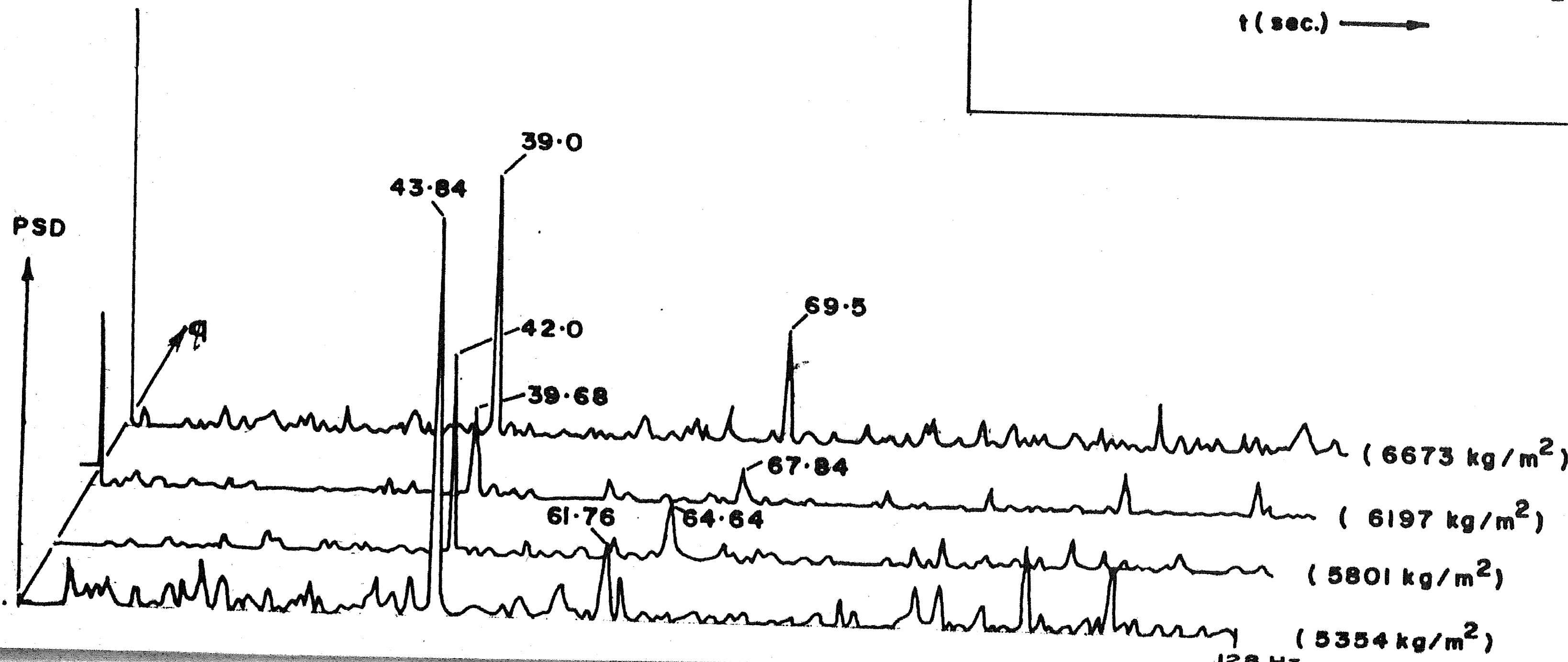
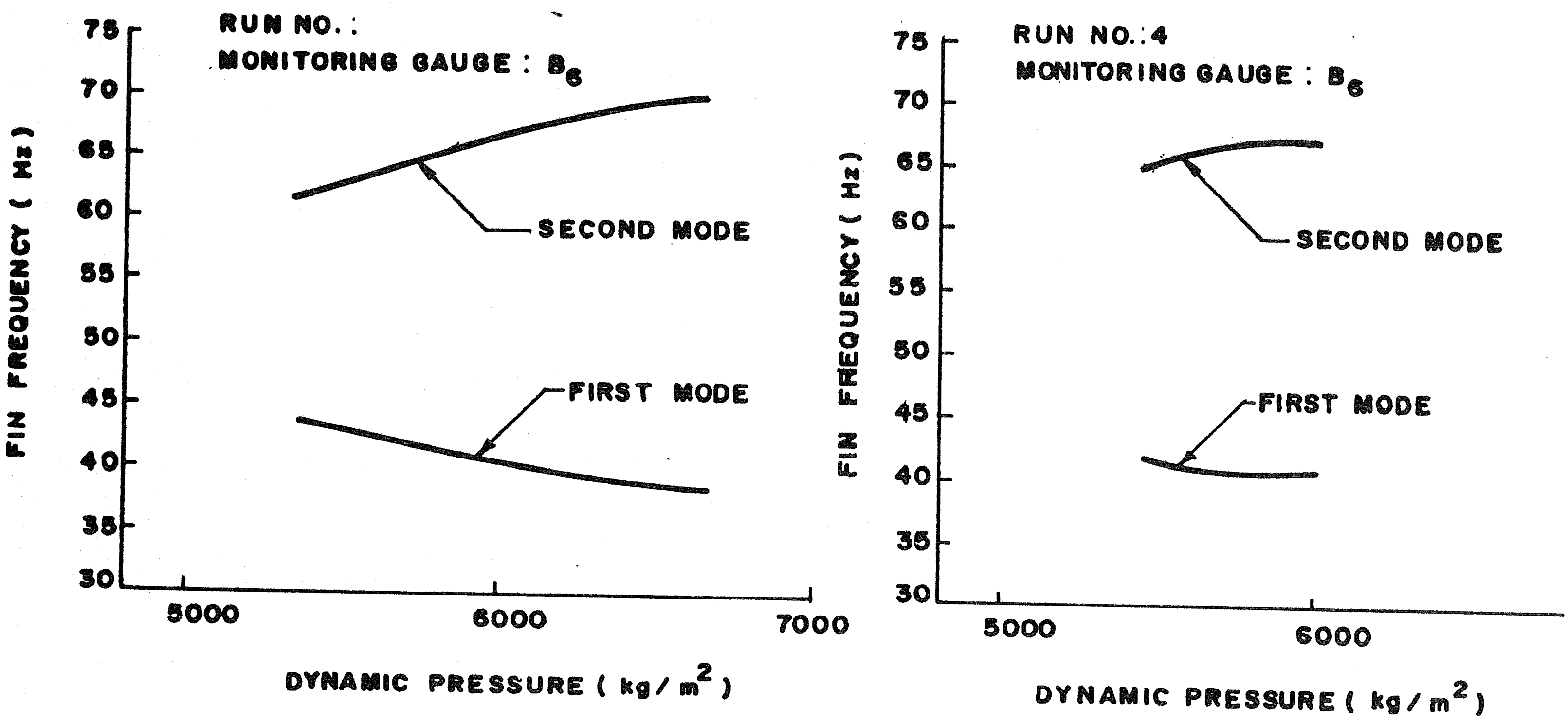


