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TOTAL MAIN ROTOR ISOLATION SYSTEM ANALYSIS

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LIST OF SYMBOLS

T_c	- thrust coefficient
n	- number of blades
n/rev	- number of blades per revelation
g	- gravity force
V_{cruise}	- cruise airspeed
GW	- gross weight
A	- area
σ	- ratio of rotor blade area to rotor disk area
R	- rotor diameter
c	- blade cord
ΩR	- main rotor blade tip speed
V_H	- maximum continuous power level flight airspeed
α_p	- angular pylon response
α_f	- angular fuselage response
α_{rb}	- angular rigid body response
Hz	- frequency in cycles per second
F_k	- spring force
d	- deflection
F_I	- inertial force
b/a	- amplification ratio
M_x	- tuning weight mass
F_1	- oscillatory reaction force due to rubber spring
F_2	- outer cylinder reaction force due to inertia pressures in liquid

LIST OF SYMBOLS (Concluded)

c.g.	- center of gravity
MMH	- maintenance manhours
FH	- flight hours
m_1	- mass of pylon
m_2	- mass of liquid in tuning port
m_3	- mass of fuselage and liquid in reservoirs
x_1	- motion of pylon m_1
x_2	- motion of mass in tuning port m_2
x_3	- motion of mass of fuselage and liquid in reservoirs m_3
K	- spring rate of spring
P	- dynamic pressure in live reservoir
a	- area of tuning port
b	- area of reservoir
ω	- forcing frequency
fsin(wt)	- forcing function from main rotor
w_2	- weight of m_2 in lbs

1. SUMMARY

The objective of this program was to establish the requirements, preliminary design, and verification procedures for a total main rotor isolation system at n/rev. For the purpose of this effort, total main rotor isolation at n/rev is considered to be such that there is no more than 5 percent of rigid body response at any point on the fuselage (i.e., 95 percent isolation) due to any main rotor shaft load at the blade passage frequency.

The isolation systems discussed in this report extend the previously limited isolation applications to all six degrees of freedom while significantly reducing the weight penalty.

The isolation system concepts described herein achieve the objective and can be universally applied to all rotor systems, and the Liquid Inertia Vibration Eliminator (LIVE) isolation element used has demonstrated 98 percent isolation efficiency in laboratory tests. This element also reduces weight by a significant factor, while providing a number of other important advantages.

The baseline helicopter selected for the purpose of establishing specific isolation system performance, risk, and system integration studies during the analytical study was the Bell Helicopter Textron Model 206LM. This is a 1814 kg (4000 lb) class turbine engine helicopter using a four-bladed soft in-plane, flexbeam rotor system.

Predesign drawings were developed showing the installation of a total main rotor isolation system on the 206LM helicopter, and a weight analysis of the isolation system hardware was performed. In addition, a work statement is included defining a second phase program to design, fabricate, and test the isolation concept.

2. INTRODUCTION

2.1 BACKGROUND AND RATIONALE

Vibratory excitations, inherent to the helicopter, cause many undesirable effects, such as: helicopter crew fatigue, resulting in decreased proficiency; unacceptable crew comfort, resulting in reduced airspeeds and thus lower productivity; and poor component reliability, resulting in increased operating costs.

In the 1970's, the military, in recognition of these adverse effects and desirous of more stable weapons platforms, reduced the acceptance level of the predominant rotor harmonic (blade passage speed or n/rev) at V_{cruise} from 0.15g to 0.05g. Commercial operators, particularly those conducting long flights to offshore oil rigs or on ambulance runs, have also demanded lower vibrations.

Paralleling these developments, new objectives for high-speed performance, high payloads, improved maneuverability, and increased agility have been set. These new goals have led to new rotor designs, soft-in-plane, rigid, articulated with large hinge offsets, and teetering rotors with added hub springs. All of these changes tend toward higher excitation shears and/or moments.

Helicopters using first generation main rotor shaft isolation systems of the 1940's and 1950's (using conventional isolators) exceeded .15g at V_{cruise}; those using second generation designs of the 1960's (using focal pylons) were generally around .15g at V_{cruise}. Therefore, helicopter manufacturers developed a third generation of isolation systems. Examples of these include the Kaman DAVI, Boeing-Vertol IRIS and BHT focal pylon/nodal beam. BHT has also recently applied an impedance matching system on the four-bladed 206L-M. Variations of these systems have been used to isolate, at least partially, from one to five degrees-of-freedom; some emphasizing force isolation; some moment isolation. Weight penalties vary from 2 to 3 percent or more of design gross weight.

It is significant to note that in the UTTAS and AAH competition, involving two competitors each, the .05g n/rev at V_{cruise} criterion was not met by any competitor.

2.2 TOTAL MAIN ROTOR ISOLATION SYSTEM STUDY

The objective of this study is to establish the requirements, preliminary design, and verification procedures for a total main rotor isolation system at n/rev. For the purpose of this effort, total main rotor isolation at n/rev is considered to be such that there is no more than 5 percent of rigid body response at any point on the fuselage (i.e., 95 percent isolation) due to any main rotor shaft load at the blade passage frequency.

The contracted effort performed herein covers a number of defined tasks:

1. The conduct of studies to determine the range of rotorcraft design parameters that result in main rotor vibratory loads of such magnitudes that total main rotor isolation is highly desirable.

2. A preliminary design analysis to define specific main rotor isolation configuration.

3. Select as a baseline, an existing helicopter configuration, with Government approval, for the purpose of establishing specific isolation performance, risk, and system integration.

4. Perform parametric analyses to ensure total isolation of all significant n/rev main rotor shaft loads.

5. Perform parametric analyses to determine those isolator design parameters that have significant impact on configuration performance.

6. Provide predesign drawings to show isolation system and changes necessary on proposed helicopter.

7. Assess the risk of achieving these design parameters.

8. Perform parametric analysis to demonstrate that the proposed isolation system is a minimum weight design and does not exceed one percent of the baseline vehicle design mission gross weight.

9. Perform analysis and provide appropriate rationale to verify overall system integration and ensure no degradation in vehicle stability, handling qualities, and augment tolerances, reliability and maintainability.

In addition to the above tasks, ground and flight test programs have been developed that will verify the effeciency of the proposed isolation system design as installed on the baseline vehicle.

In developing the isolation system concepts presented herein, BHT has used, in part, a number of isolation concepts previously developed under BHT IR&D:

a. The focal pylon

b. Nodalization (mechanical and liquid), and

c. Multidegree-of-freedom isolation.

These concepts, and particularly a unique liquid inertia vibration/eliminator (LIVE), have been used in innovative combinations to achieve the objectives of the program.

A preliminary design analysis was conducted using NASTRAN finite element models to evolve and define specific total main rotor isolation system configurations. The analyses were used to determine the general optimization parameters for best isolation.

The total isolation system concepts used in the study combines 2, 4 or 6 LIVE isolator elements with a focal pylon or a pylon nodalization approach to achieve total main rotor isolation depending on rotor type.

These approaches provide the high potential for total isolation in all degrees of freedom necessary for any type rotor system without penalizing nonmoment-producing rotors with excessive weight and complexity. It combines the advantages of the universal applicability of the focal pylon (or the multidegree-of freedom, MDOF,) isolation concept with the proven near-total isolation performance of the LIVE element. Additionally, in practice these approaches achieve significant advantages by using the LIVE system over systems using dynamically equivalent mechanical nodal beams or its counterparts, IRIS and DAVI.

To achieve the objective of total n/rev isolation of all shaft loads for any arbitrary rotor system, six LIVE isolator elements are used. However, for certain rotor types, rotor shaft flexibilities, etc, it is shown that much simpler, lighter weight systems can be used to achieve acceptable isolation while simultaneously controlling frequency placement of important modes.

3. ROTORCRAFT DESIGN PARAMETERS

The determination of whether total main rotor isolation is desirable, and the degree thereof, depends on three factors: (1) the vibratory hub and control loads; (2) rotor shaft and fuselage dynamic amplification or isolation; and (3) the vibratory criteria applied. This study addressed the mechanical, aerodynamic, physical, and environmental parameters which result in vibratory hub loads and/or dynamic amplification within the structure. The effect of these parameters in combination upon fuselage vibrations were evaluated. The criteria applied during this study were derived from the International Standards Organization ISO/DIS 2361, and RFP Requirements for UTTAS, AAH, LAMPS, and ASH.

The major rotorcraft design parameters that can result in main rotor vibratory loads of such magnitudes that total main rotor isolation is highly desirable are discussed in the following paragraphs.

3.1 MAIN ROTOR HUB LOADS

There are many factors that affect the main rotor hub loads. The strongest factors are: number of blades; dynamic tuning of the rotor/pylon system; advance ratio; rotor/wake interferance; rotor thrust coefficient; rotor hub type; and cyclic feathering.

The Rotorcraft Flight Simulation Program C81[1], has in the past been used by many investigators along with other computer programs to determine the effects of the above parameters, individually and in combination, on the magnitudes of main rotor hub loads. The major results of some of these investigations are summarized here.

3.1.1 Number of Blades

Numerous studies have shown that, if other major parameters are equal (solidity, airfoil shape, tip speed, hub type, etc.), that increasing the number of blades will reduce the magnitude of the hub loads proportionally. Thus, with a large number of blades, approximately 10 to 12, the hub loads would be low enough that a rigid pylon mounting system would reduce the transmitted load to acceptable levels. The advantages of using a rigid mounting system would then have to be weighed against the disadvantages of the extra weight and complexity of the large number of blades.

3.1.2 Dynamic Tuning

Dynamic tuning of the rotor/pylon system is one of the strongest influences on hub loads. Due to a large part of the relative low damping in the natural rotor modes, the magnitude of the hub loads due to a given aerodynamic excitation force can vary more than tenfold: from amplifications as high as five-to-one with poor frequency placement, to reductions of two- or three-to-one for rotors with very good frequency placement. Because of the very many design parameters that must be considered, it may be too much of a compromize on other systems to require of the rotor dynamics to operate in the two-or three-to-one reduction region.

It has also been found that very significant reductions in hub loads can be achieved through proper matching of the impedance of the pylon to the rotor system. By properly controlling the spring rate of the pylon mounting and mast stiffnesses relative to the transmission/mast effective mass and inertia, the rotor can be made to respond as if it were in a free-free state, transmitting only damping load to the hub. This effect has been shown to be very dramatic in the achievement of low hub loads as witnessed by the development of the SAVITAD System on the 206L-M helicopter which requires no additional isolation system or absorbers to achieve a very smooth ride.

3.1.3 Cyclic Feathering

The dynamic loads of a helicopter rotor in forward flight are influenced significantly by the geometric pitch angles between the structural axes of the hub and blade sections and the plane of the rotation.

The analytical study presented in Reference 2 includes elastic coupling between inplane and out-of-plane deflections as a function of geometric pitch between the plane of rotation and the principal axes of inertia of each blade. The difference in pitch between opposed blades gives periodical coupling terms that cause an external aerodynamic force at n/rev creating forced responses at n, n±1, and n±2/rev.

For a stiff-in-plane rotor system, the blade chordwise stiffness may be 20 to 50 times greater than the blade beamwise stiffness. The elastic structure tends to bend in the direction of least stiffness, resulting in dynamic coupling between out-of-plane and inplane motions as a function of the

geometric pitch angles due to collective pitch, built-in twist, forced cyclic feathering motions of the torsionally-rigid structure, and elastic deformation of the blade and control system in the torsional mode.

Typical cruise conditions for a modern helicopter require collective pitch angles of 14 to 16 degrees at the root, depending on the amount of built-in twist. Cyclic feathering motions of 6 to 7 degrees are required to balance the 1/rev aerodynamic flapping moments. The largest part of the angular motion in the blade-torsion degree of freedom, therefore, is the forced feathering motion due to cyclic pitch.

Periodic variations of the inplane/out-of-plane elastic coupling terms are caused when the geometric pitch angle of each blade is increased and decreased at a frequency of one cycle per rotor revolution. When one blade is at high pitch and the opposed blade is at low pitch, an asymmetrical physical condition exists with respect to a reference system oriented either to the mast axis or to the plane of rotation. One-half revolution later, the reference blade is at low pitch and the opposed blade is at high pitch. Thus, periodic dynamic coupling occurs causing blade loads at 1/rev in the rotating system and hub loads at n/rev in the fixed system.

3.1.4 Control Loads

Helicopter rotor control loads is a subject of increasing importance because of the higher oscillatory control loads associated with the expansion of the helicopter flight envelope. Through the years, the subject has received much in-house study by many companies involved in helicopter development.

In the past, a knowledge of control loads, relating to control function and stress, was sought for design purposes. Little emphasis was placed on the role of these loads in the production of fuselage vibrations. The analysis of flight-test maneuver loads and vibration data over a considerable period of time has repeatedly suggested that control loads produce fuselage vibration. The effect was not easy to detect during the normal testing of conventional configurations, because the rotor loads and control loads varied in the same manner, and the former were usually significantly larger. Subsequent tests over a wider regime of flight with large variations in important parameters have more clearly indicated a relation between control loads and fuselage vibration.

When lift and drag forces act on a deflected blade, they produce pitching moments about the feathering axis. With a blade

deflected aft, positive lift produces a nose-down moment. The resultant moment is determined by the relative magnitudes of the forces and blade deflections.

Cyclic pitch changes for a blade with an out-of-plane inertia component about the feathering axis will also cause a load in the control system.

The significance of the control loads as a source of vibration depends principally on the comparative magnitudes of rotor and control forces and the sensitivity of the fuselage to combined excitation. This excitation is beneficial or detrimental to fuselage vibration depending on specific design variables. The control loads can be eliminated from a cause of fuselage vibration if the control boost cylinders are mounted on the transmission and a total main rotor isolation system is used to isolate the fuselage from the transmission.

3.1.5 Main Rotor Hub Type

The two-bladed, teetering rotor inherently generates large 2/rev vibratory hub shears. These hub shears show a variation in magnitude that increases as a function of airspeed and at airspeeds of 150 knots can typically be equal to 25 percent of the gross weight of the helicopters. Two/rev hub moments in the pitch and roll directions can be produced with the use of hub flapping restraint springs, and 2/rev torque will be produced by a Hook's coupling effect due to flapping. These hub moments can also be of significant magnitude if very stiff hub restraint springs or a stiff mast is used.

The same effects are seen with the use of the fully gimbaled multibladed rotors with proportionate lower loads due to the number of blades.

The fully articulated rotor's hub loads vary greatly due to the distance the hinges are from the hub. Very close hinges reduce the n/rev moments to insignificantly low levels. These loads increase with the increase of stiffness and damping that is used at the hinges for control of rotor frequency placement and stability. A modification of the articulated rotor, the flex-beam rotor exibits the same effects with the effective hinge point being analogus to the actual hinge of the articulated rotor. With both these types, a large hinge offset (approximately 10 percent) will produce very large hub n/rev pitch and roll moments that will dominate the vibration of the fuselage.

The rigid rotor (or stiff chordwise and beamwise) that was popular for R&D in the '60's produces very high shears and moments at the hub since there is no relief of blade loads from softness at the hub. This rotor type would probably require a total main rotor isolation system independently of any reasonable number of blades.

3.1.6 Main Rotor Mast

The main rotor mast length and stiffness can have as much influence in the magnitude of hub loads as the percent of hinge offset has for an articulated rotor. Decreases in bending stiffness result in reductions in hub shears and moments due to the hub becoming more nearly free-free for the respective motions.

The longer main rotor mast will also reduce the effects of the rotor downwash on the cabin roof and the stabilizing surfaces of the elevator and fin. If the mast is too short, air compressibility effects as the blade passes over the cabin roof cause higher blade and hub loads.

3.2 T_C AND ADVANCE RATIO

The scope of some of the rotorcraft parameters of BHT's production helicopters and others within the industry are listed in Table 1. For these helicopters, the general trend of T_C and advance ratio on vibratory excitations is shown in Figure 1. This figure shows a very important fact that basically answers the question posed in Task 1 of the contract found in the introduction to this report. That question is: What range of rotorcraft design parameters result in main rotor vibratory loads of such magnitudes that total main rotor isolation is highly desirable? Figure 1 shows that almost independent of rotor type, hub type, or number of blades, that if a rotor is worked to high levels of T_C and advance ratio it will be producing hub loads of such significant magnitude that total main rotor isolation is highly desirable.

TABLE 1. SUMMARY OF MAJOR PARAMETERS AFFECTING ROTOR LOADS IN PRESENT PRODUCTION HELICOPTERS

Symbol	Model	GW kg	A cm^2	σ %	R m	C m	ΩR m/sec	V_H km/hr
⌂	AH-1J	4536	9806	.0650	6.71	0.69	227	222
△	AH-1T	6350	11671	.0729	7.32	0.84	238	224
⬡	OH-58C	1452	6323	.0390	5.38	0.33	199	161
⊡	206B	1452	5632	.0414	5.07	0.33	210	187
◺	206L-1	1837	6935	.0373	5.64	0.33	233	187
⊙	222	3470	8006	.0763	6.06	0.73	221	230
◇	212	5080	11671	.0516	7.32	0.59	248	188
▽	214B	6260	12671	.0700	7.32	0.84	239	240
◊	214ST	7031	13703	.0673	7.92	0.84	238	235
⬭	YUH-61	7031	12168	.0996	7.47	0.58	224	233
◺	A350	1904	6232	.05358	5.34	0.30	210	200
⌂	SA360C	3001	7200	.0754	5.75	0.34	210	235
▽	SA365	3400	7432	.0709	5.84	0.32	213	228
◹	BO105	2300	5258	.0702	4.91	0.27	218	217
◿	A109	2449	6594	.0775	5.50	0.33	221	241
◹	H500	1361	3510	.068	4.01	0.17	203	224
⬭	206LM	1905	6206	.0576	5.33	0.24	220	201
◗	YAH-63	6940	13703	.0869	7.92	1.08	229	209

4. ISOLATION CONCEPTS

Since in the previous section it was shown that total main rotor isolation is highly desirable for any rotor system that is pushed to its limits, it is therefore desirable to create a total isolation system for any rotor system. Although a single isolation system has been analyzed that will isolate 6 degrees of freedom for any rotor system, it would not meet the requirement of Task 8 of the contract. Task 8 states that the isolation system must be a minimum weight system. But, an isolation system that isolates 6 degrees of freedom would not be a minimum weight system for rotor types that produce only oscillatory shears, or does not produce an oscillatory torque moment. Therefore, for the purpose of satisfying Task 8, three different types of isolation systems are presented that are designed for rotors that produce different types of hub loads. First, the fundamental principles of isolation will be discussed; second, a unique new Live Inertia Vibration Eliminator (LIVE) isolator will be discussed; and third, the three total main rotor isolation systems will be presented.

4.1 PRINCIPLES OF ISOLATION

4.1.1 Conventional Isolation Systems

Conventional methods for isolating black boxes such as electronic packages using elastomeric springs or metal springs and friction dampers represent one of the best known fields of vibration isolation. These methods, however, cannot be applied with much success to helicopter rotor isolation. In the helicopter, two free bodies--pylon and fuselage--are in the g-field by the rotor's thrust while, for most configurations, rotor counter-torque, engine torque, and steady rotor inplane forces act across the isolating system.

Conventional isolation requires that the natural frequency of the system be below the frequency to be isolated. For common rotor-generated frequencies, this requirement makes it necessary to use a relatively soft system. The large steady forces and moments and the long-duration transients would result in large static and transient deflections across the pylon-fuselage interface--deflections that could not be accommodated by the control system and other functional components. The small motions allowable for steady and transient loading make it necessary to provide a high degree of vertical restraint. A conventional system, combining a vertical restraint with mounts having high horizontal spring rates (Figure 2), can be used to isolate the fuselage from inplane rotor excitations that tend to produce pitch and roll. Typical

plots of angular pylon response α_p and angular fuselage response α_f are shown in the figure, along with the rigid-body response α_{rb}. The first peak is a pendular mode resulting from the assumption that the thrust force is vertical and invariant. This assumption is not valid for extremely low frequencies. In this mode, the rotor thrust and the g-field act as restoring forces. The second or pylon mode, which involves deflection about the elastic axis, is usually located below normal rotor operating speed.

With this system, the best isolation is achieved with the softest springs or elastomeric mounts that other considerations will permit. Two of these considerations are: (1) the requirement to minimize torsional deflections that cause input-shaft misalignments if the engine is not rigidly attached to the pylon, and (2) the requirement to minimize pylon response to pilot control inputs and to subharmonic oscillations produced by gusts. These considerations set a lower limit on the spring rates, which is higher than desired for isolation.

4.1.2 Focal Isolation Systems

Focal elastomeric mounts are often used to decouple the translational and rotational modes in the mounting of black boxes. The helicopter industry's first generation pylon isolation systems consisted of conventional spring isolators in certain selected degrees of freedom, generally inplane shear or moments, with limited attenuation achieved. The focal isolation[3] system, first introduced in the early 1960's, was the first attempt to create an antiresonant isolation concept.

Focal isolation in the helicopter is achieved by the use of a pair of kinematic linkages (Figure 3) attached by pinned joints across the pylon-fuselage interface and directed toward the desired focal axis. A metal or elastomeric mount provides the necessary restoring spring. For the undamped case that is shown, both the pylon and the fuselage exhibit optimum (theoretically zero) response points. The upper focal arrangement is relatively stiff, and the pylon mode may occur at frequencies above normal rotor speed. These arrangements permit the thrust of the rotor to be rigidly restrained and provide pitch and roll (angular) isolation to inplane shear forces. The available focal depth, which is independent of the mounting breadth, is virtually unlimited.

A simplified analysis has been used to study the dynamic behavior of the helicopter in flight. The equations for the angular pylon response α_p and the angular fuselage response α_f to rotor hub forces and moments were derived. The rigid body response α_{rb} is found by considering the two bodies, pylon and fuselage, locked together with an infinite spring rate.

With the proper combination of system parameters, focal depth, and spring rate, it is possible to minimize the pylon's response to rotor subharmonics and simultaneously to minimize fuselage response to higher integral multiples (n/rev) of the rotor speed without amplification at the fundamental rotor frequency (n=1).

As an example, the BHT Model 206, a 1315 kg (2900 lb) gross weight helicopter, has a silhouette that is conventional for single-lifting rotor helicopters. The pylon, which consists of the main transmission, rotor shaft, and rotor, is entirely above the fuselage structure, shown in Figure 4. The Model 206 uses the BHT semirigid two-bladed rotor, which transmits oscillatory forces, but no significant vibratory moments, into the rotor shaft. The predominant excitation frequencies are 1/rev (6.57 Hz) due to out of track and out of balance and 2/rev (13.14 Hz) due to aerodynamic loading and dynamic blade response.

Figure 5 shows a typical response to a ground vibration test made by suspending the helicopter by its rotor hub with a shock cord to put the rigid body vertical frequency below 1 cps. A roll-response plot of vertical acceleration of the pilot's seat per pound of lateral hub force is compared in Figure 5 with the simple analysis calculated data. This figure shows the typical antiresonance isolation valley at the blade passage frequency. Good pitch isolation, similar to that shown in roll, was also obtained.

4.1.3 Fuselage Nodalization

In 1970, Kidd, et al.[4], reported on studies in fuselage dynamics and the identification of inflight nodal points of the fuselage. The emphasis needs to be placed on the work in flight, since the only nodes of interest are those that occur when all the forces are acting on the fuselage. The usual objective is to design the structure so that one of the nodes is in the cabin area. This was done in the UH-1C and AH-1G helicopters, as illustrated in Figure 6.

There are some problems associated with this approach because the shape of the inflight mode may vary with fuselage loading. Furthermore, areas of an extended cabin will be far from the nodal points and could therefore vibrate as much as they would if the designer had ignored the problem altogether. A way around this would be to suspend the entire payload from inflight nodal points. Ideally, this would provide perfect isolation regardless of the loading condition of the helicopter.

When a simple elastic beam is excited by a vibratory force applied at a point along the beam, nodal points can be observed if the forcing frequency is above a certain value[5]. It is important to note that the nodal points cross the natural frequencies smoothly, and that at definite frequencies the response of the beam becomes zero at the point of excitation (Frahm damping principle). It is possible to operate away from natural frequencies (resonance) in order to reduce the amplitude of response and structural loads in the beam, and yet have well-defined nodal points. This consideration would lead us to design a structure with a low natural frequency.

On the other hand, for most designs the structure must carry its static loads with minimum deflection, a requirement that tends to give the structure a high natural frequency. These two requirements -- that for a high natural frequency (stiff beam), and that for a low natural frequency (low response) -- are both met for the case at hand when the ratio of forcing frequency to the natural frequency of the first mode is between 1.1 and 1.5. The forcing frequency is the blade passage frequency and the rpm can vary more than customary operational practice would permit without shifting the nodal points appreciably.

Any weight attached to the forced nodal points does not oscillate and does not alter the dynamics of the beam at the forcing frequency. The nodes cannot transmit oscillating forces to the supported load, and therefore isolation is not a function of that load.

As one might expect, any damping causes quadrature-phased motion of the beam and eliminates the modes. However, it is still possible to identify regions of low response on the beam, and it takes a large amount of damping to eliminate their usefulness.

The object of nodalization is to make use of these points by suspending loads from them. The main advantage of this method over conventional soft mounting is that a much stiffer structure can be maintained with lower transmissibility. This is particularly important where the controls and driveshafts, which can accommodate only limited relative motions, attach to the moving pylon and the isolated fuselage. The procedure to find the optimum isolation is extremely simple: first locate the inflight nodes with the loads detached; then attach the load to the nodal points.

To understand the principle of nodalization, a schematic is shown in Figure 7. In this system, an oscillatory force is applied to the transmission by the main rotor at the blade passage frequency. As this force causes the transmission to vibrate vertically, two reactions are produced in the attachments to the fuselage. First, as the spring is strained, a spring force is reacted by the fuselage that is equal to the spring rate times the deflection ($F_K = Kd$). Second, at the nodal beam pivot point on the fuselage, an inertial force is created that is out of phase with the spring force and equal to the product of the tuning weight mass, its acceleration, and the amplificaiton ratio of the nodal beam lever arm ($F_I = \frac{b}{a}(Mx)$). By proper selection of the size of the tuning weight, the inertial force can be made equal to, and thus cancel, the spring force, therefore transmitting no oscillatory force to the fuselage, thus creating a nodal point at the fuselage attachment.

The response of the vibrating structure does not change when the isolated structure is attached at the nodal points so long as the material remains linearly elastic. With damping present, there will not be true nodal points (zero response), but even with significant amounts of damping, attaching at the minimum response points lowers vibration levels almost as much as in the zero damping case.

At this point, it was necessary to consider special cases such as maneuvers and crash load transients. Stops will usually be required to transfer the load to hard structure to meet severe strength requirements such as for crash loads on the helicopter's fuselage.

The use of nodalization in practice is extremely effective. The nodal beam installatation from one of BHT's nodalized helicopters, the 206-L1, is shown in Figure 8.

4.1.4 Live Isolation

Although the nodal beam provides excellent isolation performance, it has several inherent drawbacks: nonlinearities due to changes in spring rate as the beams move through large angles (high g's), damping, mechanical complexity, the space required for moving weights and arms, and substantial weight penalty and cost. As the result of these factors, an alternate method of achieving the same isolation performance was developed. Research started using a hydraulic fluid in cylinders with different areas to amplify the motion of a tungsten piston as a tuning weight. This concept progressed to a very compact system using a high density, low viscosity liquid (mercury) as both the 'hydraulic fluid' and the tuning weight.

The action of this Liquid Inertia Vibration Eliminator (LIVE) unit is shown schematically in cross section in Figure 9a. An inner cylinder is bonded to an outer cylinder with a layer of rubber as in a coaxial bushing rubber spring. Cavities, top and bottom, are enclosed creating reservoirs for the 'hydraulic fluid.' The inner cylinder is attached to the transmission, and the outer cylinder is attached to the fuselage. The hole or 'tuning port' through the inner cylinder connects the upper and lower reservoirs.

To understand the action of the LIVE system, it is useful to compare it to the mechanically amplified inertia isolator, Figure 7, since their actions and reactions are Analogous. In the LIVE system, the area ratio of the outer cylinder to the tuning port is Analogous to the length ratio of arms on the mechanical spring, and the inertial effect of high density liquid in the tuning port is Analogous to the inertial effect of the tuning weight on the arm. Therefore, if the spring rate of the elastomeric spring, the weight of the liquid in the tuning port, and the area ratio of the LIVE system are equal to their analogus counterparts on the nodal beam, then the LIVE system will isolate the same frequency with the same efficiency as the nodal beam system. This action can be seen in Figure 9b where an oscillatory force is applied to the transmission attachment lug. This applied oscillatory force creates an oscillatory reaction force in the outer cylinder due to the strain in the rubber spring ($F_1 = Kd$). At the same time, the liquid is pumped through the tuning port creating oscillatory accelerations of the liquid mass.

These accelerations create oscillatory pressures in the upper and lower reservoirs out of phase with the force created by the rubber spring. When the size of the tuning port is correct, the force on the outer cylinder due to the pressure in the reservoir ($F_2 = PA$) cancels the force due to the rubber spring and the outer housing is nodalized at the excitation frequency. Figure 11 shows the static and dynamic motions the isolator goes through as different flight conditions are encountered.

4.1.4.1 Analysis of LIVE System Motions

To further understand the dynamics envolved in the LIVE System an analysis of the equations of motion is summarized here. Two assumptions are made about the sytem to simplify the analysis: (1) zero damping and (2) harmonic motion. For this analysis refer to Figure 10a for a simplified schematic of the LIVE System. Let the pylon mass be attached to the inner cylinder, and the fuselage be attached to the outer cylinder. There are four unknowns to solve for; x_1, x_2, x_3 and P.

Notice that the mass of the liquid in the reservoirs must have the same vertical motion as m_3. Due to the principles of hydraulics there is a constraint equation that causes the motion of any one body to be proportional to the difference in the motion of the other two bodies. This can be seen by fixing m_3 (the fuselage) and forcing a displacement on m_1 (the pylon and observing the motion of m_2 (the tuning weight). The equation of this motion is:

$$x_1 = \frac{bx_3 - ax_2}{(b-a)} \qquad \text{Constraint equation (1)}$$

By observing the dynamic loads applied to the free body diagram of m_1 in Figure 10b, a force balance yields:

$$-m_1\ddot{x}_1 = F\sin(wt) + 2P(b-a) - k(x_3-x_1) \qquad (2)$$

Similarly a force balance of m_2 in Figure 10c yields:

$$-m_2\ddot{x}_2 = 2Pa \qquad (3)$$

and a force balance of m_3 in Figure 10d yields:

$$-m_3\ddot{x}_3 = K(x_3-x_1) - 2Pb \qquad (4)$$

These four equations then give us the necessary information to solve for the four unknowns. This yields:

$$P = -\omega^2 m_2 x_2/2a; \qquad x_1 = \frac{bx_3 - ax_2}{(b-a)}$$

$$x_2 = \frac{F\sin(wt)(a(b-a)m_3\omega^2+Ka^2)}{\omega^2 a^2(m_1+m_2+m_3)K-\omega^4(m_1m_2b^2+m_1m_3a^2+m_2m_3(b-a)^2)}$$

$$x_2 = \frac{F\sin(wt)(b(b-a)\omega^2 m_2-Ka^2)}{\omega^2 a^2(m_1+m_2+m_3)K-\omega^4(m_1m_2b^2+m_1m_3a^2+m_2m_3(b-a)^2)}$$

To solve for the isolation frequency set $x_3 = 0$, then;

$$\frac{b}{a} m_2 \omega^2 - \frac{Ka}{b-a} = 0 \quad \text{or} \quad f_i = \frac{1}{2\pi} \left(\frac{Ka^2}{m_2 b(b-a)} \right)^{1/2}$$

to determine the tuning mass required for a given area ratio and spring rate;

$$m_2 = \frac{Ka^2}{(2\pi f_1)^2 \, b(b-a)}$$

the resonant frequency is;

$$f_n = \frac{1}{2\pi} \left(\frac{Ka^2 (m_1+m_2+m_3)}{m_1 m_2 b^2 + m_2 m_3 (b-a)^2 + m_1 m_3 a^2} \right)^{1/2}$$

BHT's experience shows the LIVE system has these advantages over the mechanical inertia isolators:

1. Reduced complexity
2. Bearingless
3. Motion safety stops inherent to the concept
4. Smaller envelope for installation (no external masses moving through large amplitudes)
5. Linear response at high g's
6. Much lower weight and cost
7. Very low R&M requirements

The initial test hardware consisted of the isolator shown in Figures 9a and 9b in conjunction with lead blocks to simulate pylon weight and fuselage weight. This assembly was used for the fundamental research performed to investigate the isolation potential for different combinations of parameters. Figure 12 shows a schematic of the test installation. The LIVE unit is placed between the fuselage mass and pylon mass with the total assembly suspended from a bungee cord below an electromagnetic shaker. The shaker inputs a vertical force into the pylon mass thus simulating a helicopter in flight. A typical normalized response to the fuselage mass relative to rigid body response is plotted versus frequency in Figure 13.

This figure shows isolation of 98 percent at the blade passage frequency with 90 percent isolation over a 10 percent frequency band. Variations in the area ratios from 12:1 through 27:1 were evaluated by sleeving the tuning port. Although area ratios to 27:1 still achieve very good isolation, they are impractical for the helicopter application because units with area ratios greater than about 20:1 become too small to be structurally feasible. In comparison, it is difficult to find space for length ratios greater than 10:1 for mechanical inertial isolators. The main parameters that were found to control the percent of isolation are the reduction of turbulence in the fluid and the damping in the rubber. By using low damped, broad temperature rubber and careful design of the inlets to the tuning port, the total damping could be reduced to less than 2 percent. For this reason, 2 percent damping is assumed in the LIVE unit for the NASTRAN analyses performed for this study. Figure 14 shows the isolation achieved as a function of force for the research isolator. These effects (the improvement in isolation with the reduction in damping) demonstrate that the LIVE concept is a true inertial isolator and not a viscous damper as initial inspection might indicate. Although the LIVE unit's construction resembles that of some shock absorbers, the shock absorbers rely on high viscous effects (damping) where in the LIVE concept, damping reduces performance.

Many fluids have been tested in the experimental unit and, as expected, any low viscosity fluid will work, with the overall size of a unit required to isolate a given frequency being inversely proportional to the square of the fluid density. Figure 15 shows the effect of fluid density on the LIVE isolator size. Figure 16 compares the size of two dynamically identical isolators, one using mercury, and one using selenium bromide.

4.2 TOTAL ISOLATION SYSTEM CONCEPTS

4.2.1 Two LIVE Units Plus Focus Pylon

The first application of the LIVE isolator shown in Figure 17, has been to the Model 206B helicopter. In this configuration, two LIVE units are installed, one on each side of the transmission and act in-phase to achieve vertical isolation and out-of-phase to isolate roll. This combination produces total isolation of a rotor system that produces only shears. The vertical location of the system at the lateral pylon nodal point gives a high degree of lateral translation isolation. Pitch and fore-and-aft isolation is provided by the focal pylon system in the same manner as for the standard 206B. Response plots from NASTRAN analysis of this system are shown in Figures 18 through 22. Due to the very short drive shaft on the 206B, the vertical travel had to be limited to less than on the 206L. This resulted in a stiffer vertical system, placing the vertical mode close to the blade passage frequency resulting in less than 95 percent isolation. The actual response of the c.g. vertical at 2/rev is 24.13 cm/sec^2 (9.5 in/sec^2) (.025 g's) for a 4448N (1000 lb) vertical hub shear. The 206B/LIVE actually produces 2669N (600 lb) of vertical hub shear at V_H. Since this results in such low vibration level, no attempt was made on the 206B/LIVE to improve the percent isolation.

A comparison between vibration test and NASTRAN is shown in Figure 23. This plot shows the vibration test response at the pilot's heel and compares it to the c.g. response from NASTRAN. This plot shows the expected reduction in isolation at 2/rev due to the flexible fuselage, and shows the high correlation in frequency placement that justifies the use of a rigid fuselage for preliminary design studies.

Since the 206B/LIVE system is dynamically equivalent to the nodal beam on the 206L, the size and complexity advantages can be seen by comparing Figure 17 to the 206L installation in Figure 18. These first prototype units for the 206B, designed before the R&D testing on the unit in Figure 9 was complete, has an area ratio of only 15:1. A production unit now in design will have a significant reduction in size using a 20:1 area ratio.

In addition to the incorporation of the LIVE isolators on the 206B, a number of other changes were incorporated to allow the units to operate properly and to take full advantage of the isolation potential. First, since with the LIVE installation there is now vertical motion of the transmission relative to the fuselage, the rotor controls were decoupled from this vertical motion.

Second, since the focused pylon on the original 206A was tuned to optimize the ride without vertical isolation, it had to be retuned to minimize pitch response with the LIVE isolators. Third, since the vibration in the fuselage due to excitation at the rotor has been nearly eliminated, other sources of excitation, such as main rotor downwash on the elevator, became the dominate sources of the remaining vibrations in the fuselage. These other sources required vibration treatment in order to achieve the desired ride levels.

The results of flight tests on the 206B/LIVE system are shown in Figure 24. This figure compares the spread in vibration levels for all GW/c.g. combinations at all seat locations. The vibration levels in all seats are significantly reduced from those of the production 206B, and are comparable to the levels for the 206L, BHT's smoothest riding nodal beam installation.

In addition to the ride improvement, maximum speed is no longer limited by vibration, and the helicopter can be flown at maximum continuous power with no discomfort, approximately 24.14 km/hr (15 mph) faster than a pilot cruises a standard 206B due to vibration levels. This allows an increase in the transmission power limit to raise V_H whereas it was previously impractical with airspeed vibration limited. The weight of the production LIVE unit is 6.49 kg (14.3 lb) using steel construction.

4.2.2 Multi-Degree-of-Freedom Isolation System

The multi-degree-of-freedom (MDOF) isolation system concept extends the principle of nodalization to isolate main rotor shaft loads in five degrees of freedom. These added directions employ the physical and universal response characteristics of the free-free pylon to hub shear and moment excitation as a function of frequency. The translation and rotation of the pylon to a hub shear combine at each frequency to produce a spatial nodal point. For a rigid pylon, this point traverses in accordance with the (solid) curve shown in Figure 25. For an applied hub moment, the rotation occurs about the pylon c.g. independent of frequency (dashed line).

Further, as compared to the assumed rigid body pylon, when the actual rotor shaft flexibility is introduced into the analysis, the nodal points for shear and moment move closer together. Additionally, flexibilities can be introduced to cause these two nodal points to more closely coincide.

In Figure 26, a nodal beam configured to isolate vertical shaft loads is vertically located at the predetermined waterline of the inplane spatial node point of the pylon. This vertical location of the nodal beam is selected such that complete isolation of fuselage rotational motion to inplane forces (or moments) is achieved with the same nodal beam. Additionally, since the beam is located at the plane of the pylon nodal point, no inplane motion or loads are induced, thus effecting complete translational isolation of the fuselage to inplane forces (or moments).

By configuring the vertical isolation system to have four nodal beam elements: two isolators on each side, one located forward and one aft of the center of the pylon, for hub forces and pitch and roll moments, complete isolation is accomplished.

Four configurations have been studied: UH-1H, n = 2; Model 222, n = 2 and n = 4; OH-58C, n = 4. NASTRAN analyses of these configurations show the MDOF approach to be universally applicable for total isolation of main rotor shaft loads in 5 degrees of freedom. Oscillatory yaw shaft loads would not be isolated. The results of this study for these four ships are shown in Table 2.

During these studies, several significant, positive, and useful characteristics of the MDOF system were demonstrated:

a. Total isolation of hub shear and moments simultaneously, based upon the nodal point curves of Figure 25, would not theoretically be possible. Initial analysis shows, however, that using a compromise waterline for placement of the isolation system, determined by the superposition of shear and moment at the phase and magnitude predetermined from a detailed rotor loads analysis, and the use of a flexible mast over 95 percent isolation is achieved in all axes to both n/rev shear and n/rev moment excitations. Figures 27 through 31 show these responses. Included in this plot are:

   1. Longitudinal response to longitudinal shear and pitching moment

TABLE 2. PERCENT ISOLATION RELATIVE TO RIGID BODY

Response/ Aircraft	Vertical to Vertical Force	Pitch to F/A Force	F/A to F/A Force	Pitch to Pitch Moment	Roll to Lateral Force	Lateral to Lateral Force	Roll to Roll Moment
UH-1H 2 Blades	97.5	92.5	NA	*	99.0	98.0	*
222 2 Blades	95.0	99.1	99.2	*	99.8	99.0	*
222 4 Blades	95.0	98.0	97.0	79.0	96.0	94.0	78.0
OH-58C 4 Blades	93.8	97.4	92.2	92.7	96.0	91.5	93.3

* No calculated data since two bladed teetering rotors do not produce hub moments

NA - Data not available

Note: For this study single loads (shears or moments) were applied in the NASTRAN model to determine the best waterline location for each load. The isolators were then placed at a compromised waterline to assure good isolation. This procedure was used since an accurate determination of the magnitude of the forces and moments and their relative phase was not possible. If an accurate determination of force and moment magnitude and phase can be made, then the procedure would be to place the combined loads at the hub to determine the superimposed mode shape. This procedure results in very good isolation with the inflight node at the waterline of the isolators.

2. Pitch response to longitudinal shear and pitching moment

3. Lateral response to lateral shear and roll moment

4. Roll response to lateral shear and roll moment

5. Vertical response to vertical shear

b. Control over the frequency placement of both the pylon rocking frequency and the mast bending mode can be effected by varying the spacing between isolators as shown in Figure 32. The most significant factor to note is that these changes do not affect the isolation notch placement at n/rev.

c. Accurate waterline location of the pylon nodal point at n/rev is necessary for total isolation. To demonstrate this, changes in pitch response as the waterline of the isolators is varied ±5.08 cm (±2 inches) are shown in Figure 33. Note that even with this large change, over 90 percent isolation is achieved at n/rev. Similar results are obtained in each the pitch/longitudinal and roll/lateral directions.

A configuration of the four LIVE systems plus pylon nodalization isolation system concept is illustrated in Figure 34 as it might be installed on a Model 206L-1.

An additional study was performed to determine what rotor types could use the four LIVE systems plus pylon nodalization. This study is summarized in Table 3. In this study, the top of the transmission was at waterline 94. Therefore, any nodal point in Table 3 above waterline 94 would not allow the use of this system.

4.2.3 Six-Degree-of-Freedom Isolation System

A number of rotor types produce large hub moments and are often used in conjunction with short, very stiff masts to reduce fatigue loads. For these rotor systems, neither the two LIVEs plus focus pylon nor the four LIVEs plus pylon nodalization will achieve total isolation. For these rotors, a third isolation system is needed.