FIG.6.4 . FIN FREQUENCY VARIATION WITH DYNAMIC PRESSURE



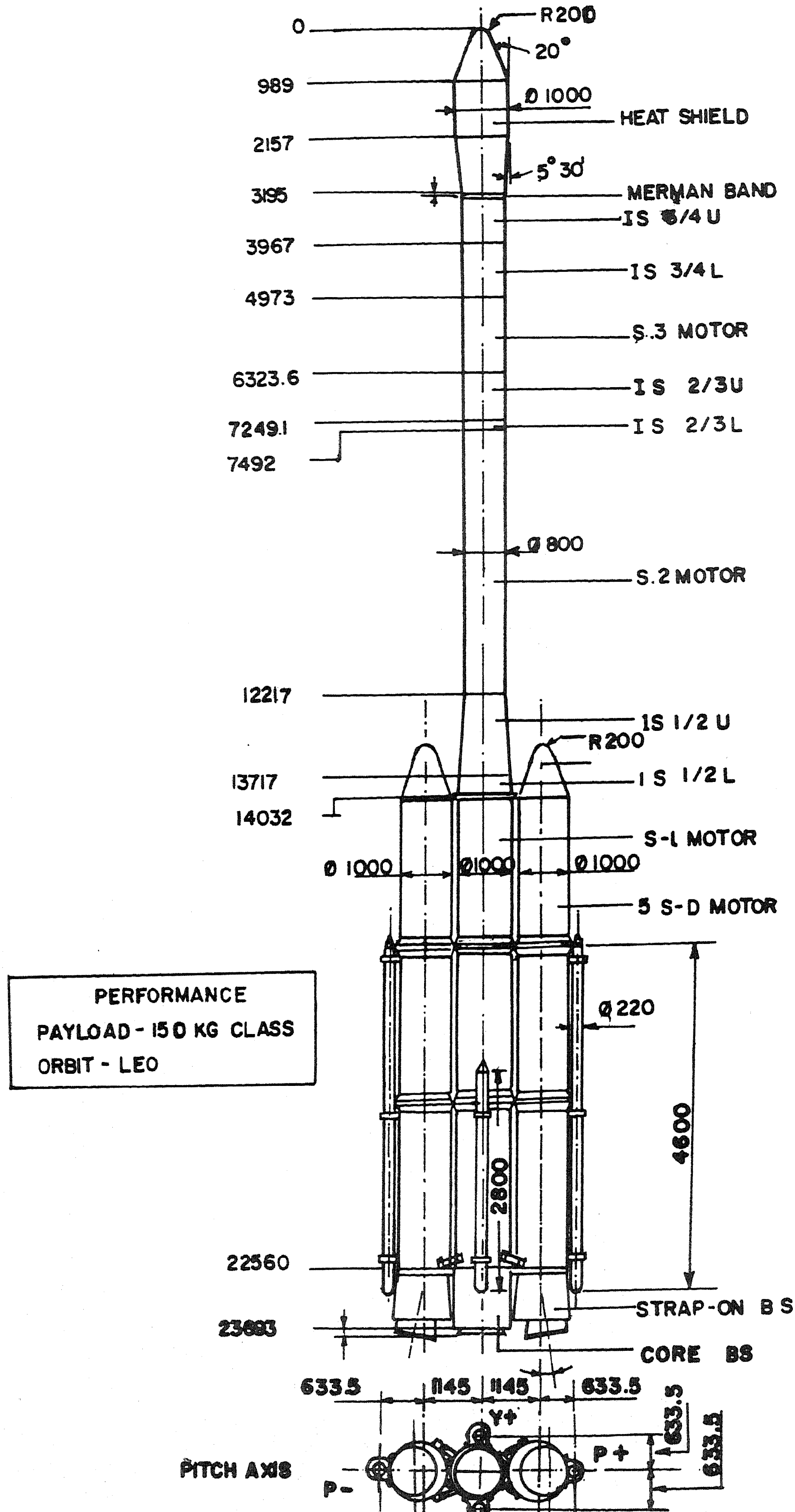
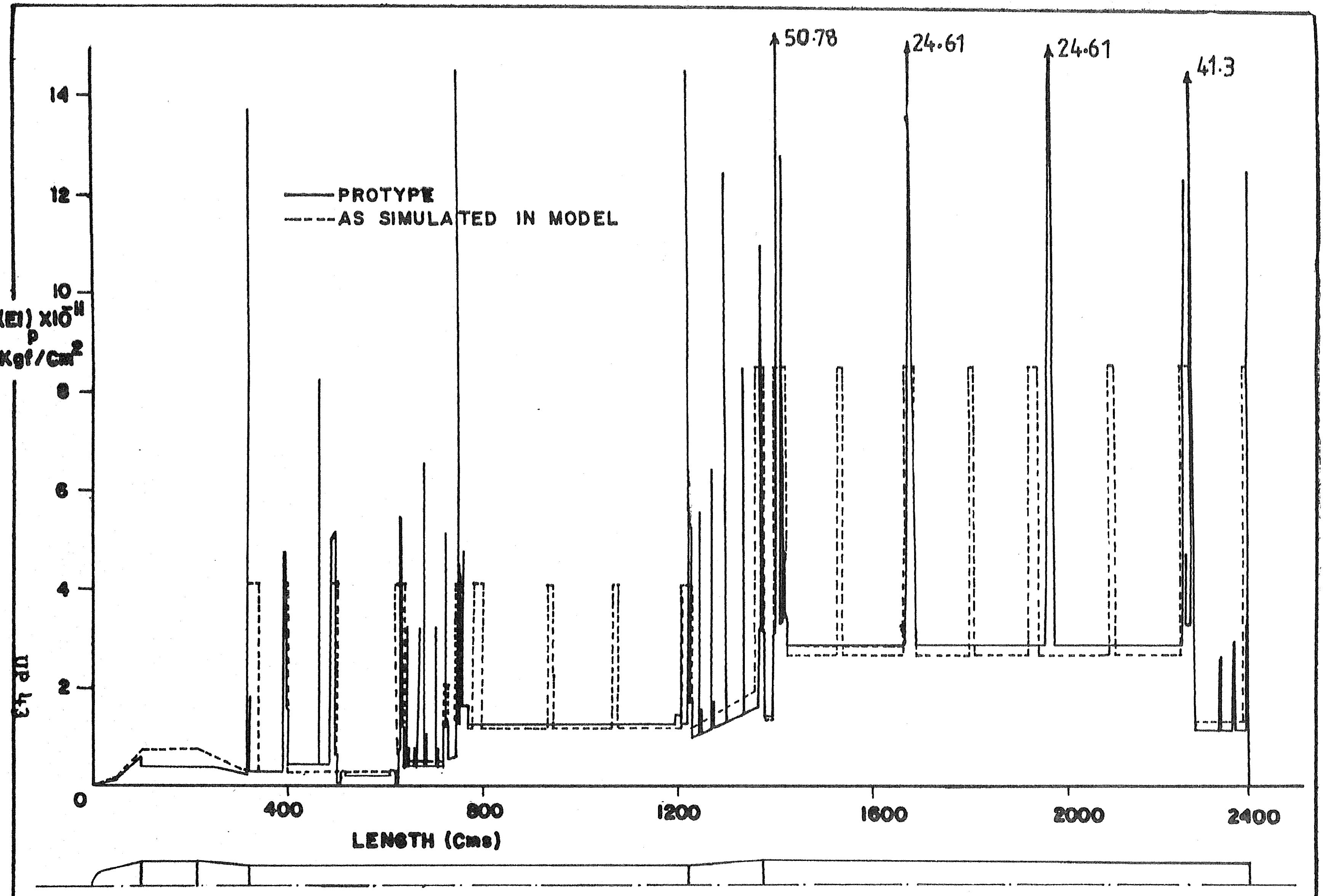