TABLE III. WATERLINE OF TRANSMISSION FOCAL POINT AS A FUNCTION OF ROTOR TYPE AND HUB LOAD

Case	Rotor Description	N/Rev Freq.	Waterline - Inch					
			F/A Shear	Pitch Moment	Lateral Shear	Roll Moment	F/A Shear & Pitch Moment	Lateral Shear & Roll Moment
1	Two bladed teetering M_{HUB} = 128 kg I_{HUB} = 0.0 N-cm^2	13.2 Hz	88.25	103.5	90.0	105.0	--	--
2	Two bladed with a hub spring M_{HUB} = 128 kg K_{HUB} = 1.03 x 10^6 cm-N/rad	13.2 Hz	89.75	103.0	91.5	103.5	--	--
3	Four bladed rigid rotor with a flexible mast M_{HUB} = 159 kg I_{HUB} = 7.40 x 10^6 N-cm^2	26.4 Hz	83.0	82.8	82.9	82.7	--	--
4	Four bladed rigid rotor with a rigid mast M_{HUB} = 159 kg I_{HUB} = 7.40 x 10^6 N-cm^2	26.4 Hz	183.0	98.5	181.0	99.25	--	--
5	Four bladed lo-hinge offset M_{HUB} = 79 kg I_{HUB} = 3.70 x 10^6 N-cm^2	26.4 Hz	83.0	82.8	82.9	82.6	--	--
6	Four bladed hi-hinge offset M_{HUB} = 139 kg K_{HUB} = 4.42 x 10^9 cm-N/rad	26.4 Hz	79.2	84.25	78.9	82.7	--	--
7	Four bladed hi-hinge offset M_{HUB} = 139 kg K_{HUB} = 4.42 x 10^9 cm-N/rad Phase = 0°	26.4 Hz	--	--	--	--	79.3	78.8
8	Four bladed hi-hinge offset M_{HUB} = 139 kg K_{HUB} = 4.42 x 10^9 cm-N/rad Phase = 90°	26.4 Hz	--	--	--	--	79.15	78.9
9	Four bladed hi-hinge offset M_{HUB} = 139 kg K_{HUB} = 4.42 x 10^9 cm-N/rad Phase = 180°	26.4 Hz	--	--	--	--	79.0	79.05

Case 1 BHT 2 bladed 206L teetering rotor

Case 2 BHT 2 bladed 206L teetering rotor with hub spring

Case 3 & 4 Fictitious rotor, total rigidity

Case 5 BHT 4 bladed 206LM rotor, 2½% hinge offset

Case 6 MBB, BO-105* 4 bladed rotor, 16% hinge offset

Case 7,8,9 Same as Case 6 with simultaneous hub shear and moment

* Data from Boeing Vertol Company report USAAMRDL-TR-75-50, "Validation of Rotorcraft Flight Simulation Program through Correlation with Flight Data for Soft-in-Plane Hingeless Rotors," January 1976.

4.2.3.1 LIVE Isolation Link

Consider the LIVE isolator integrated into a pinned-pinned link shown in Figure 35. The mechanics of a classical pinned-pinned link is such that only axial loads can be transmitted; no moments can be input through the spherical bearings at its ends. If the LIVE unit in the link is tuned to isolate the blade passage frequency, then no osicllatory loads at the blade passage frequency in any direction will be transmitted through the link. By using six pinned-pinned isolator links attaching the pylon to the fuselage (in any configuration that is statically stable in all six degrees of freedom) with no other attachments, then every attachment will isolate the blade passage frequency and no oscillatory loads will be transmitted in any degree of freedom. Two examples of the six degrees of freedom are illustrated in Figures 36 and 37, and typical frequency response plots are shown in Figures 38 through 45.

4.2.3.2 Parameters Controlling Isolation

With this system, any change to the rotor, mast, transmission, or fuselage will not change the isolation valley from the blade passage frequency as long as the LIVE isolators are tuned to the same frequency. The effects of varying parameters affect the frequency placement of the natural modes and the depth of the isolation valley (percent isolation) but not its frequency placement. This can be seen in Figure 46 where the link angle is changed on all six links affecting all the natural modes but not affecting the frequency placement of the isolation valley.

The parameters that were varied during the parameter study of the six LIVE systems include: hub weight, inertia and impedance; mast stiffness and length; transmission weight and inertia; LIVE link angle, length, spacing and stiffness; and overall aircraft size. The results of this study are summarized in Figures 47 through 55 for the effects on natural frequency placement, and Tables 4A and 4B for the effects on percent of isolation. In general, the percent of isolation is simply a function of the closeness of the second pylon mode and the mast bending mode to the blade passage frequency. In Tables 4a and 4b, there are a number of responses that achieved significantly less than 95 percent isolation. In all these cases, although the antiresonant valley was at the blade passage frequency, there was too much modal participation due to the second pylon mode or the mast bending mode being too close (within 20 percent) to the antiresonance. It is obvious that although the LIVE system can isolate well over 95 percent, it cannot overcome poor natural frequency placement.

SIX DEGREE OF FREEDOM PARAMETER STUDY

TABLE 4a. PERCENT ISOLATION OF C.G. WITH RESPECT TO RIGID BODY RESPONSE AT THE FOUR-PER-REV FORCING FREQUENCY

Force & Response Direction	Percent Isolation of CG - % Subcases								
	Baseline	PFU	PFD	PFI	PFO	PFS1	PFS2	HB1	HB2
Vertical	96.2	96.2	96.2	92.3	97.8	95.2	96.8	95.2	97.2
Longitudinal	96.5	96.5	96.2	98.4	95.8	97.8	95.5	96.4	96.1
Lateral	96.5	96.5	96.2	98.4	95.8	95.8	96.8	96.4	96.1
Pitch	96.6	97.0	96.7	98.8	96.0	98.1	96.0	96.9	96.2
Roll	95.3	95.8	95.3	98.2	94.4	94.7	95.6	96.2	94.0
Yaw	99.0	99.0	99.0	99.8	98.0	99.3	98.6	98.5	99.3

PFU - Fuselage and pylon attach points moved up 12.7 cm (5 inches) W.L.
PFD - Fuselage and pylon attach points moved down 12.7 cm (5 inches) W.L.
PFI - Fuselage and pylon attach points moved in radially 25.4 cm (10 inches)
PFO - Fuselage and pylon attach points moved out radially 25.4 cm (10 inches)
PFS1 - Fuselage and pylon attach points moved toward pylon 12.7 cm (5 inches) along F.S.
PFS2 - Fuselage and pylon attach points moved from pylon 12.7 cm (5 inches) along F.S.
HB1 - Hub mass and inertias changed - x ½
HB2 - Hub mass and inertias changed - x 2

SIX DEGREE OF FREEDOM PARAMETER STUDY

TABLE 4b. PERCENT ISOLATION OF C.G. WITH RESPECT TO RIGID BODY RESPONSE AT THE FOUR-PER-REV FORCING FREQUENCY

Force & Response Direction	Percent Isolation of CG - % Subcases								
	MI1	MI2	MT1	MT2	FDN	FUP	FS1	FS2	X4X
Vertical	97.8	94.4	96.5	96.2	93.4	98.1	95.5	96.8	96.2
Longitudinal	97.8	93.4	90.7	96.8	97.8	95.5	97.8	95.2	96.2
Lateral	97.8	93.4	90.7	97.1	97.4	95.5	95.8	96.8	96.2
Pitch	98.2	93.9	90.0	97.4	98.6	95.5	98.0	95.3	96.5
Roll	97.4	91.3	85.7	96.4	97.9	93.7	94.9	96.0	95.2
Yaw	99.3	98.5	99.0	98.9	99.2	99.9	99.1	98.9	99.0

MI1 - Mercury isolator mass and stiffness changed - x ½
MI2 - Mercury isolator mass and stiffness changed - x 2
MT2 - Main rotor mast stiffness changed - x ½
MT2 - Main rotor mast stiffness changed - x 2
FDN - Fuselage attach points (only) moved down 20.32 cm (8 inches) W.L.
FUP - Fuselage attach points (only) moved up 10.16 cm (4 inches) W.L.
FS1 - Fuselage attach points (only) moved toward pylon 12.7 cm (5 inches) F.S.
FS2 - Fuselage attach points (only) moved from pylon 12.7 cm (5 inches) F.S.
X4X - HB + MI + MT and pylon/fuselage C.G. masses and inertias changed - x 4

To evaluate helicopter size effects, all masses, inertia and stiffness in the NASTRAN model was increased by a factor of four (1814 kg (4000 lb) to 7258 kg (16,000 lb) GW). This resulted in no change in isolation frequency or percent isolation. Since a 7258 kg GW helicopter would have a blade passage frequency much less than that of a 1814 kg (See Figure 56) helicopter with the same number of blades, this comparison is not valid. The 7258 kg helicopter would probably use an rpm between 250 and 300, and the 1814 kg helicopter would probably use an rpm between 350 and 450. On the average, this would result in a frequency difference between the two size helicopters of about 1.5:1. Using this frequency ratio, 2.25 times (1.5^2) as much tuning weight must be added to the LIVE units on the 7258 kg helicopter. By doing this, the proper blade passage frequency is achieved for the heavier weight class helicopter. A secondary advantage of the 6-isolator system is the ability, with proper selection of parameters, to isolate both 1/rev and 2 n/rev in addition to n/rev (see Figure 46).

4.3 SELECTION OF ISOLATION SYSTEM TYPE

The particular isolation system to be used would depend then on which hub loads are produced. The two LIVEs plus focus pylon system used on the JetRanger IV would be used for rotors that produce only hub shears; i.e., two bladed teetering rotors, fully gimbaled multibladed rotors, and small hinge offset articulated or flexure type multibladed rotors.

The four LIVE system mounted in the plane of the pylon nodal point would be used for those rotors that produced shears, pitch and roll moments as long as the transmission had a relatively soft mast to isolate yaw and produce a low pylon nodal point. In addition, it is necessary that the magnitude of the shears and moments and their relative phase could be determined within sufficient accuracy to determine the waterline of the nodal point on the transmission. These rotors include 2-bladed rotors with stiff flapping springs and multibladed rotors with moderate hinge offset.

The six LIVE system would be used with rotor systems that produced high shears and moments including yaw moment due to the use of a stiff mast. This would include high hinge offset, rigid, and any other rotors that incorporated a stiff mast such that yaw would not be isolated and the pylon nodal point was too high to attach the fuselage.

5. BASELINE HELICOPTER

The baseline helicopter selected for the purpose of establishing specific isolation system performance, risk, weight analysis, and system integration studies during the analytical study was the BHT Model 206LM. This is a 1814 kg class turbine engine helicopter using a 4-bladed, soft in-plane, flexbeam rotor system.

The isolation system selected for the baseline helicopter is a modification of the six LIVE system using the LIVE unit in a pinned-pinned link (Figure 35).

Predesign drawings were produced that show a design installation of the LIVE links with no modification to the transmission or the fuselage structure. This installation can be seen in Figure 57. The parts that would be changed from the standard 206LM are shaded for clarity in Figure 58. A NASTRAN model of this geometry was constructed and tuned for optimum isolation, pylon and mast modal placement, static motions, and drive shaft coupling angles. The NASTRAN model had a rigid fuselage and the fully flexible pylon from the BHT Model 206LM. The effective mass and inertia of the rotor at 4/rev from Myklestad were included at the hub. This method gives very good results at 4/rev but will produce some error in frequency placement at the natural frequencies. The NASTRAN model for this installation is shown in Figure 59. The mode shapes of the natural modes through 40 hertz are shown in Figures 60a through 60e. These modes are listed in the following table.

TABLE 5. BASELINE HELICOPTER NATURAL FREQUENCIES

Mode	Frequency-Hz
First Pylon Yaw	2.58
First Pylon Roll	2.91
First Pylon Pitch	3.02
First Pylon Lateral Translation	8.42
First Pylon Longitudinal Translation	12.53
First Pylon Vertical Translation	14.14
First LIVE Isolator Lateral	20.84
First LIVE Isolator Longitudinal	22.01
First LIVE Isolator Yaw	25.97
Longitudinal Mast Bending	36.66

The only frequency that shows any placement problem is the LIVE Isolator Yaw mode at 25.97 Hz with 4/rev at 26.26 Hz. This mode shows a very weak response in the yaw response plot (Figure 61). So far, no independent parameter has been found that can move this mode without producing greater problems with other modes. Additional study will be performed during the detail analysis phase to move this mode.

The response plots of the Baseline Helicopter NASTRAN model are shown in Figures 61 through 68. These plots show very good isolation of all 4/rev shaft loads in six degrees of freedom. In addition, they show good frequency placement at 1/rev (6.56 Hz) and low response at 8/rev (52.5 Hz). This installation on the 206LM helicopter has the advantages of simplicity, light weight, total isolation, and simple retrofit to an existing helicopter.

6. WEIGHT ANALYSIS

The purpose of the weight analysis performed for this study was to determine the weight penalty of a total isolation system. To accomplish this, four assumptions were made.

1. The comparison would be between the weight of a total isolation system and a system with the pylon rigidly attached to the fuselage.

2. No weight would be included in the rigid system analysis to improve the fatigue strength of the structure to handle the higher oscillatory loads that would not be isolated.

3. Increased weight of the input driveshaft coupling would be included in the total isolation system due to the higher misalignment angles that would have to be accommodated.

4. Increased weight of additional hardware for control decoupling would be added in for the total isolation system.

The weight analysis is divided into two phases:

1. The effects of varying parameters (number of blades, area ratio, etc.) that influence weight.

2. The detail weight analysis for the proposed isolation system on the baseline helicopter.

The parameters that highly influence the weight of the isolator unit itself are area ratio, spring rate, stop clearance, and liquid density. The effects of area ratio and spring rate are shown in Figure 69. From this figure it can be seen that once the area ratio becomes greater than approximately 20:1, the gains in the reduction in tuning weight become small relative to the overall weight of the unit. Also, this figure shows that the tuning weight goes up directly proportional to an increase in stiffness. The volume of the reservoirs are directly proportional to the area of the tuning port times the area ratio times the stop clearance. The liquid in the reservoir plays no role in the tuning of the LIVE unit other than creating the pumping action and reaction. Therefore, any excessive reservoir length is wasted weight of high density fluid. The effect of liquid density can be determined from Figure 15 of Section 4.2.4. This figure shows the increase in size of the LIVE unit as the density of the liquid is

decreased. If the isolator is assumed to be made from the same material, and the weight of the liquid remains basically the same (lower density but proportionally higher volume), the weight of the isolator will go up approximately proportional to the square of the size ratio. The effect of frequency and spring rate on tuning port volume are shown in Figure 70.

6.1 EFFECTS OF VARIOUS PARAMETERS ON WEIGHT

The results of the parameter investigation show a number of effects on weight. This section summarizes these effects with all of the weight changes normalized relative to gross weight.

6.1.1 Two-Isolator System

Figure 71 shows the effects of weight versus frequency for all three isolation systems. Although the two-isolator system is more weight efficient than the four-or six-isolator systems, the two-isolator system can only be used with rotor systems that do not produce hub moments. As the plot shows, for the large, low RPM two-bladed helicopters, this size effect can be very costly in weight penalty. Plotted on this curve for comparison are the production JetRanger IV LIVE system and the 206L and 214ST nodal beam systems. The difference between the JetRanger IV LIVE and the estimated curve is due to the fact that the JetRanger IV LIVE unit is made with steel, and the estimated curve assumes that the steel parts would be made with composites. The solid curves assume that the area ratio is 20:1 and that the spring rate is such that the first vertical mode is at 80 percent of the blade passage frequency. Since the 80 percent criterion is required to achieve over 95 percent isolation, the spring rates must go down with the blade passage frequency and therefore drive the driveshaft angles up as the aircraft gets larger (larger aircraft produce lower frequency, see Figure 56). From this analysis, aircraft above approximately 9072 kg (20,000 lb) gross weight would require a multibladed rotor to keep the weight penalty below 1.0 percent.

The dashed curve assumes that the spring rate of the LIVE units remains constant, and that the area ratio is 20:1. The spring rate selected is equal to that used for the solid line at the blade passage frequency of 17.5 Hz. This would result in the weight penalty of the driveshaft coupling and the decoupling of controls to remain constant and the weight penalty of the LIVE unit would decrease faster above 17.5 Hz since the spring rate would not be increasing.

6.1.2 Four-Isolator System

Figure 71 also shows the effect of weight versus frequency for the four-isolator system. The four-isolator system results in a small increase in weight since, although the four units are smaller than the two units, they are not one-half the weight, and the attaching structure that is added for the four isolators is heavier than the bi-pod and focus pylon restraint spring for the two isolators. Otherwise, the effects of the parameters affecting weight are the same as for the two-isolator systems.

6.1.3 Six-Isolator System

Figure 71 also shows the effect of weight versus frequency for the six-isolator system. In addition to other flight loads, the isolators in the six-isolator system must also carry the main rotor torque load in the axial direction whereas the two- and four-isolator systems carry torque in the radial direction. This additional load requirement necessitates an increase in the axial spring rate of the isolators to create a total system stiff enough to not exceed allowable driveshaft misalignment angles. This increase in axial stiffness results in a larger, heavier unit. In addition, there are now six isolators required instead of four or two. One advantage of the six-isolator system over the four-isolator system is the basic truss arrangement. This allows the six-isolator system to have lighter attachment structure. Also plotted on this figure are the specific weight points for the proposed 206LM isolator system and a similar system using composites to minimize weight.

6.2 WEIGHT PENALTY FOR 206LM SYSTEM

The following weight analysis represents the detailed breakdown of the required 206LM isolation system parts that would be required over and above a rigid installation.

6.2.1 Steel LIVE Units

The proposed demonstration test hardware will use isolators with the housings made from steel for simplicity of manufacturing and reduced cost. The following table shows a breakdown of these parts. Refer to Figure 57 for an illustration of this unit.

TABLE 6. WEIGHT BREAKDOWN FOR STEEL LIVE UNIT

Part	Total Volume (cm^3)	Density (kg/cm^3)	Weight (kg)
Bolts, nuts and washers	18.022	0.008	0.1412
Elastomer	95.194	0.001	0.1423
Inner cylinder	191.794	0.008	1.5025
Outer cylinder	7.082	0.008	0.0555
Cap, uniball end	82.815	0.008	0.6487
Cap, link end	18.458	0.008	0.1446
Containment cylinder	89.367	0.003	0.2474
Mercury	66.910	0.014	0.9075
Rubber seal	13.962	0.001	0.0209
		Total weight/unit	3.8105

There are 6 units per system:

6 x 3.8105 = 22.8631 kgs/system

In addition to the LIVE units, there is an increase in weight of the input driveshaft couplings. By using the Kaflex coupling from the JetRanger IV for the higher misalignment angles instead of a diaphragm-type coupling, the increase in weight is:

Kaflex coupling weight 1.882 kg x 2 = 3.765 kg.
Minus diaphragm coupling weight 1.5508 kg x 2 = 3.1018 kg.
Total increase in coupling weight 0.6632 kg.

For the change in the controls for control decoupling, it is estimated that three bellcrank support brackets will have to be lengthened 5.588 cm resulting in a total weight increase of 0.283 kg.

Therefore, the total weight penalty for the steel six-isolator system is:

Six LIVE units	22.863 kg.
Coupling change	0.663 kg.
Bellcrank supports	0.283 kg.
Total weight penalty	23.809 kg.

The 206LM is a 1871 kg gross weight helicopter. Therefore, the weight penalty is 1.27 percent of gross weight.

6.2.2 Composite LIVE Units

For comparison purposes, a composite LIVE unit was designed to determine what the probable weight penalty of a production system would be since the higher initial costs and complexity would be offset by large volume production and lower weight. The following table shows a breakdown of these parts. Refer to Figure 72 for an illustration of this unit.

TABLE 7. BREAKDOWN OF COMPOSITE LIVE UNIT

Part	Total Volume (cm^3)	Density (kg/cm^3)	Weight (kg.)
Bolts, nuts and washers	18.022	0.008	0.1412
Elastomer	95.194	0.001	0.1423
Inner cylinder	191.794	0.002	0.3716
Outer cylinder	57.748	0.002	0.1119
Cap, uniball end	62.107	0.002	0.1204
Cap, link end	39.493	0.002	0.0762
Containment cylinder	89.367	0.003	0.2474
Mercury	66.910	0.014	0.9075
Rubber seal	13.962	0.001	0.0209
		Total weight/unit	2.1394

There are six units/system:

$$6 \times 2.1394 = 12.8367 \text{ kg/system}$$

Coupling change	.6632 kg
Bellcrank support	.2830 kg.
Total weight penalty	13.7822 kg.

When at a gross weight of 1871 kg, the weight penalty is 0.74 percent of gross weight.

7. RISK ASSESSMENT

To assess the risk of achieving total main rotor isolation, a number of evaluations were conducted for each of the three isolation systems. These evaluations include the effects of the LIVE unit parameters on percent isolation, coupled effects of the fuselage and pylon modes, and dimensional tolerance stack up.

7.1 LIVE UNIT

The parameters that can contribute to error in the isolation frequency of the LIVE unit are control of spring rate, damping, temperature, and force magnitude. The spring rate can only be controlled (without excessive cost) to ±10 percent with the use of the low damped elastomer. This could result in a 5 percent error in the isolation valley frequency placement if the change in spring rate were not compensated for. Therefore, the LIVE units are individually adjusted by designing the tuning port diameter to yield the desired isolation frequency for the highest spring rate expected. This allows exact tuning of each LIVE unit by measuring the spring rate after the ejection molding process of the elastomer and then reaming the tuning port diameter to compensate for the spring rate.

Any increase in damping will also reduce the isolation efficiency and therefore must also be controlled. This is accomplished by specifying a low damped elastomer and holding the manufacture to close tolerances on their rubber stack.

The effects of temperature have a twofold effect on isolation. The elastomer increases both spring rate and damping at low temperatures, and at -43°C (-45°F) the spring rate is increased tenfold over its value at room temperature. In addition, at -43°C the damping has increased from 2 percent to 28 percent of critical. This would result in no isolation at all under these conditions. The increase in damping, though, is beneficial to the LIVE unit. When the helicopter is started, this damping causes rapid warmup of the rubber due to the hysteresis loss under relative motion. In actual application this causes the rubber to warm up to over -18°C (0°F) in just a few minutes (by the time the helicopter is ready to lift off) and to standard temperature in approximately seven minutes. At standard temperature, the spring rate is only 6 percent stiffer than at room temperature, and the damping has reduced to 4 percent of critical. The unit will continue to warm up and stabilize at approximately 32°C (90°F) with an ambient temperature of -24°C (-12°F). These effects of isolator

performance have been verified by a cold weather flight test of the 206B/LIVE system in Colorado during February of 1980. During this test, after an overnight cold soak outside of -26°C (-14°F), within 15 minutes of engine start up, the vibration levels at the seat location were within the data scatter measured at normal temperatures. For this reason, BHT decided that the production JetRanger IV with the LIVE system would not need any type of heating device for cold weather operation.

7.2 TWO-LIVE SYSTEMS PLUS FOCAL PYLON

The risks identified that are peculiar to this system include proper selection of focus points and spring rates, the closeness of the second lateral pylon mode and mast bending modes to n/rev, and the relative magnitude of any hub moments due to hub springs, etc. Tolerance buildup in dimensional accuracy has been found to have an insignificant effect on isolation. The low frequency pylon modes (relative to the first vertical mode) result in a deeper, broader isolation valley than the vertical response valley. Therefore, a wider range in focus pylon spring rate is acceptable and still achieves good isolation. The allowable range is approximately ±6 percent and still achieves over 95 percent isolation. Because elastomeric spring rates vary more than this in a typical production run, steel springs would have to be used or rejection of all springs outside of the allowables in order to remain below 95 percent isolation on all ships. The closeness of the resonance to n/rev has a large effect on percent isolation. This effect is the same for all three isolation systems. By referring to Table 4 the effect of the resonance frequency on percent isolation by halfing and doubling the spring rate can be seen. For example, the isolation of the vertical force reduces from 97.8 percent to 94.4 percent with a factor of 4 change in spring rate (MI1 vs MI2). This represents a difference in the fuselage response of the high spring rate system of 2.3 times over the lower spring rate system. This effect must be considered when designing the system, and the pylon modes must be kept as far away as possible within the constraints to optimize the system and reduce the risk of not meeting the isolation goals.

The focus pylon cannot isolate both hub forces and shears at the same frequency. If the focus pylon is tuned to have an isolation valley at n/rev for hub forces, it will only reduce the response to hub moments between 40 and 60 percent. Therefore, if the rotor can produce significant hub moments, due to a hub spring for example, there becomes a large risk of not achieving the desired ride levels with the two LIVE plus focus pylon system.

7.3 FOUR-LIVE SYSTEM PLUS PYLON NODALIZATION

The risks associated with the four-LIVE system are similar to those of the two-LIVE system with the exception of those relating to the focus pylon. In addition, there is significantly more risk involved due to the necessity for accurate determination of the pylon nodal point.

Referring to Figure 33, a significant loss of isolation results from an error of two inches between the pylon nodal point waterline and the LIVE attachment waterline. This effect requires careful design analysis at the preliminary design stage. There are few changes that can be made during developmental testing other than mast length and stiffness that will move the nodal point if the inertial isolators have been placed at the wrong waterline. Since the nodal point is sensitive to hub impedance, it must be either accurately calculated with the coupled rotor/fuselage model or measured on an existing rotor system. In addition, if the rotor produces large moments as well as shears, the realitive phase and magnitude must be determined so that the nodal point due to the superimposed loads can be determined. Nevertheless, if these parameters can be determined accurately, this isolating system offers the advantage of lighter weight and less complexity over the six-isolator system.

7.4 SIX-LIVE LINK SYSTEM

The six-LIVE link system offers the least risk of the three isolation systems. Because of its basic principle, all connections between the pylon are pinned-pinned isolated links; it is very difficult to not achieve good isolation. The only problem becomes keeping adequate margin between the mode placement and the blade passage frequency. The percent of isolation will be dependent on the margin. The designer is faced with the problem of adequate margin, pylon mode placement for stability and 1/rev considerations, and static stiffness for controllability and drive shaft coupling angles. The isolation valley will always be at the blade passage frequency if the LIVE links are tuned properly.

8. RELIABILITY AND MAINTAINABILITY

The reliability and maintainability impact of installing the LIVE system on the 206L and OH-58A has been assessed. The LIVE configuration will result in reliability improvement relative to both the standard and OH-58A helicopters, and a maintainability improvement for the 206L. The following table shows the R&M estimates for proposed and present pylon support configurations.

	LIVE	206L	OH-58A
Reliability (Mean-Time-Between-Failures)	1495	1235	885
Maintainability	.005	.01	.0024

8.1 RELIABILITY

Proposed changes which will improve reliability are:

206L

- Simplification of design by elimination of the nodal beam components.
- Increased pylon link bearing reliability

OH-58A

- Elimination of problems experienced in field usage on drag pin, isolation mount, and transmission attach points.
- Improved reliability on other aircraft components due to reduction of vibration levels.
- Increased pylon link bearing reliability.

8.2 MAINTAINABILITY STUDY

This study was made to compare the maintainability characteristics of the LIVE pylon isolation system with those of the nodal beam system and the 206A/B series pylon mounts.

Of the three mounting systems, actual maintainability data are available for only the 206A/B system. These data were obtained from the Navy "3M" system for the TH-57A as follows:

Component	MMH/FH
Pylon Support/Link	.000657
Drag Link/Pin	.001567
Pylon Upper Support	.000186
Total	.002410

Using this system as baseline, the characteristics of the other two systems can be derived on a relative basis.

In the nodal beam system, the four link assemblies are analogus to the two link assemblies of the 206A/B system. The nodal beam system also includes two arm and flexure assemblies and a transmission restraint, for which there are no corresponding 206A/B components. Removal of the transmission restraint requires removal of the main drive shaft. This requirement, plus the additional parts count, results in an estimated four-fold increase in MMH/FH, i.e., approximately 0.01 MMH/FH.

As compared to the nodal beam, the four LIVE pylon links are analogus to the four nodal beam link assemblies. The two LIVE F/A and lateral restraints are analogus to the transmission restraint. The two arm and flexure assemblies of the nodal beam are eliminated. It appears that the LIVE restraints can probably be removed with the drive shaft in place. Captive nuts on the restraint fitting would help in this regard. If these restraints can be easily removed, maintainability should approach that of the 206A/B system and should not exceed .005 MMH/FH.

A potential problem area is leakage of mercury onto aluminum structure, which could result in considerable maintenance. Since the LIVE unit is conservatively designed for 5000 hours, this should not be a problem. The outer seal on the LIVE unit will prevent such leakage should the elastomer or inner seal fail. It is recommended that the outer seal be made of a suitable clear material for easy visual inspection of mercury leakage past the primary seals. If the leakage of mercury becomes a maintenance problem, then the unit should be changed to use one of the other high density fluids and the size and weight penalty accepted for better maintainability.

9. GROUND AND FLIGHT DEMONSTRATIONS

The primary means used in the ground and flight demonstration program to verify the proposed isolator design installed on the baseline vehicle will be ground vibration tests. Shear and moment excitation will be applied separately in all six degrees of freedom. Attenuation across the isolators and acceleration magnitudes at the crew and passenger seat vertical, lateral, and fore-and-aft responses will be measured for each excitation.

As the program progresses into flight test, excitations other than through the main rotor shaft are introduced. Thus, transfer functions will be obtained during shake test to permit an analysis of force determination from measured flight data, so that an accurate assessment of isolator performance in flight can be made.

The five separate tests required for this verification are:

1. A single LIVE unit vibration test
2. A vibration test with the total pylon and six LIVE units installed on the floor
3. A total helicopter vibration test
4. A ground resonance test
5. A flight test

The following sections will detail each of these tests.

9.1 SINGLE LIVE LINK TEST

A single LIVE unit will be installed in a test fixture with a load cell at each end as shown in Figure 73. The electromagnetic shaker will be used to input oscillatory loads at the top of the LIVE link. There are Three main purposes for this test:

1. Tune the LIVE link to the blade passage frequency of the 206LM (26.2Hz), by reaming the tuning port.
2. Determine the percent isolation of a single link, the percent damping in the link, and the response versus force magnitude.
3. Isolator Static Load test and Proof Load test to assure safety of flight.

Note: No fatigue test will be necessary due to short duration of tests and large design margins that will be used on prototype steel parts.

For this test, a special end cap will be made with small necked down sections for strain gages (shown in Figure 73) so that accurate measurement of the low magnitude oscillatory force can be made.

9.2 PYLON ISOLATION TEST

The object of this test is to determine the percent isolation that would be achieved by the isolation system if installed on a rigid body fuselage. This will be accomplished by measuring the forces and moments input at the hub and measuring the forces output at the bottom of the six LIVE links. The test set up to be used for this purpose is shown in Figure 74. A special mast will be used for this test that has been reduced in wall thickness in the top 18 inches so that accurate force and measurement strain gages can be installed. See Section 9.3 for the details of the mast measuring instrumentation. This change in wall thickness will have a negligible effect on the pylon modes, and a small but acceptable effect on the mast bending modes. The special LIVE link end caps used in the single LIVE link test will be used at each end of all six isolators so that accurate measurement of transmitted forces can be made. A special computer program will be written to calibrate the input forces and moments at the hub to the output forces at the floor. Since six independent links are used with no redundant load path, this calibration can be performed just like a balance for a wind tunnel. With the mast cross section at the strain gage location tailored for large strain output at the expected load levels, this procedure will result in a high level of accuracy.

The test that will be performed will include frequency response to determine pylon modes, mast modes, and percent isolation at 26.2 Hz, and linearity with load magnitude will be determined. In addition, the LIVE links will be replaced by rigid links, and the difference between an isolated fuselage and an unisolated fuselage will be determined.

For lateral and fore/aft and vertical force excitation at the main rotor mast, an electromagnetic exciter capable of 6672N (1500 lb) oscillatory force with the necessary power supply, function generator, and servocontroller will be used. A hydraulic rotary actuator capable of 226,000 cm-N (20,000 lb) oscillatory moment with the necessary hydraulic power supply, function generator, and servocontroller will be used for exciting pitch and roll hub moments as well as main rotor mast torque. The electromagnetic exciter and hudraulic rotary actuator will be mounted on a shaker tower for all tests except for torsional excitation of the main rotor mast. For main rotor torsional excitation, a test fixture will be used to suspend the rotary actuator above the main rotor mast.

The instrumentation system that will be used for all the ground vibration tests is shown in Figure 75.

9.3 HUB FORCE MEASUREMENT

9.3.1 General Approach

Direct measurement of hub forces is based on the use of the mast as a six-degree-of-freedom force and moment sensor. This approach is now feasible due to several refinements in strain gage instrumentation techniques that have been developed by BHT in recent years. The key development is a cross-talk compensation method which removes unwanted cross-axis sensitivity from a transducer through the use of a compensating signal obtained from an extra sensor for the offending cross-axis load.

9.3.2 Moment Sensors

Strain gages for sensing mast bending moments both parallel and perpendicular to the reference (red) blade will be installed. One set of strain gages will be installed at approximately Sta 6.0, and an additional set will be installed at Sta 16.0. Undesired output due to torsion and other cross-axis loading will be eliminated through the use of the cross-talk compensation technique described above.

Mast torsion will be measured through the use of strain gages installed at approximately Sta 16.0. Crosstalk compensation will be applied if needed.

9.3.3 Shear Sensors

Three components of net shear force applied to the mast will be measured. Two of the components will be oriented in a plane perpendicular to the mast centerline, with one being parallel to, and the other being perpendicular to the reference (red) blade. These two components will be measured using the difference signal from two interconnected half-bridge moment sensors at Stations 6.0 and 16.0. Undesired output due to torsion and bending moment inputs will be eliminated by compensation. Due to the low magnitude of expected load, only the oscillatory portion of these two components of shear load will be measured.

The third shear force component will be measured through the use of an axial strain gage bridge applied at approximately Sta 11.0. Due to the low magnitude of axial strain in the mast, special care in compensation and conditioning of this signal will be required. Previous experience has shown that

crosstalk compensation for torsion, bending moment, and shear loading are all required. Large, high assistance strain gages are also used to increase output through the use of a 20-volt bridge excitation supply. Due to the difficulty of temperature compensation, only the oscillatory portion of the axial force will be measured.

9.3.4 Calibration

Shear and moment sensors on the mast will be calibrated through the application of known forces and moments using standard BHT procedures and equipment. Crosstalk compensation for each sensor will be accomplished prior to actual calibration loading. Copies of all calibration will be provided.

9.4 ROTOR/FUSELAGE FORCE DETERMINATION

In the solution of a vibration problem, a significant and essential ingredient is the correct identification of the vibratory source of excitation. This is especially true in the process of evaluating helicopter ride comfort, since only a portion of the vibratory levels may be induced through the rotor shaft. Strong emphasis must be placed on identification of all excitation sources such as rotor wake impingement on the cabin and stabilizing surfaces, as well as designing the rotor for minimum excitation, and on more careful structural optimization for minimum amplification of induced forces.

Identification of excitation sources is investigated through a combination of shake test transfer function 'calibration' and flight test measurements. The tests have demonstrated, for example, that significant (unisolated) cabin vibrations are induced through the horizontal stabilizer and vertical fins as a result of rotor wake impingement.

For the flight test portion of testing, it is very desirable to be able to determine the actual rotor loads being input to the mast, and the magnitude of forces, if any, being input from other sources. For this purpose, the third test will be a force determination/calibration vibration test to determine fuselage responses to all known excitation sources. For this purpose, the third test will be a force determination/calibration vibration test to determine fuselage responses to all known excitation sources. For this test, a new computer program currently in development at BHT and over one-half complete will be made available. This program, called FORCE, uses a technique developed by Kaman Aerospace Corporation

under contract to the Applied Technology Laboratory, USARTL (AVRADCOM)[6] and is a method for determining the magnitudes and phasing of vibratory rotor forces and moments (and other external forces and moments) on a helicopter in flight through accelerometer measurements on the fuselage only. This program will be completed by BHT and available for the time frame of this portion of the testing. The following section briefly outlines the tests and procedures to be used during the force determination testing.

9.4.1 Airvehicle Configuration

The test vehicle will be the Model 206LM helicopter with the following modifications:

1. For testing the total main rotor isolation system configuration, the 206LM SAVITAD pylon system will be replaced with links that contain the LIVE system. The strain gaged end caps on the LIVE links will be replaced with the flightworthy end caps.

2. The tail rotor hub and blades will be removed and replaced with dummy weights of equal mass.

3. The main rotor hub and blades will be removed and replaced with dummy adjustable weights having two different inertia capabilities. This will allow simulation of effective weight and inertia at 4/rev and at 1/rev.

4. The helicopter will be configured for a gross weight of 1814 kg with a neutral center of gravity.

9.4.2 Suspension System

The helicopter will be suspended from the main rotor mast cap on a low frequency (below 1 Hz) shock cord or air mount suspension system. The suspension system will be installed with as much free cable length as possible between the suspension system and the rotor hub.

9.4.3 Exciters

Exciters are for lateral and fore/aft shear excitation at the main rotor mast, lateral excitation at the 90° gearbox, and

vertical excitation at the elevator and main rotor mast. An electromagnetic exciter with a 6672N force capability and the necessary power supply, function generator, and servocontroller will be used. A hydraulic rotary actuator with 226,000 cm-N moment capability and the necessary hydraulic power supply, function generator, and servocontroller will be used for exciting pitch and roll hub moments as well as main rotor mast torque. The electromagnetic exciter and hudraulic rotary actuator will be mounted on a shaker tower for all tests except for excitation of the elevator and torsional excitation of the main rotor mast. The electromagnetic exciter will rest on the floor for the elevator excitation. For main rotor torsional excitation, a test fixture will be used to suspend the helicopter and position the rotary actuator above the main rotor mast.

9.4.4 Instrumentation and Data Acquisition

Accelerometers and strain gages will be located for the various tests at the positions indicated in Figure 76. The main rotor mast will be instrumented to measure torque, bending moments, hub shears, and axial loads. This instrumentation will be conditioned through an airborne data system and stored on magnetic tape.

Additional instrumentation will be installed on the helicopter and between the helicopter and the exciter. The ground vibration data acquisition system will be used to condition these signals. This additional instrumentation, as well as signals from the airborne data system, will be used to create online data plots through the use of the Ground Vibration Excitation and Data Acquisition System shown in Figure 75. The load cell between the exciter and helicopter will also be used to control the shaker.

9.4.5 Modal Analysis

In addition to the acquisition of the transfer function required for the force determination in flight test, BHT's computer program MODAL will be used to determine the modal parameters of the pylon and fuselage modes through the first main rotor mast bending modes (approximately 35 Hz). Modal analysis is the technique of using measured frequency response data to identify the natural frequencies, damping factors, and mode shapes of a finite number of predominate modes in an elastic body.

9.5 GROUND RESONANCE TESTING

Although the 206LM skid gear mounting is retained unchanged, and the first longitudinal and lateral pylon modes of the six LIVE system are placed near where the original modes were placed, a short ground resonance test is justified since the LIVE units have less damping than the original 206LM pylon.

This ground resonance test will consist of gradual sweeps of RPM with various amounts of control inputs to excite the pylon. A continuous monitoring of online data with BHT's computer program INACT allows rapid (10 seconds) determination of pylon/rotor damping to assure adequate margins for stability.

9.6 FLIGHT TESTING

After completion of the ground resonance testing, the flight test will begin. The ride quality will be determined for flight conditions within the 206LM flight envelope. By use of the transfer functions obtained with the FORCE computer program, the hub forces and moments will be determined along with forces to the elevator, vertical fin, tail rotor, and controls for selected flight conditions. The forces and moments obtained for the main rotor hub will be compared to the levels measured with the mast measuring instrumentation. After the completion of the testing with the six LIVE system, and if the schedule allows, the LIVE links will be replaced with rigid links to compare the degree of isolation achieved by the LIVE system. The rigid link system will be flown through selected test conditions for comparison purposes only, so that the airframe will not be subjected to unacceptable loads.

9.7 DATA ACQUISITION INSTRUMENTATION

The instrumentation system that will be used for the force determination vibration test, the ground resonance test, and the flight test will be a standard BHT flight instrumentation package. This system is described under the force determination section 9.4.4.

10. SCHEDULE

The proposed schedule and the distribution of manhours for individual tasks are shown in Figure 77 which covers a period of 18 months. The first 3 months will be used for a detailed study to finalize all parameters that control frequency placement, degree of isolation, pylon motions, and driveshaft angles.

The detail drawings of all major hardware will be completed and an oral review will be held before the start of fabrication of hardware starts. The next four months will include the fabrication of all hardware, the modification of the aircraft and the delivery to flight test. A second oral review will be held at this time before commencing tests. Testing will cover five months and after a sixth month for completion of data analysis a third and final oral review will be held. The draft report will be complete at the end of the 15th month and the final report at the end of 18 months.

LIST OF REFERENCES

1. USAAMRDL-TR-76-41A, "Rotorcraft Flight Simulation with Coupled Rotor Aeroelastic Stability Analysis," Prepared for Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia 23604, by Bell Helicopter Textron, May 1977.

2. Harvey, Keith W.: The Effect of Cyclic Feathering Motions on Dynamic Rotor Loads. Presented at ASH/NASA-Ames Specialists' Meeting on Rotorcraft Dynamics, February 13-15, 1974.

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4. Kidd, D. L., Balke, R. W., Wilson, W. F., and Wernicke, R. K.: Recent Advances in Helicopter Vibration Control. Presented at the 26th Annual National Forum of the American Helicopter Society in Washington, D.C., June 1970.

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6. Flannelly, W. G., Bartlett, F. D., Jr., and Forsberg, T.: Laboratory Verification of Force Determination, a Potential Tool for Reliability Testing. Kaman Aerospace Corporation, USAAMRDL-TR-76-38, January 1977.