FIG. 7.1. ASLV CONFIGURATION



14
12
10
8
6
4
2
0
(EI) $_p$ X10^{-11}
Kgf/Cm^2
PROTYPE
AS SIMULATED IN MODEL
50·78
24·61
24·61
41.3
400
800
1200
1600
2000
2400
LENGTH (Cms)

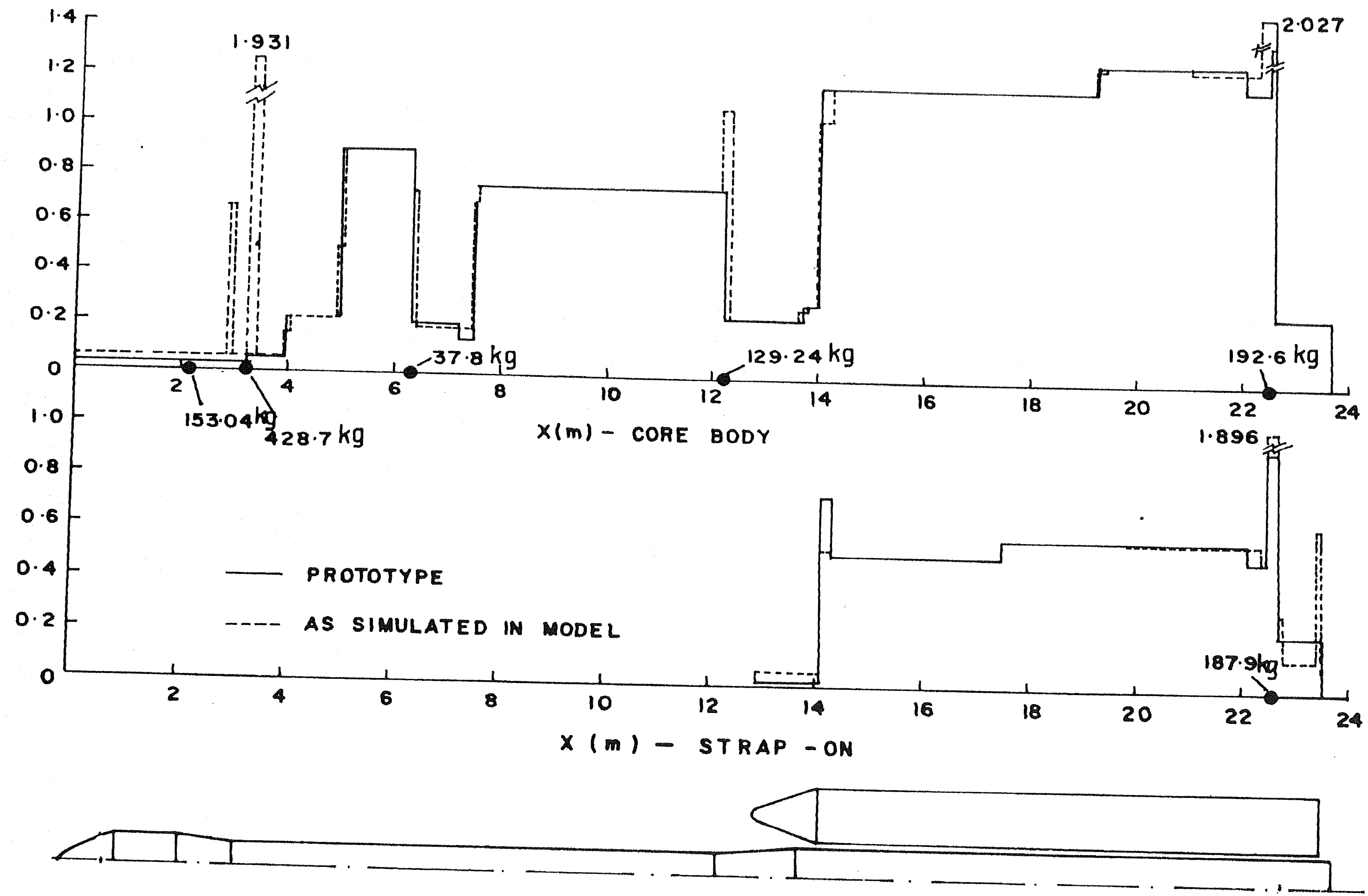


FIG. 7.3ASLV MASS DISTRIBUTION

FIG. 7.3 ASLV MASS DISTRIBUTION

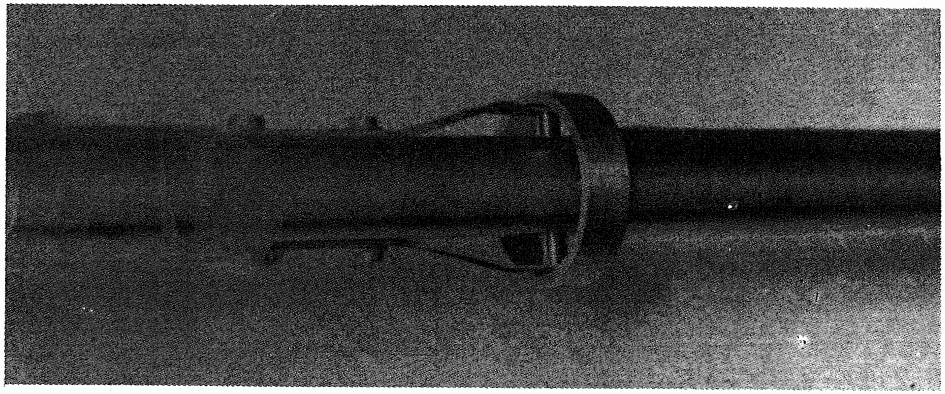


FIG. 7.4. SPRING SUPPORT SYSTEM FOR ASLV BUFFET MODEL

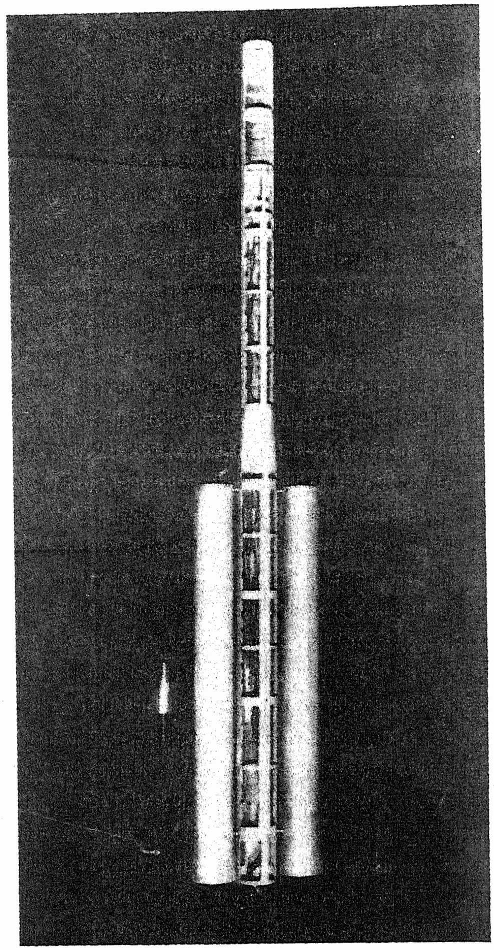