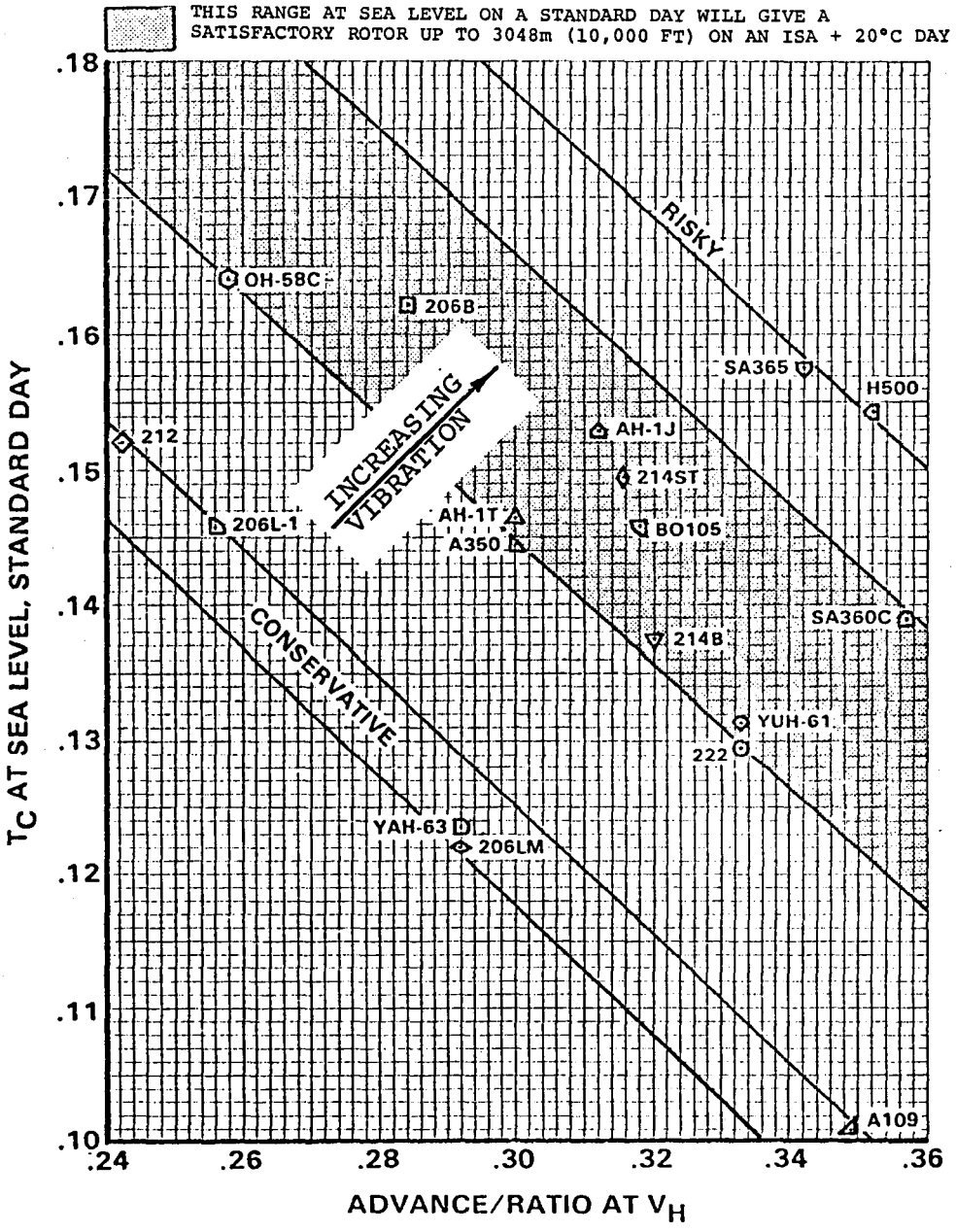


Figure 1. Vibration Increases as a Function of T_C and Advanced Ratio

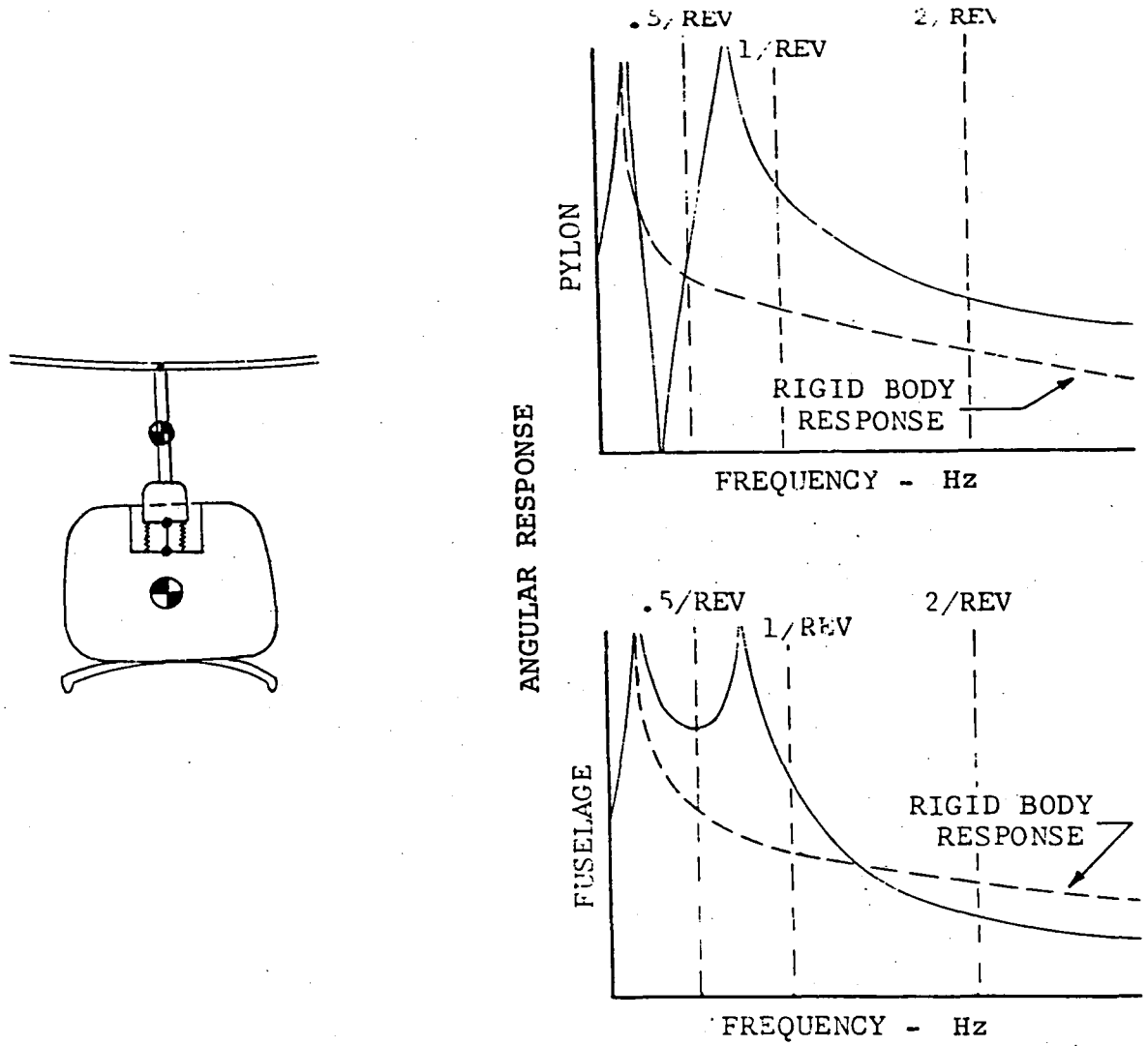


Figure 2. Response of Conventional Isolation System.

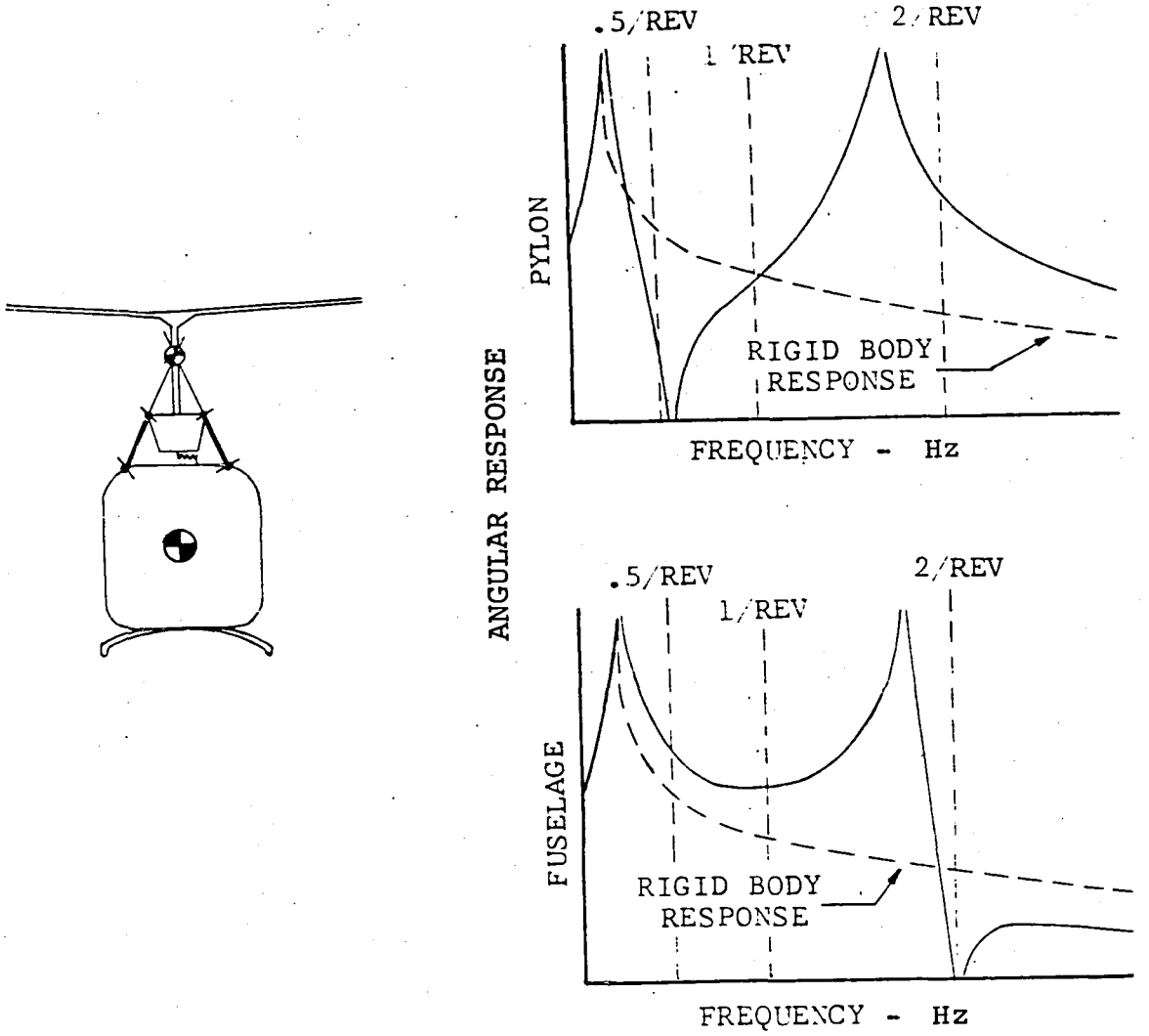


Figure 3. Response of Up Focused, Focus Pylon Isolation System.

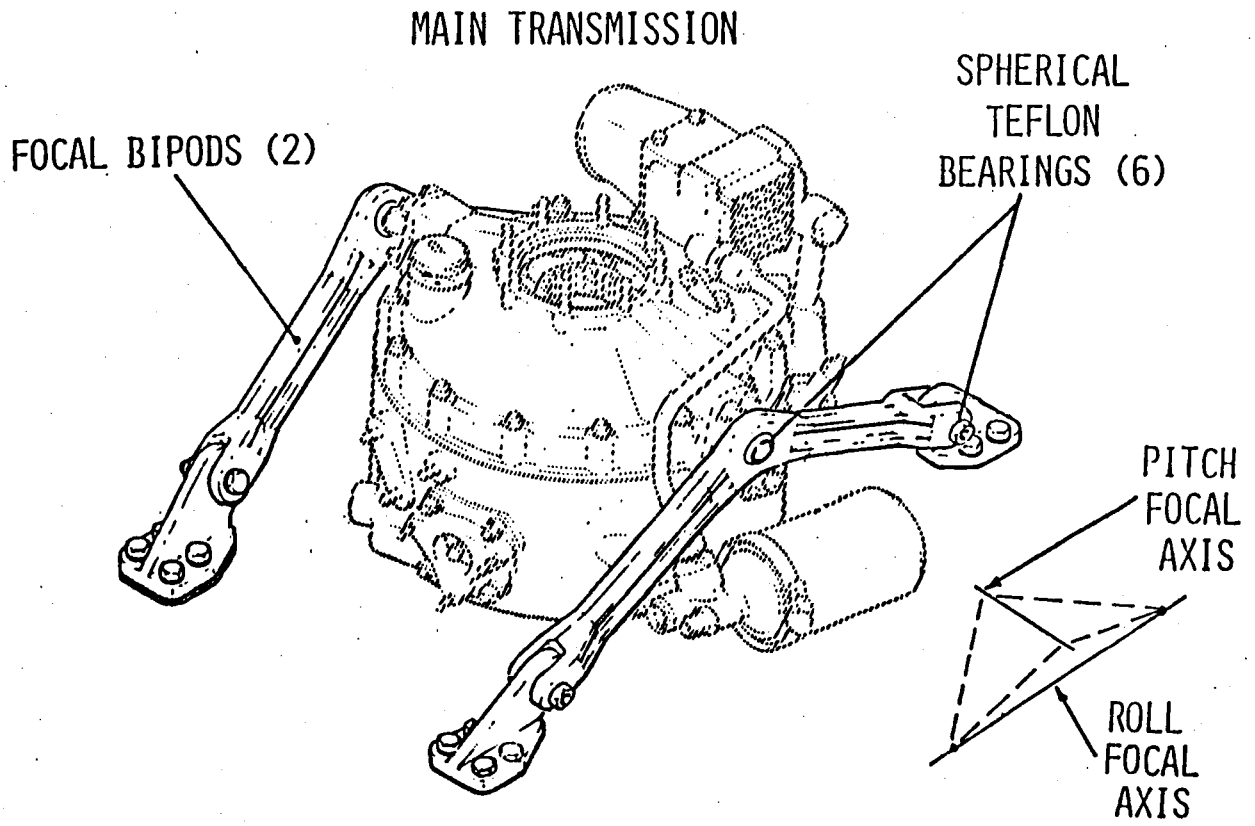


Figure 4. Illustration of 206/OH-58 Focus Pylon.

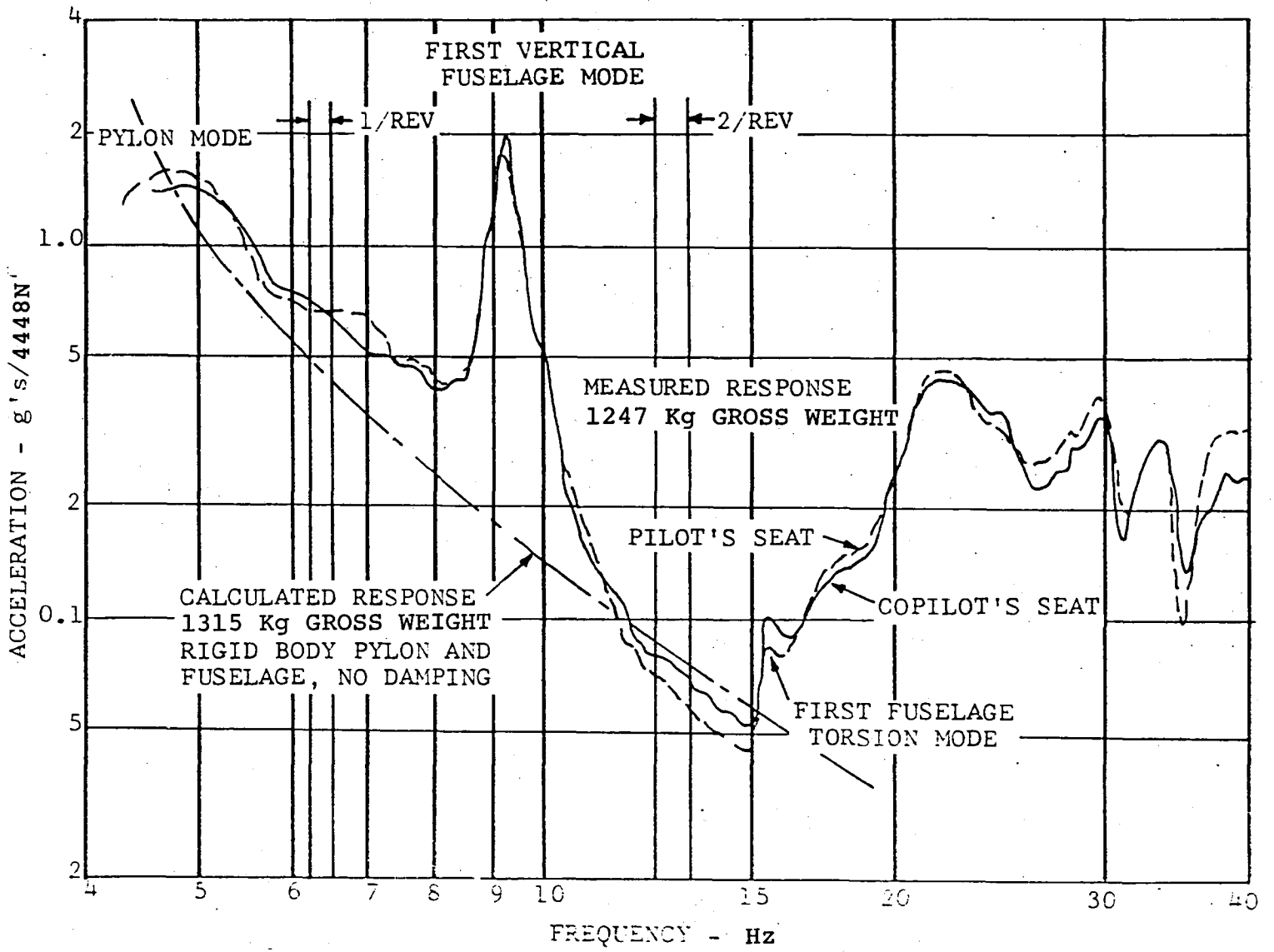


Figure 5. Measured Response of Isolation at Crew Seats Using Focus Pylon From Vibration Test.

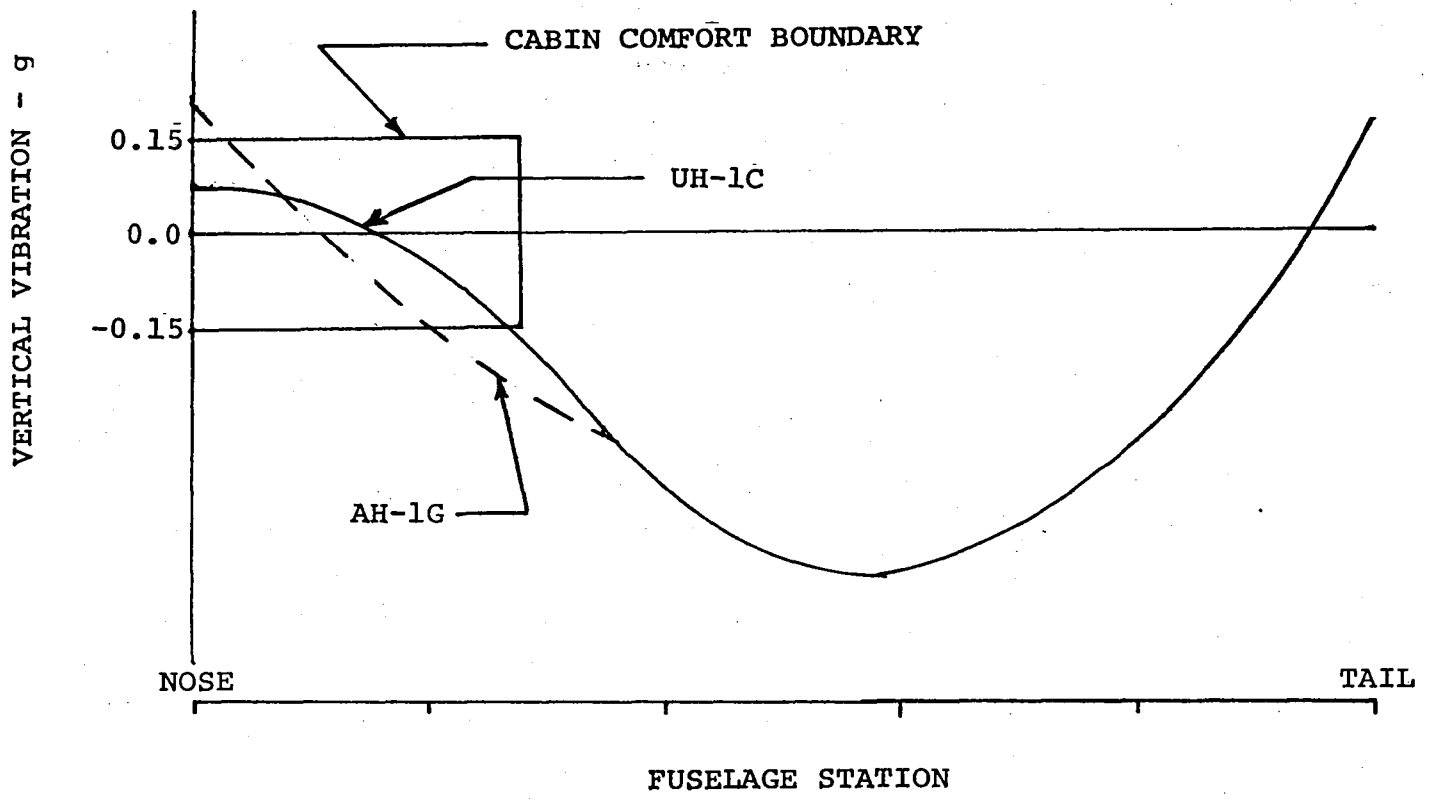


Figure 6. Application of In-Flight Nodal Point to Reduce Cabin Vibrations.

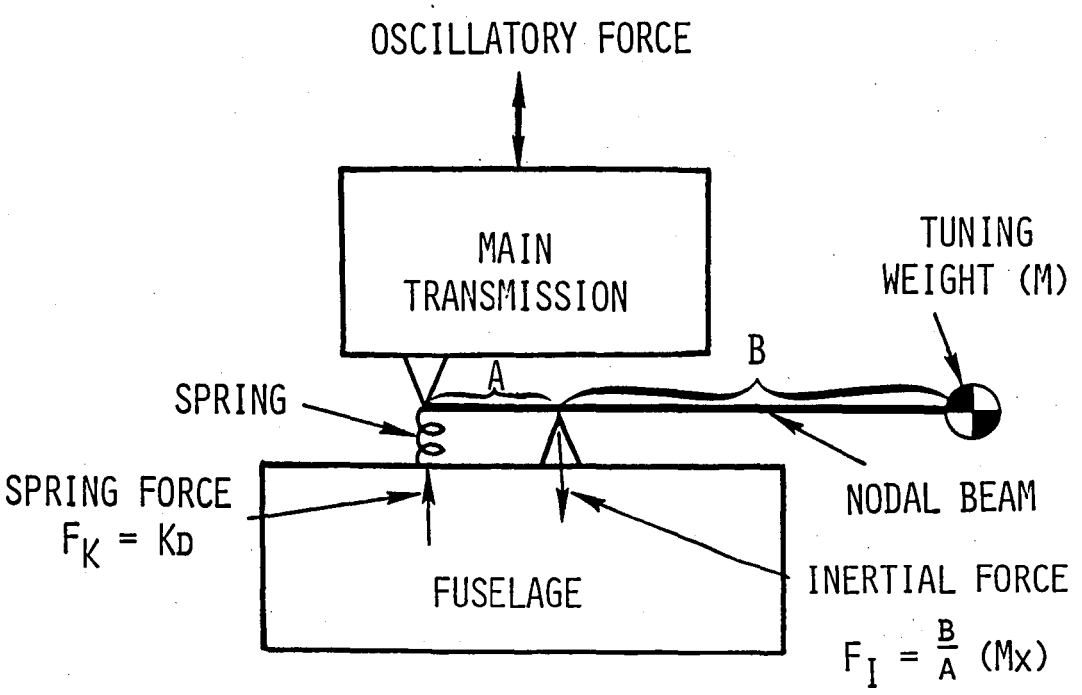


Figure 7. Principle of Nodalization.