FIG. 7.5. SECTIONAL VIEW OF ASLV BUFFET MODEL

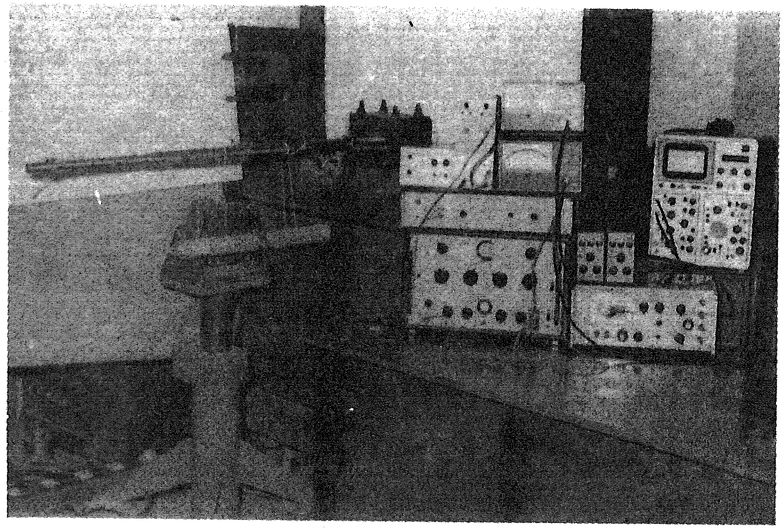


FIG. 7.6. ASLV BUFFET MODEL BOOSTER UNDERGOING GROUND VIBRATION STUDIES

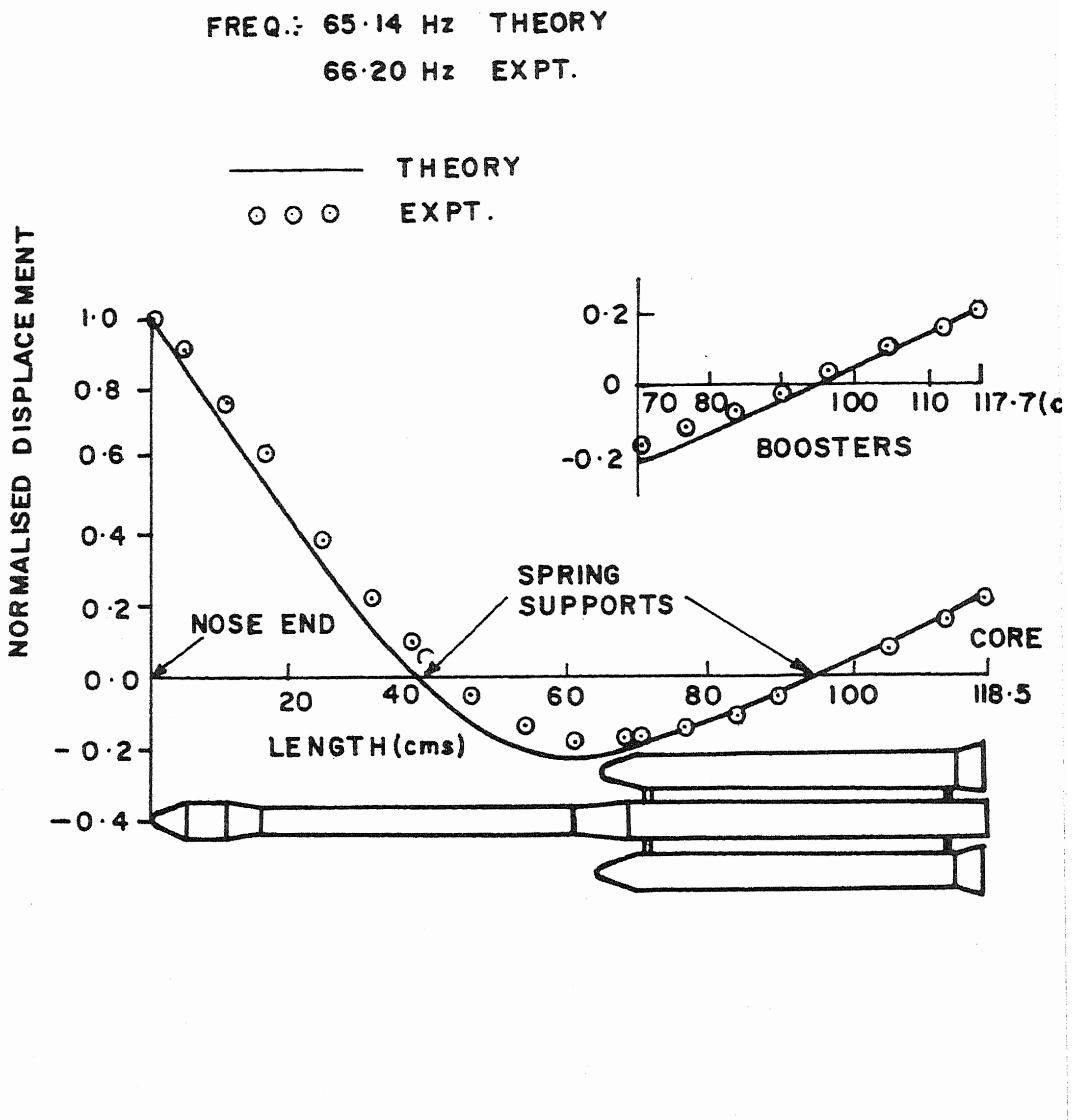