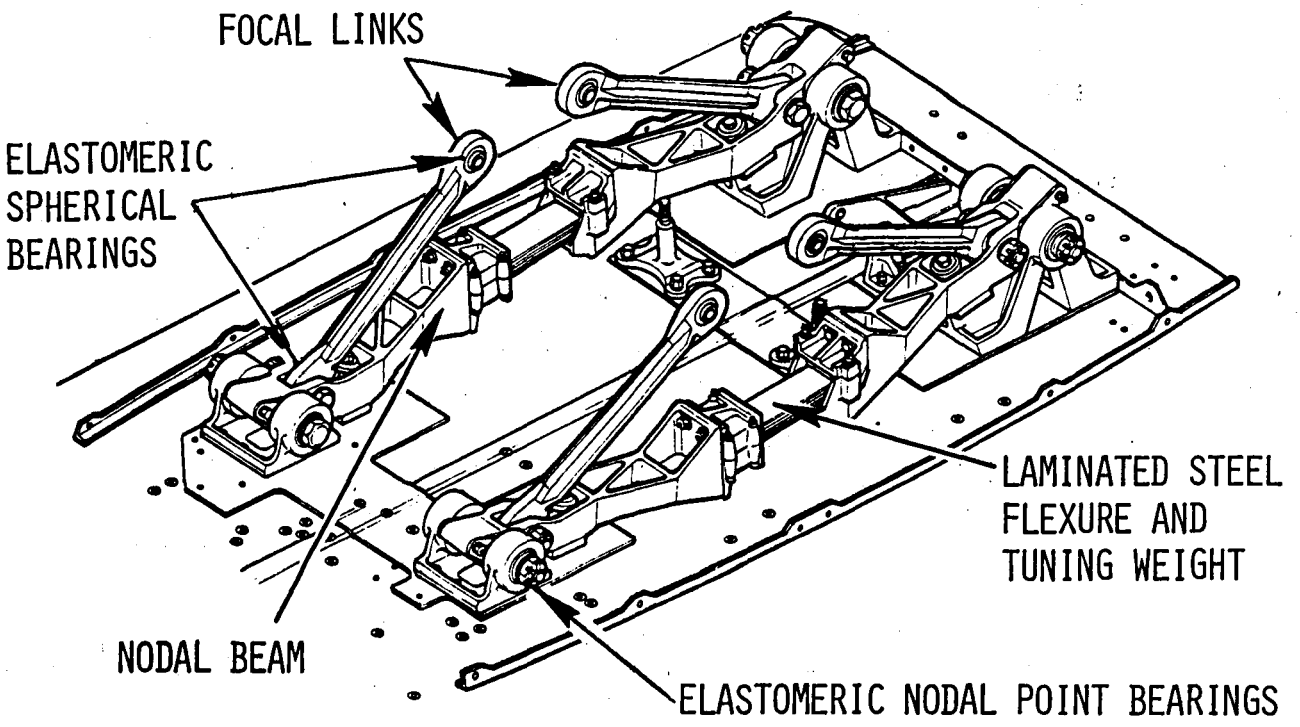


Figure 8. Model 206L Nodal Beam Installation.

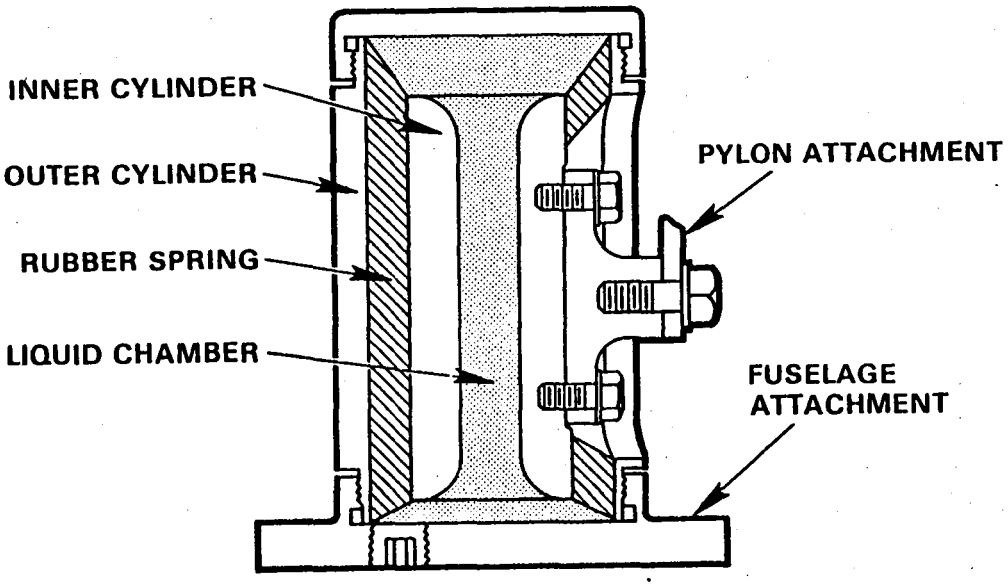


Figure 9a. Design of LIVE Isolator

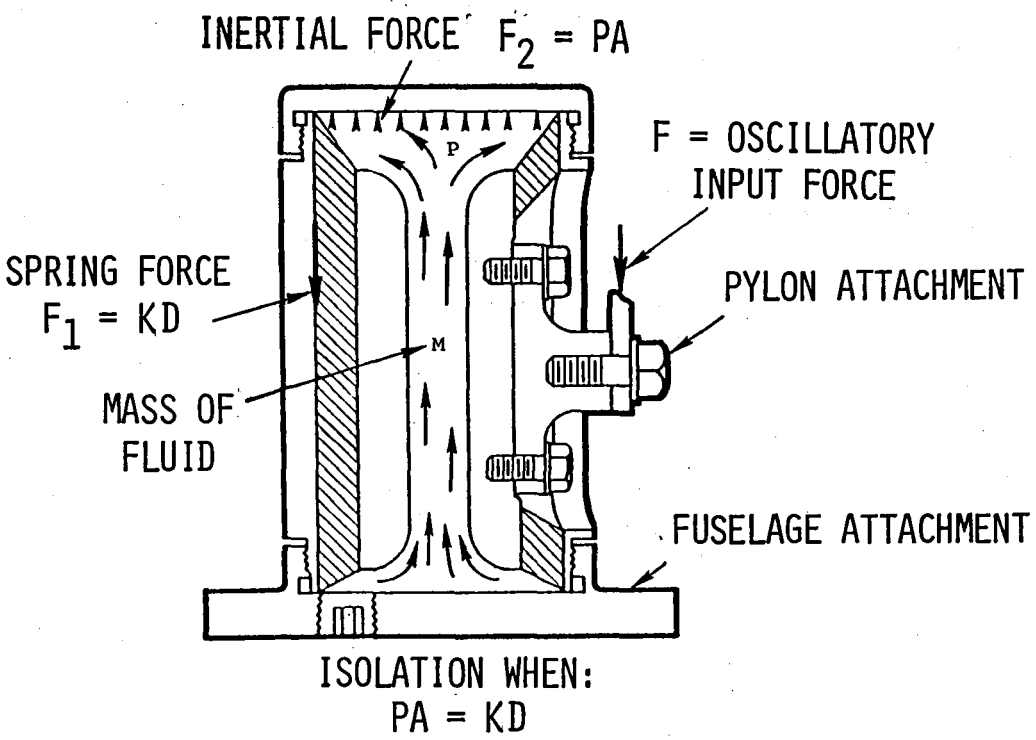


Figure 9b. Principle of LIVE Isolator.

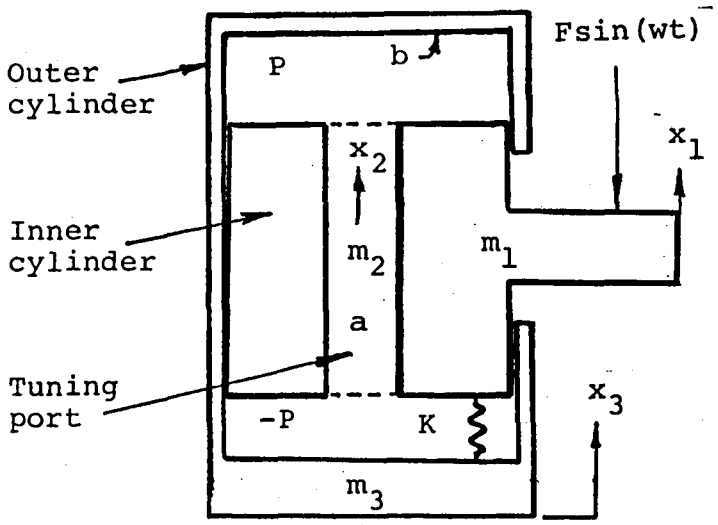
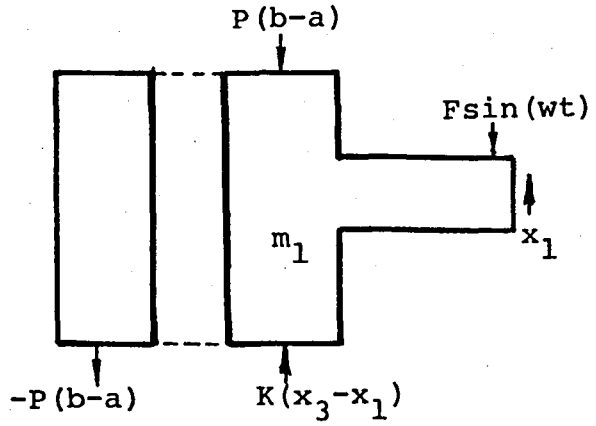
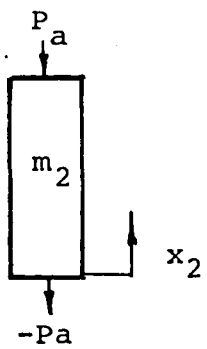


Figure 10a. LIVE Schematic.



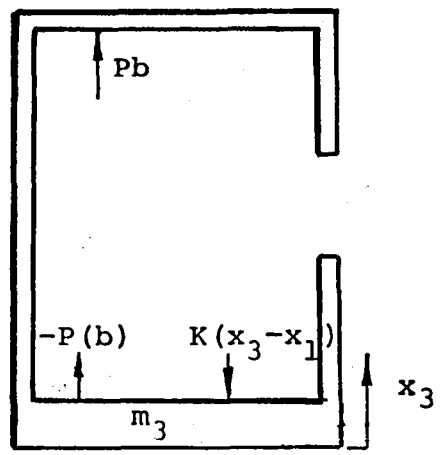
$$-m_1\ddot{x}_1=F\sin(wt)+2P(b-a)-K(x_3-x_1)$$

Figure 10b. Free body of m_1



$$-m_2\ddot{x}_2 = 2Pa$$

Figure 10c. Free body of m_2



$$-m_3\ddot{x}_3 = K(x_3-x_1) - 2Pb$$

Figure 10d. Free body of m_3

Figure 10. LIVE Analysis Free Body Diagrams and Equations of Motion.

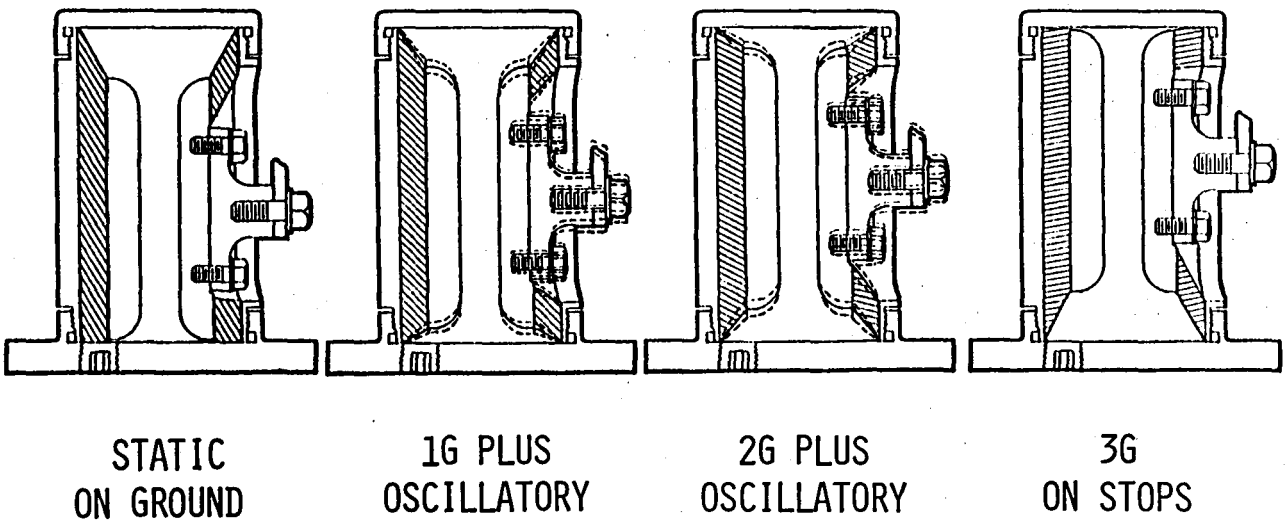


Figure 11. Flight Motions of LIVE.

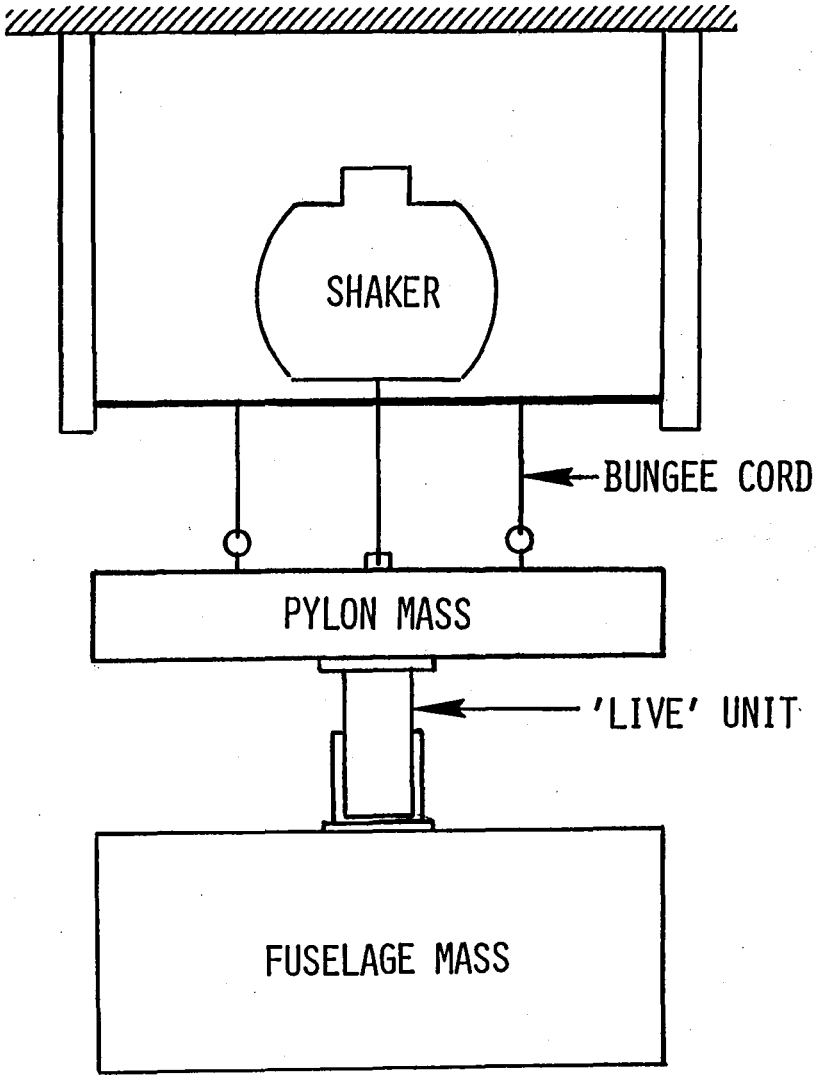


Figure 12. Schematic of LIVE Test Installation of the Research Unit.

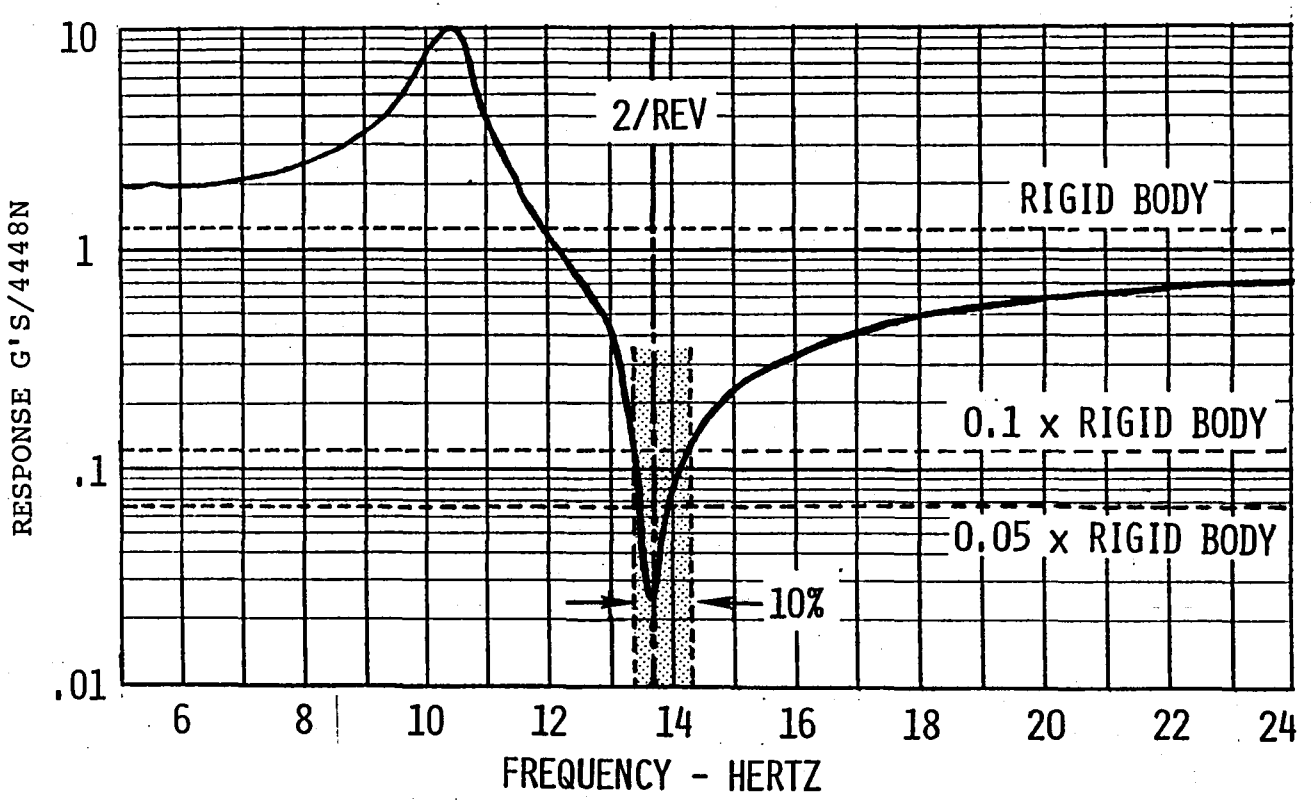


Figure 13. Response of Fuselage Mass Using LIVE Isolation.