FIG. 7·7. FIRST FREE-FREE BEAM BENDING MODE OF

ASLV BUFFET MODEL

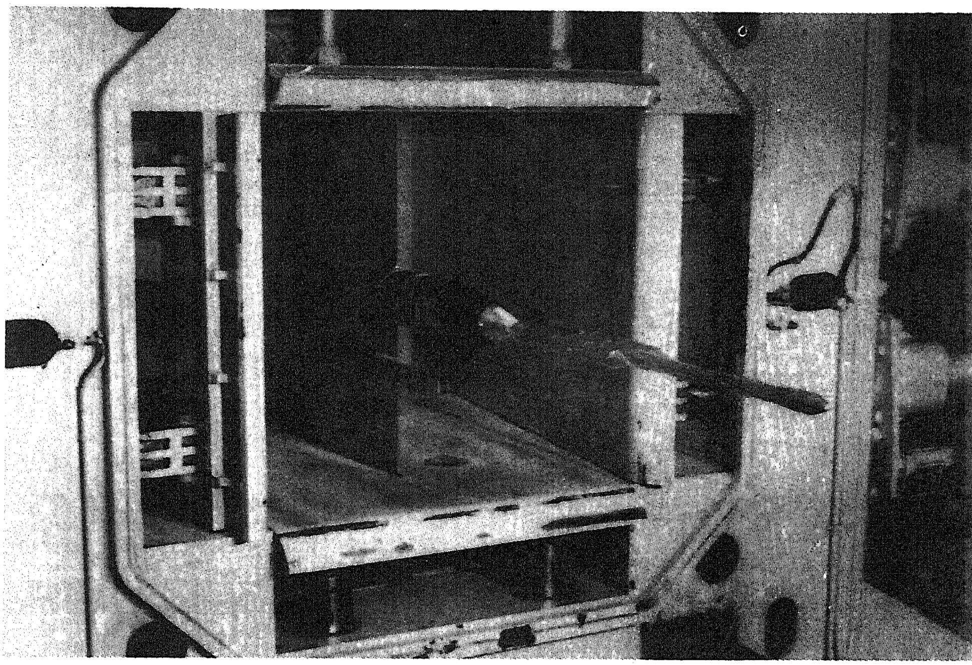


FIG. 7.8. ASLV BUFFET MODEL MOUNTED IN THE TEST SECTION OF 1.2m. TRISONIC WIND TUNNEL

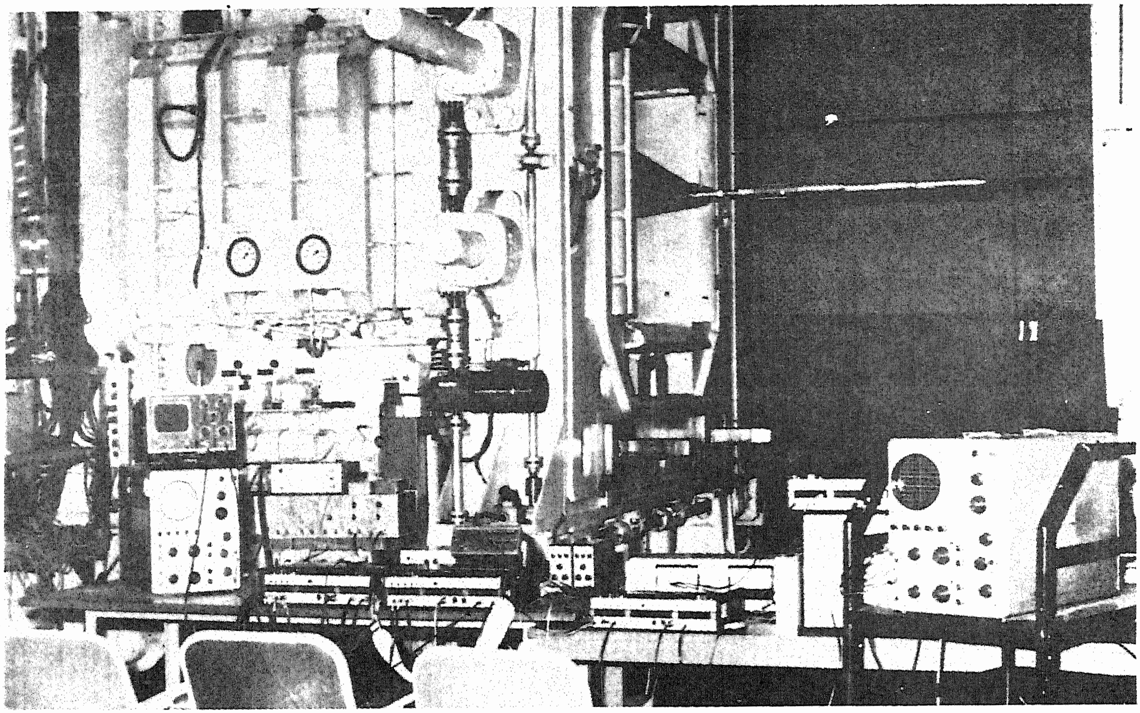
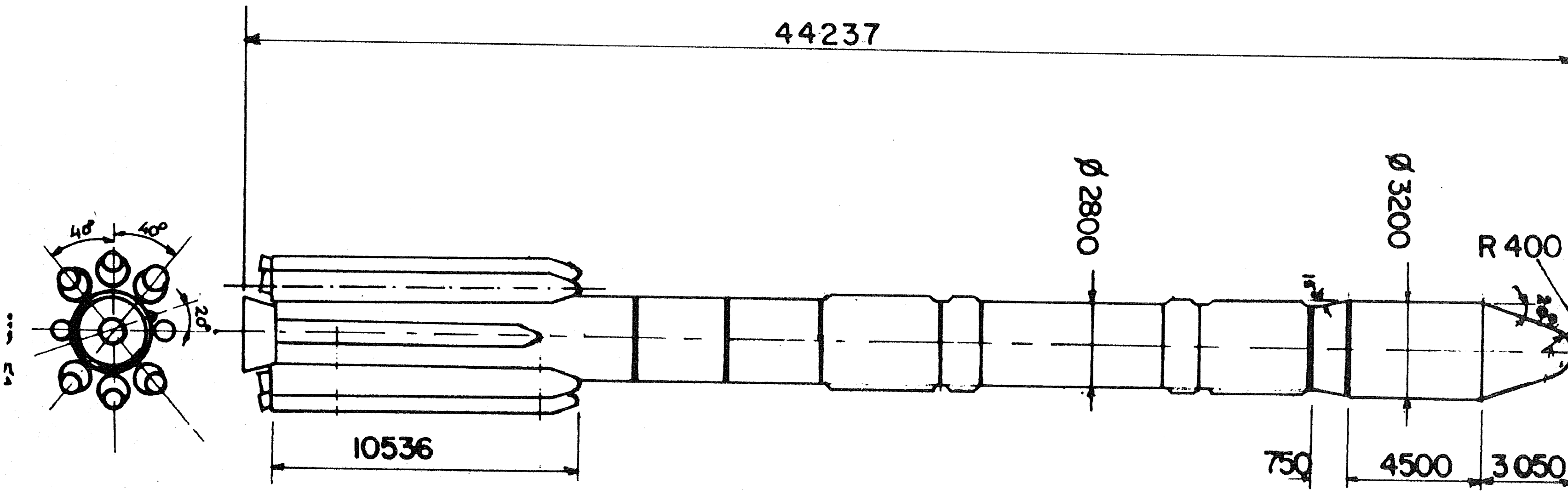


FIG. 7.9. INSTRUMENTATION USED DURING THE WIND TUNNEL TESTING OF ASLV-BUFFET MODEL IN 1.2 m TRISONIC WIND TUNNEL



ALL DIMENSIONS ARE IN MM

FIG. 8.1 PSLV CONFIGURATION DETAILS