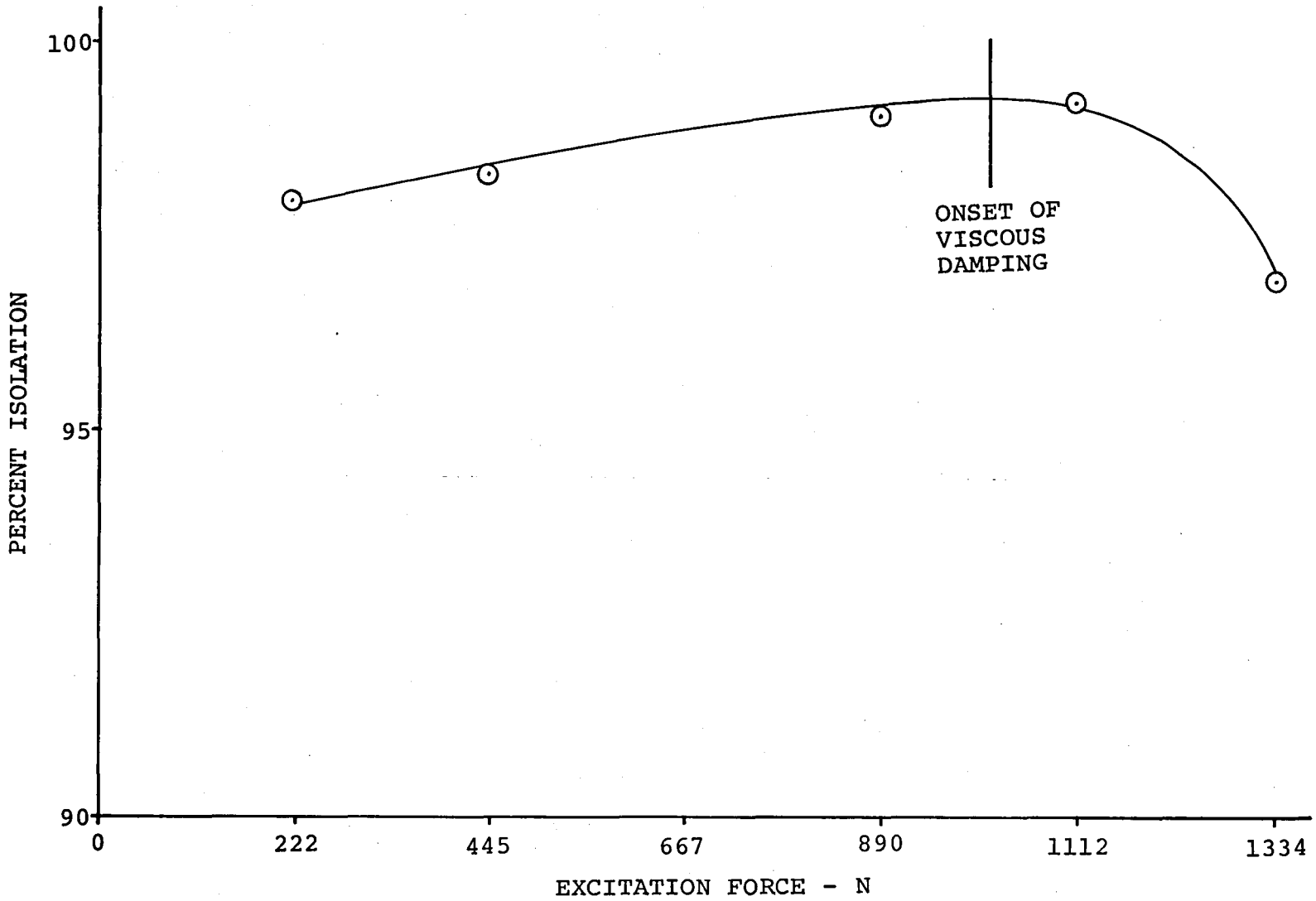


Figure 14. Measured Isolation of Research Isolator

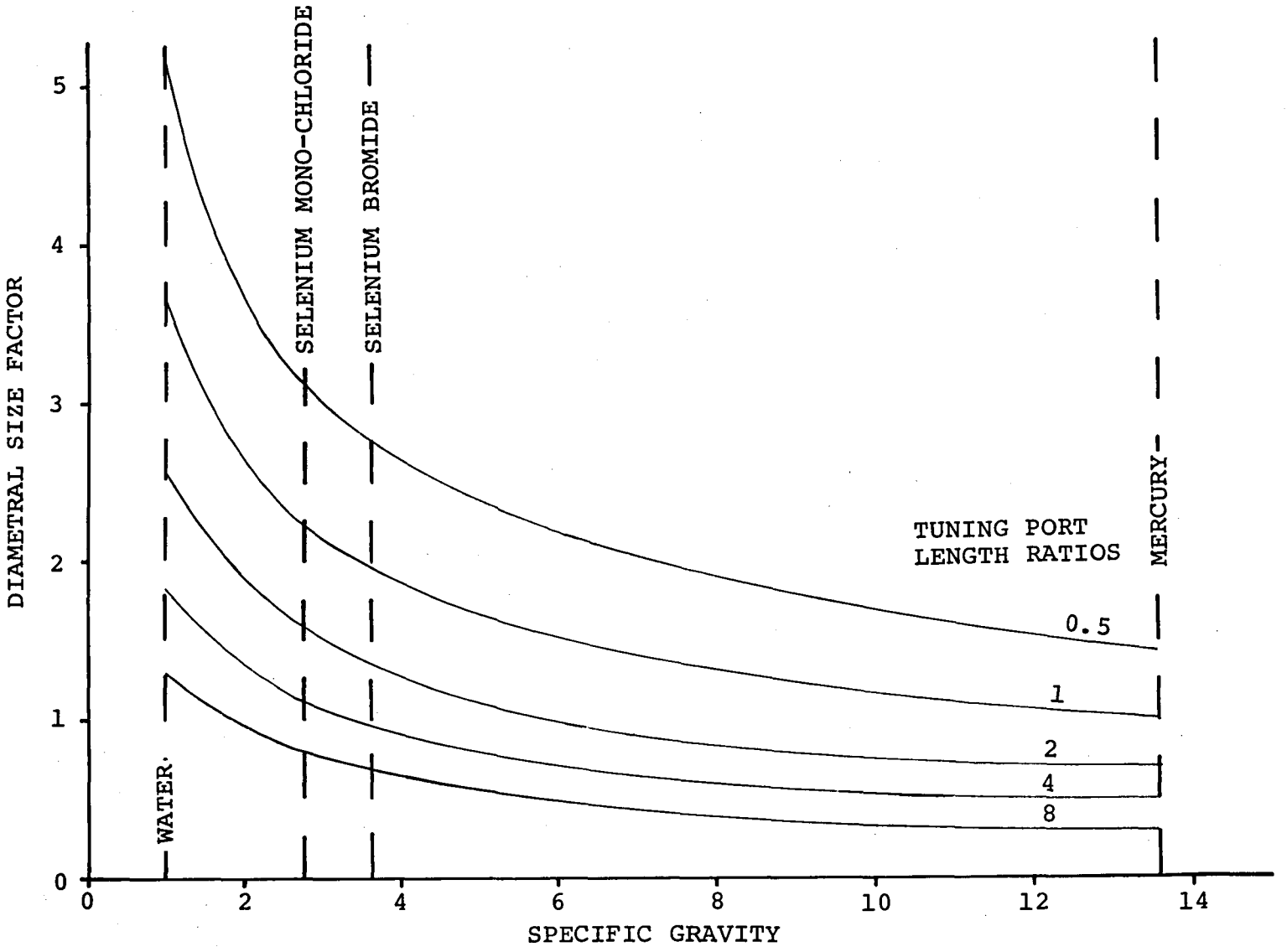
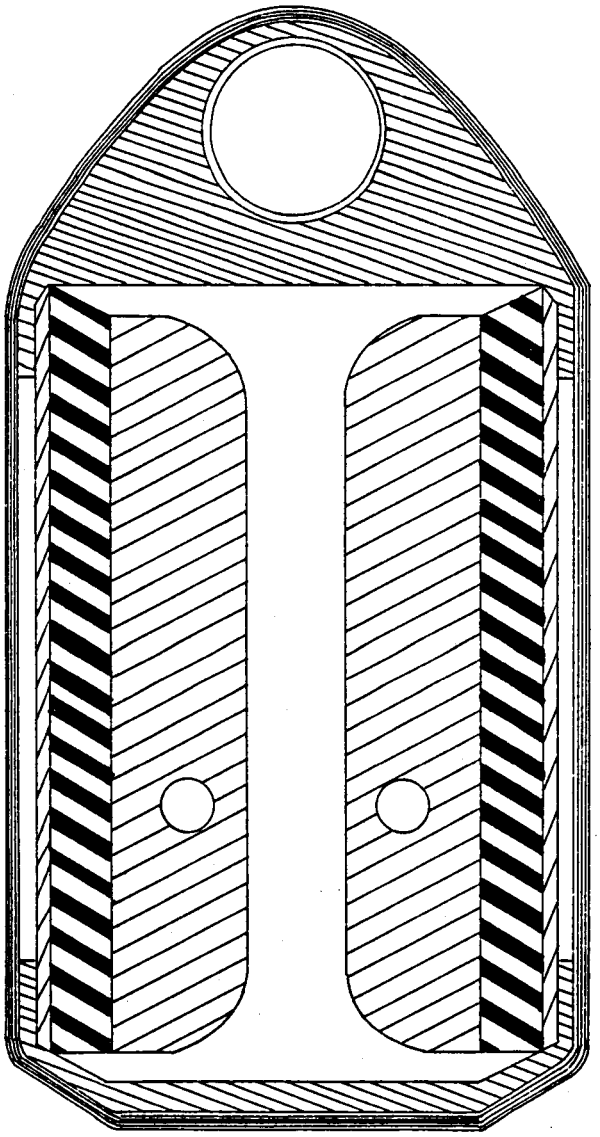
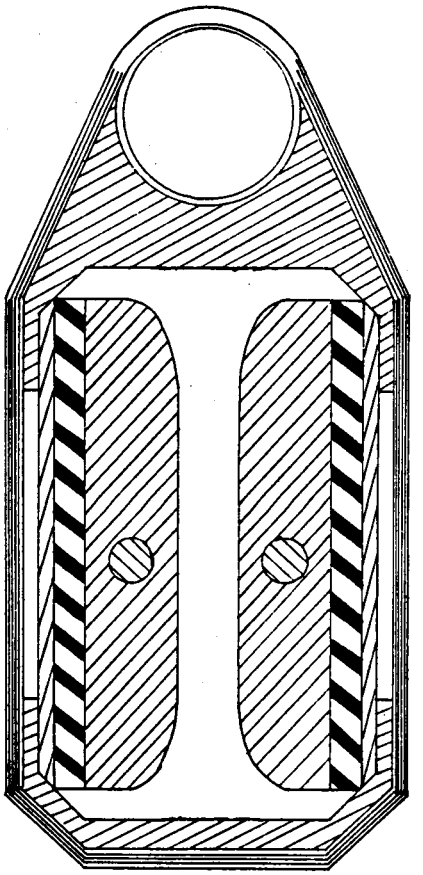


Figure 15. Effects of Specific Gravity on LIVE Unit Size.



Selenium Bromide LIVE



Mercury LIVE

Figure 16. Size Comparison of LIVE Units with a Density Ratio Difference of 4:1.

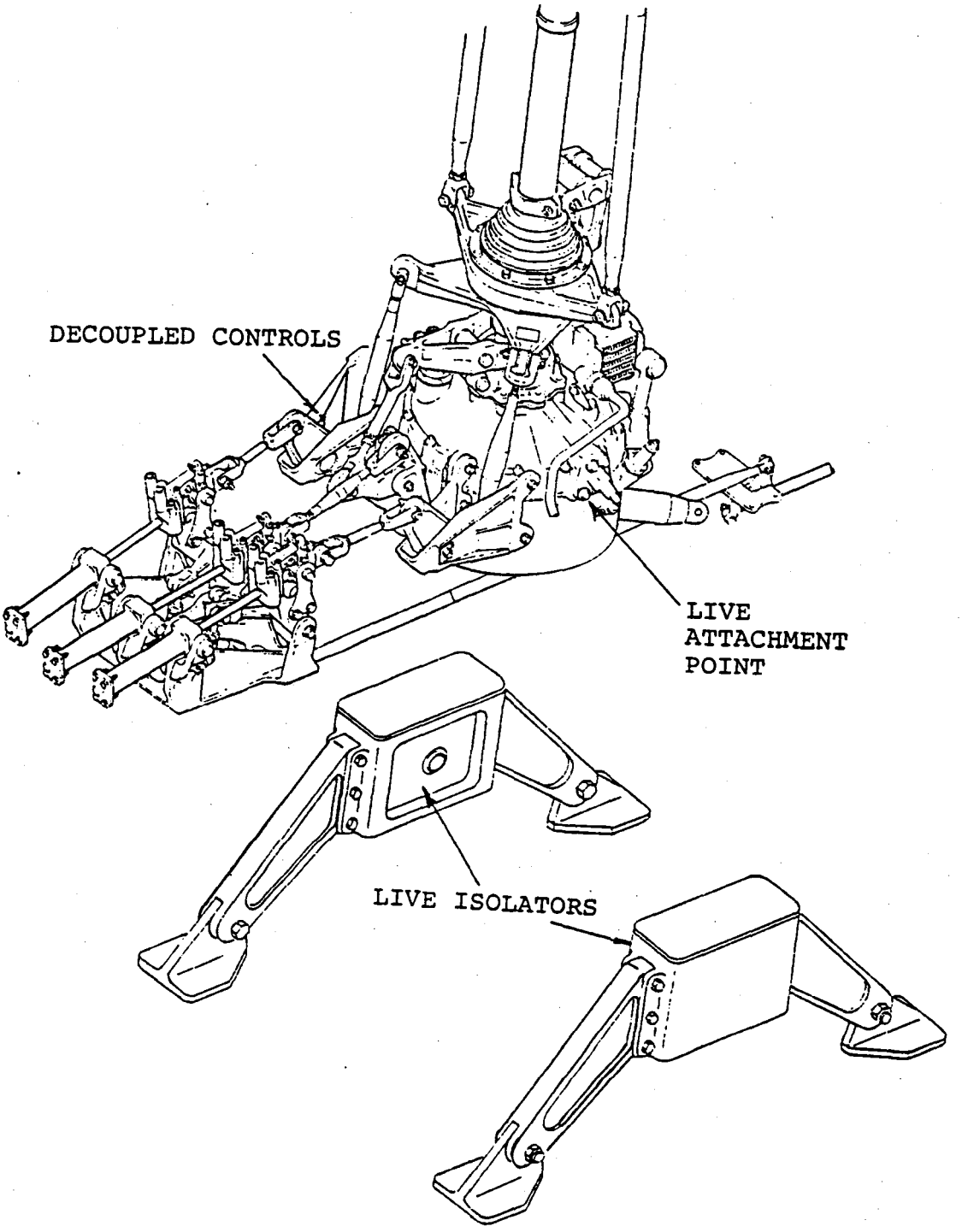


Figure 17. 206B LIVE System.

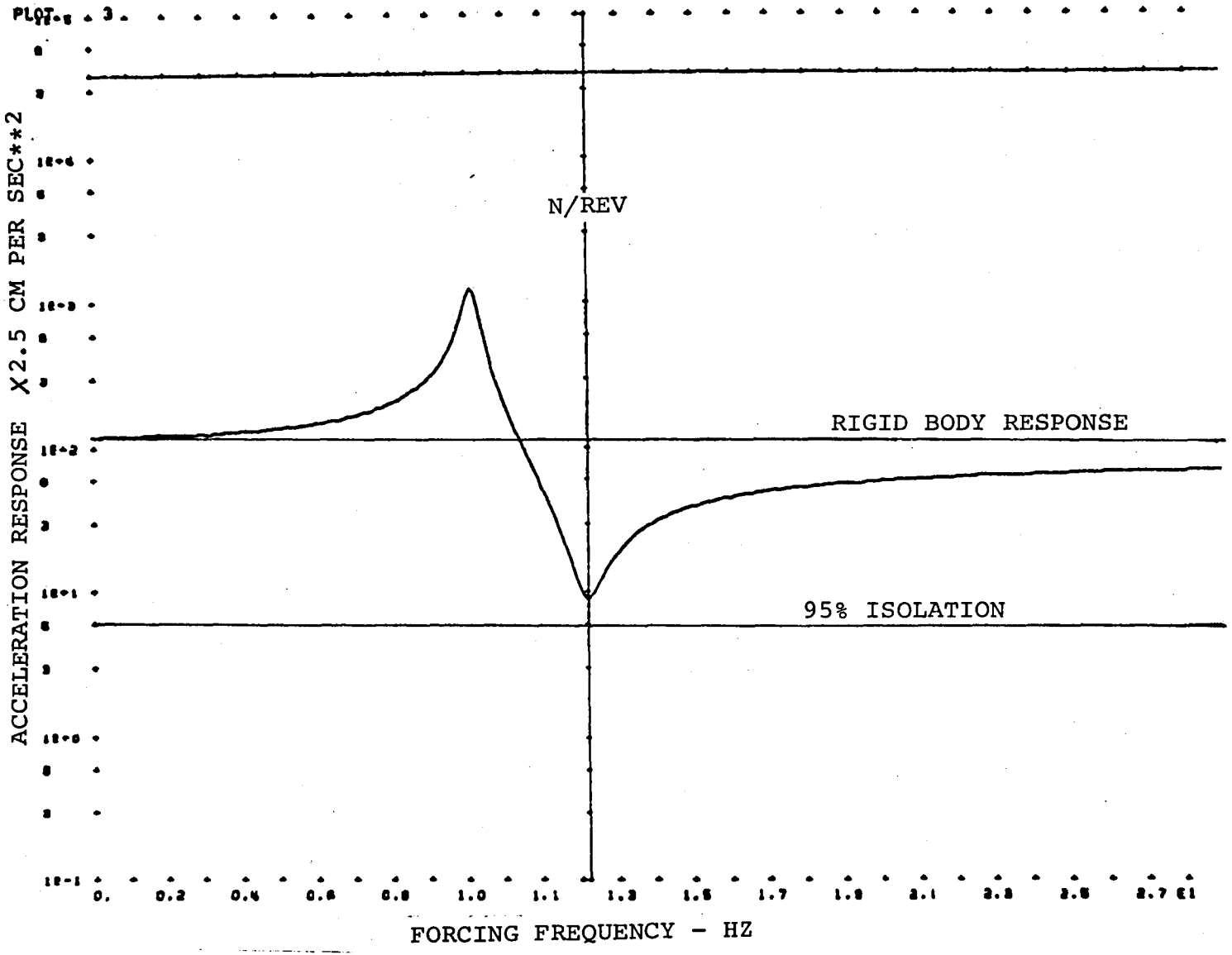


Figure 18. 206B/LIVE C.G. Vertical Response to a 4448N (1000 LB) VERTICAL HUB FORCE

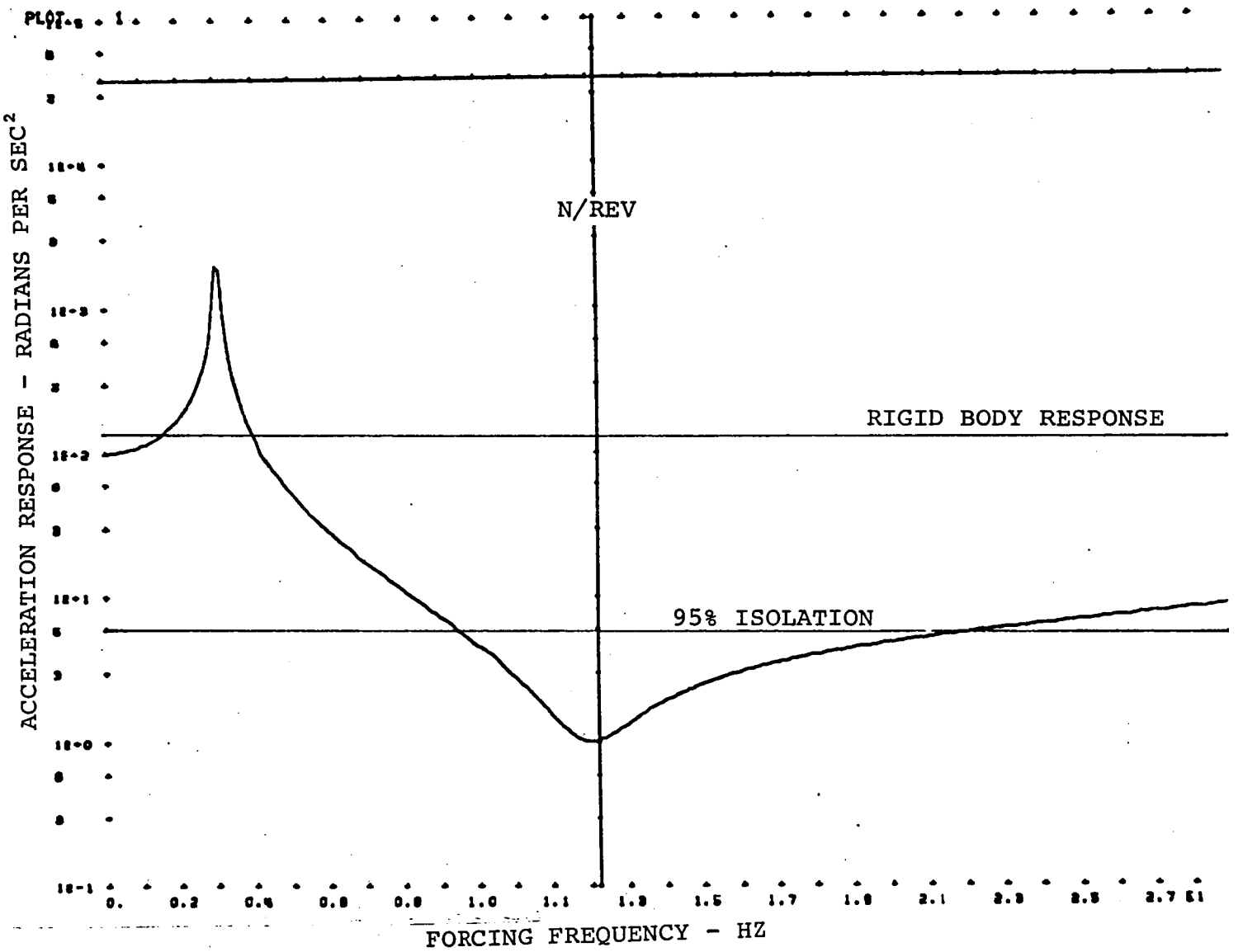


Figure 19. 206B/LIVE C.G. Pitch Response to a 4448N (1000 Lb) Longitudinal Hub Force

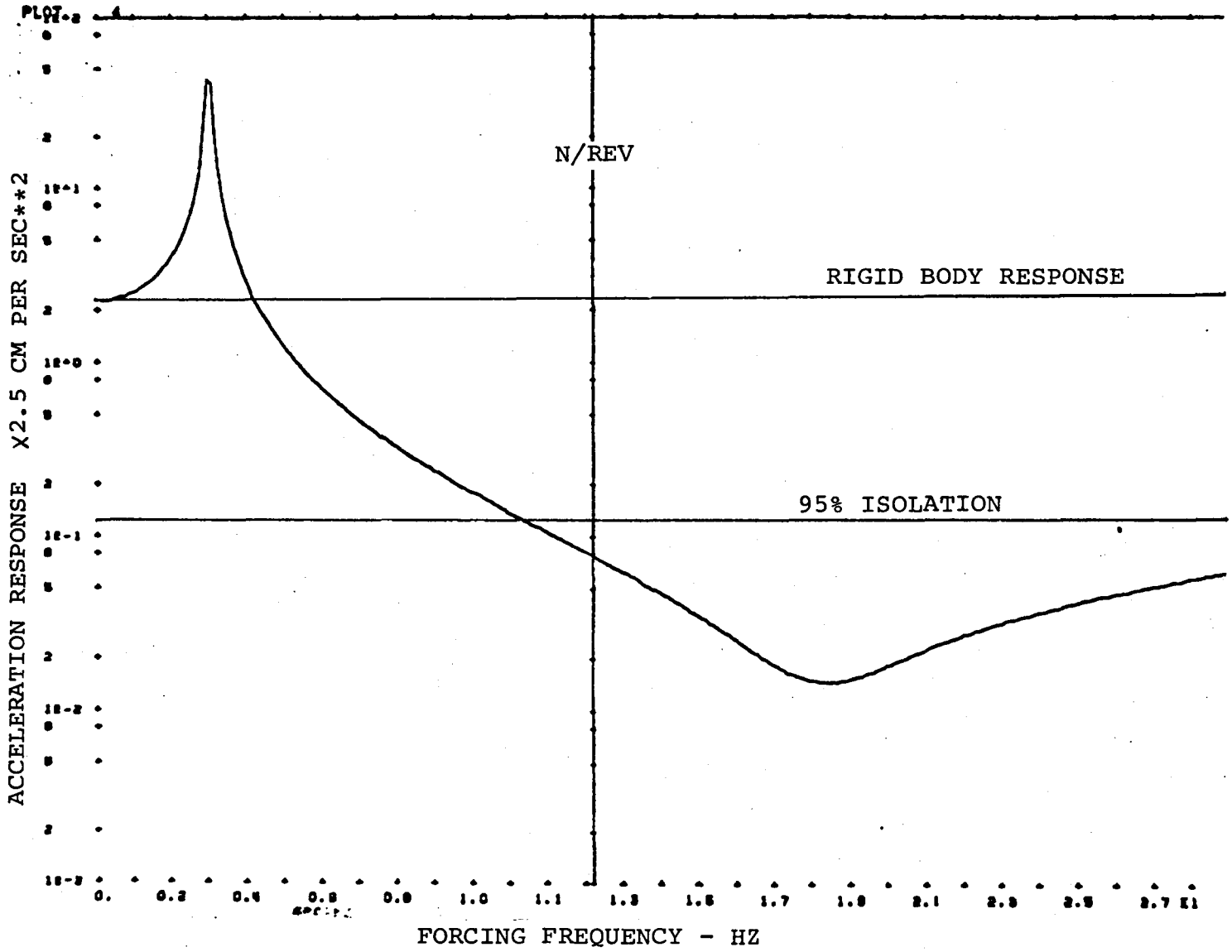


Figure 20. 206B/LIVE C.G. Longitudinal Response to a 4448N (1000 Lb) Longitudinal Hub Force

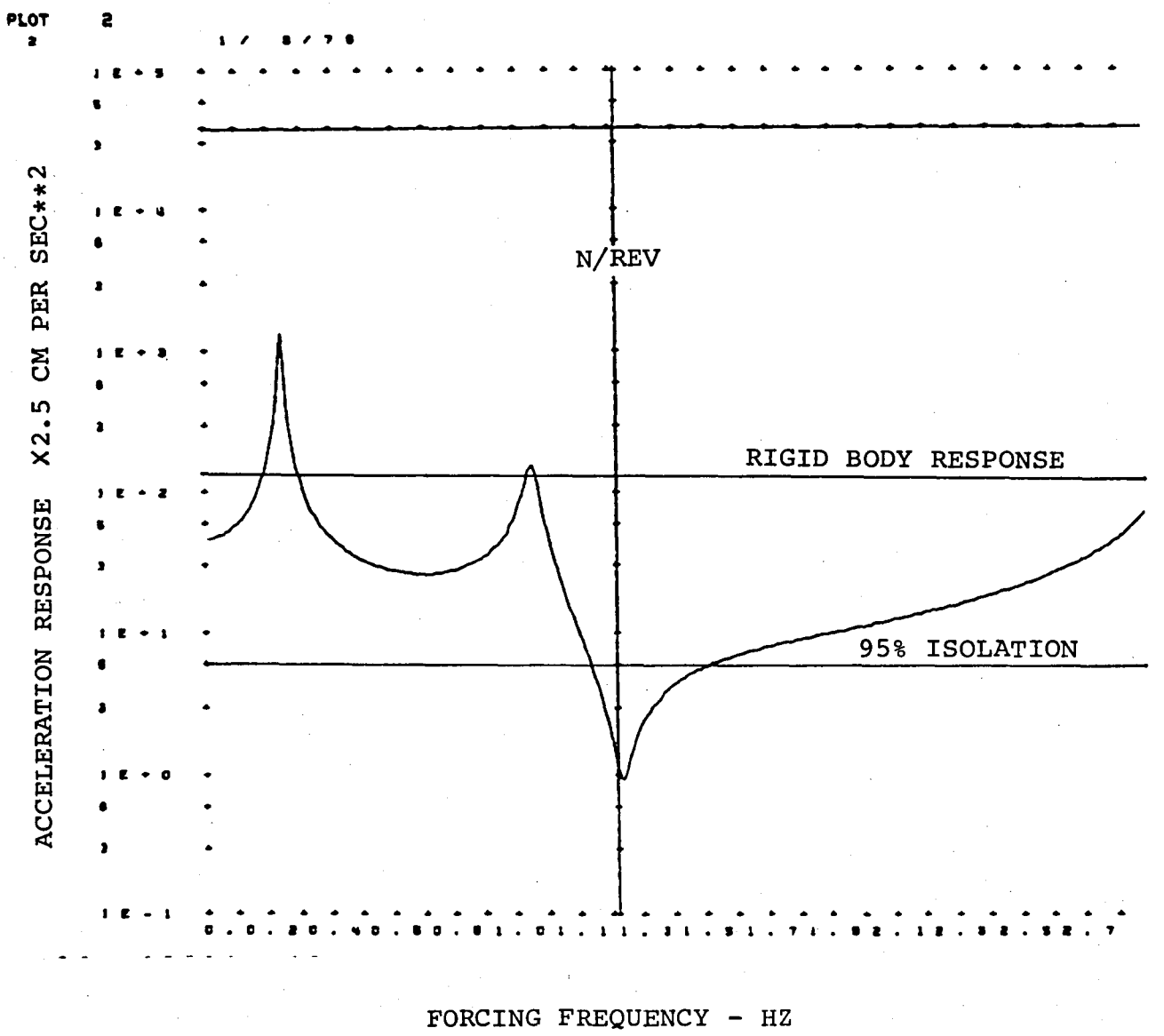


Figure 21. 206B/LIVE C.G. Lateral Response to a 4448N (1000 Lb) Lateral Hub Force

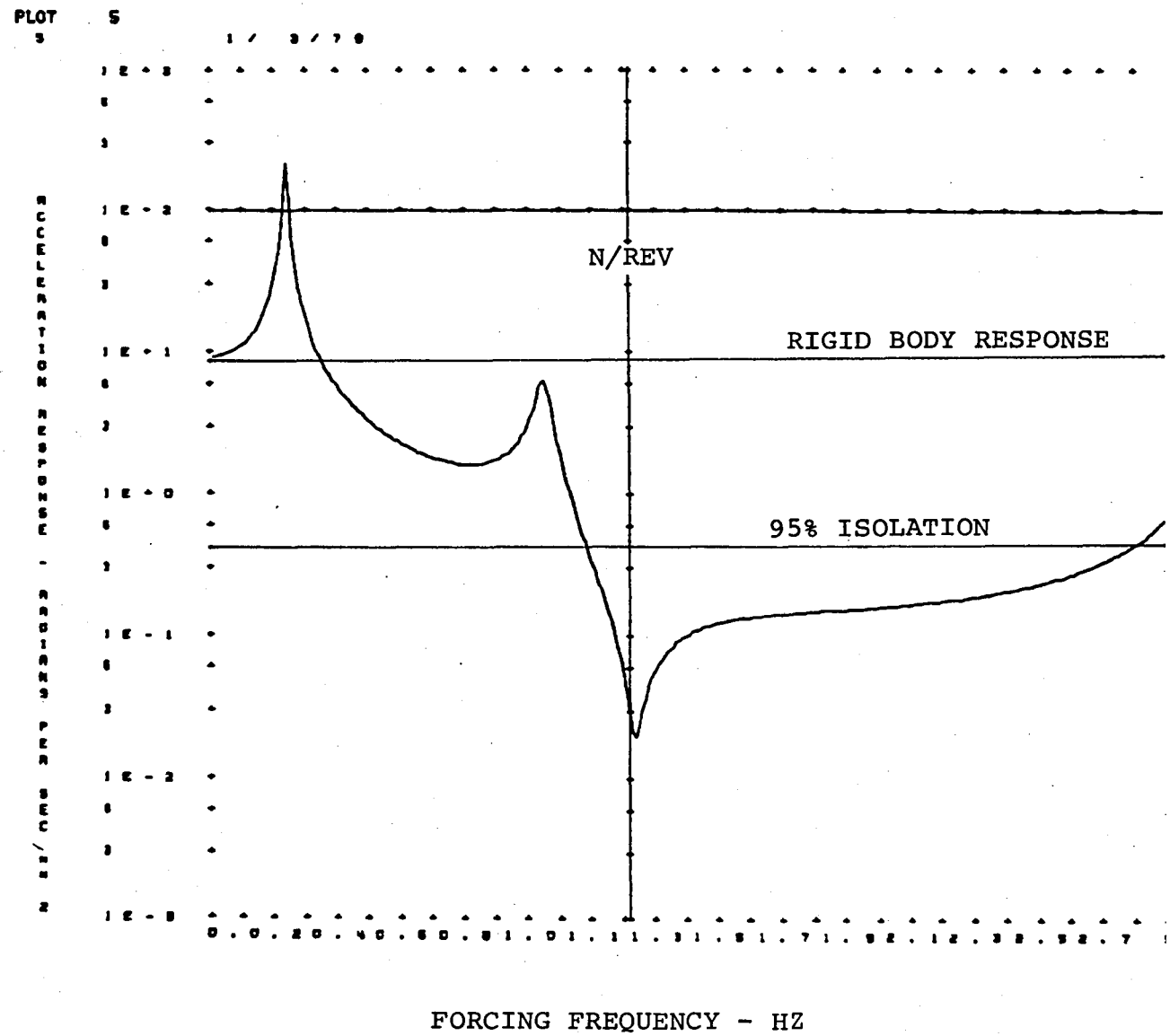


Figure 22. 206B/LIVE C.G. Roll Response to a 4448N (1000 Lb) Lateral Hub Force

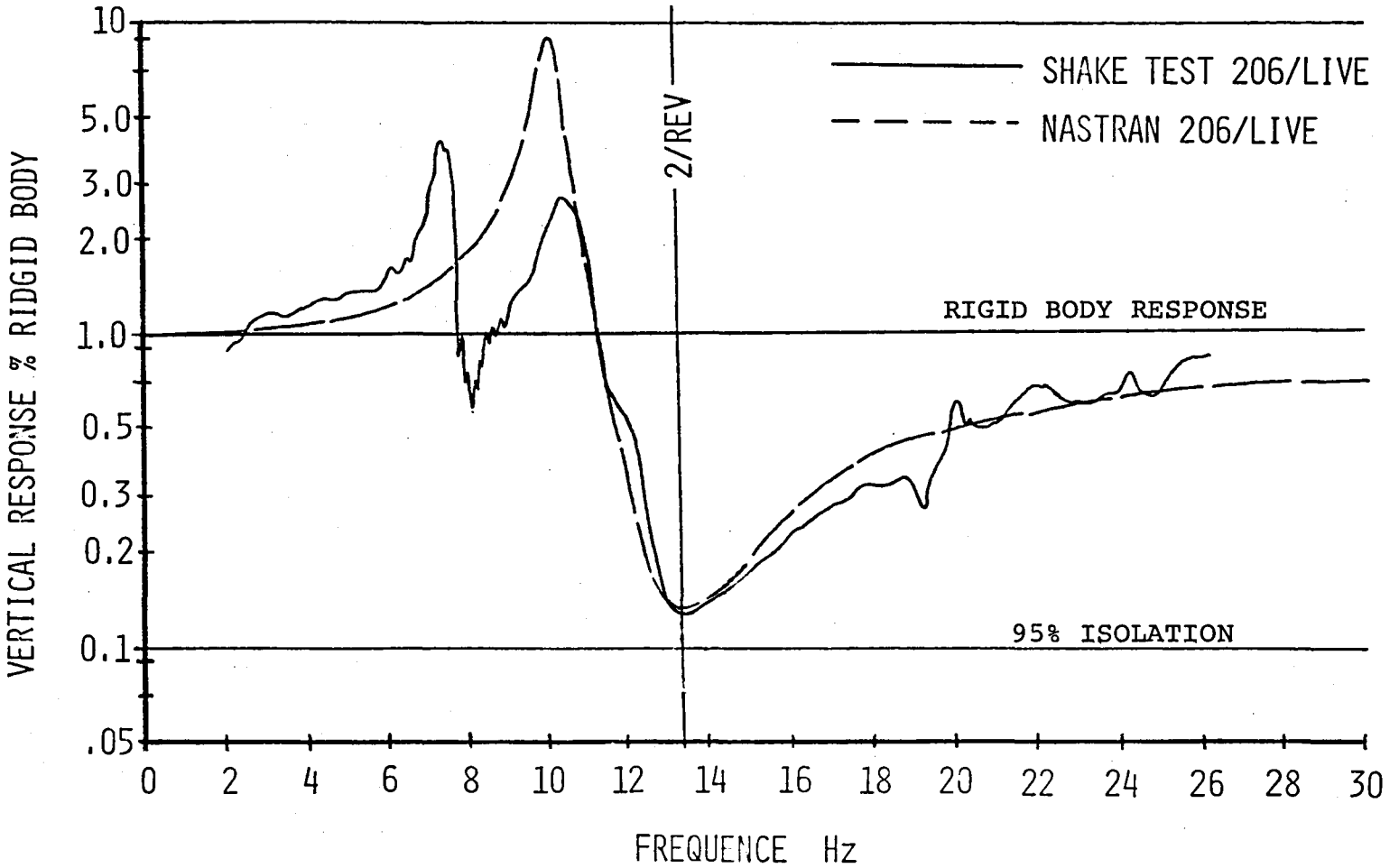


Figure 23. Comparison of NASTRAN and Vibration Test Response to a Vertical Excitation at the Hub

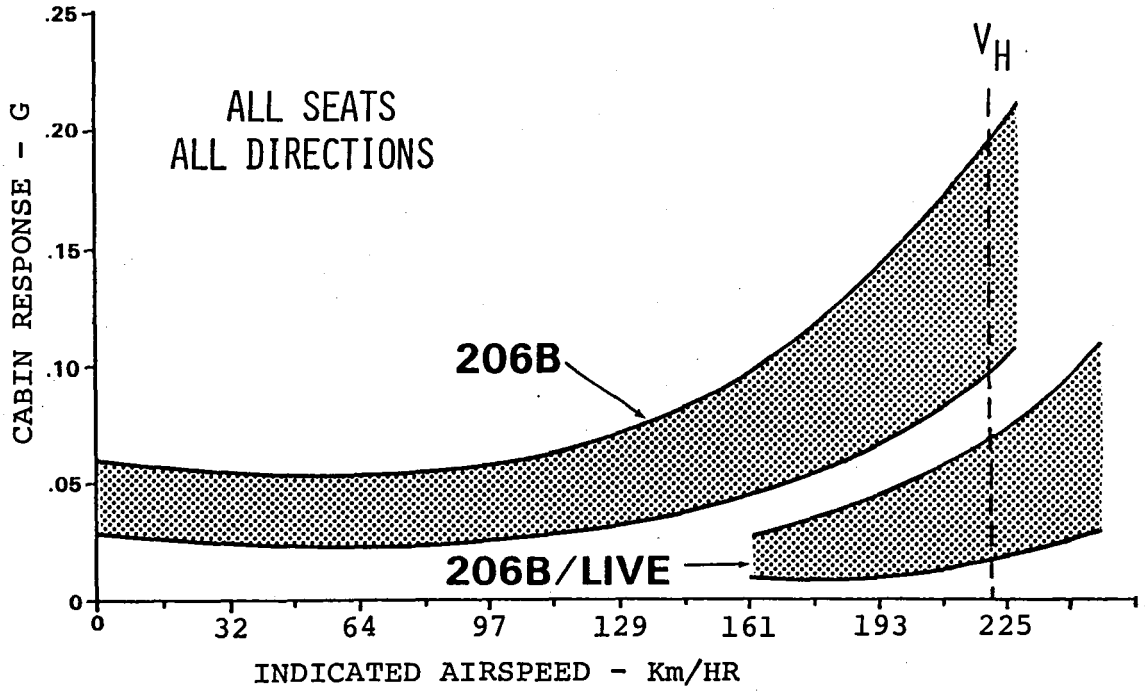


Figure 24. Vibration Comparison of a 206B with and without the LIVE System.

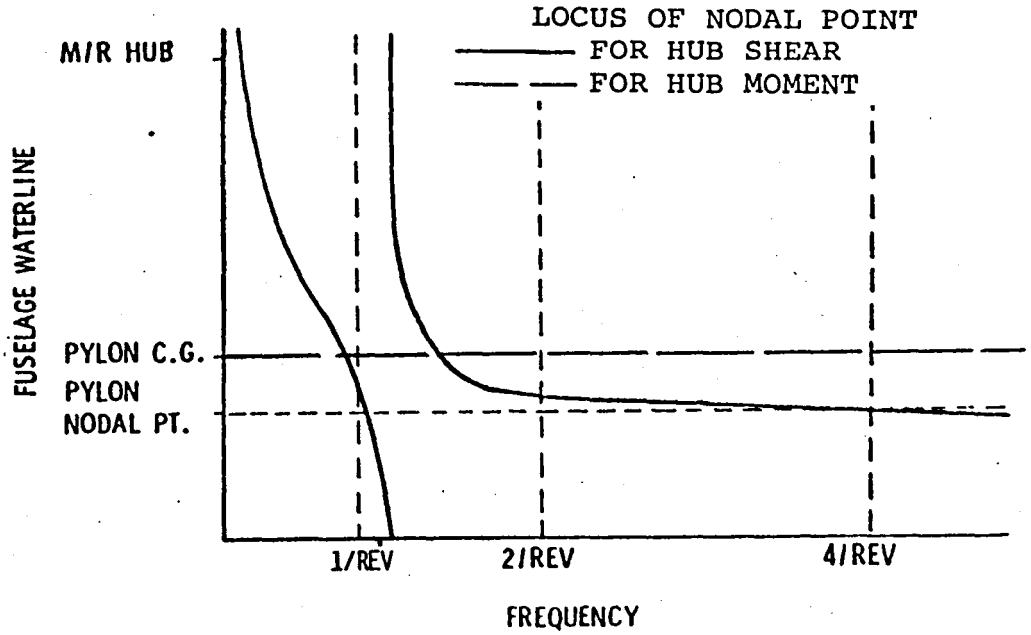


Figure 25. Locus of Transmission Nodal Point Vs. Frequency For Rigid Body Transmission

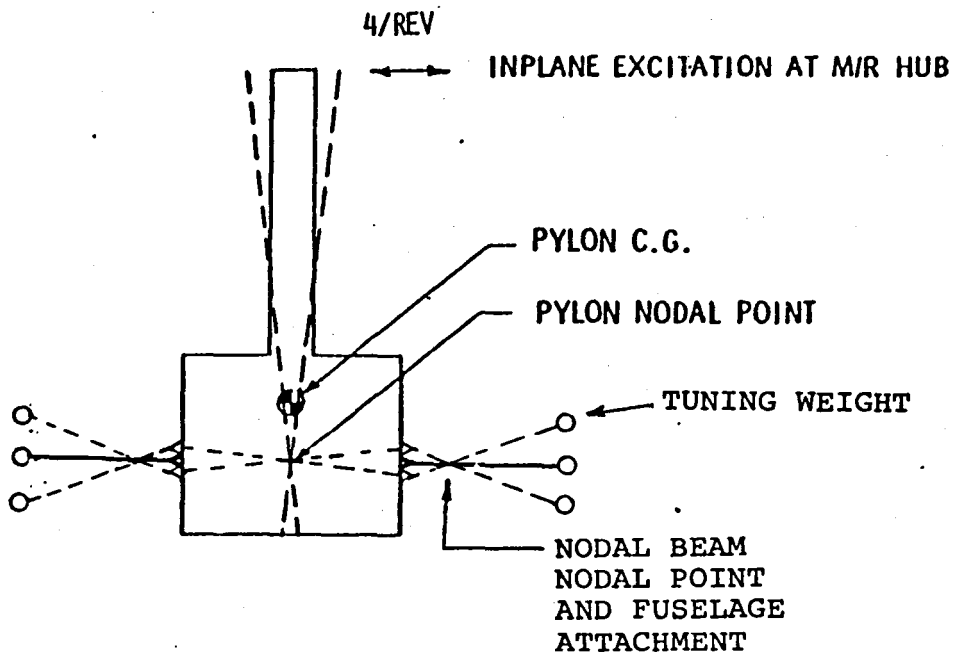


Figure 26. Principle of Multi-Degree-of-Freedom Isolation System

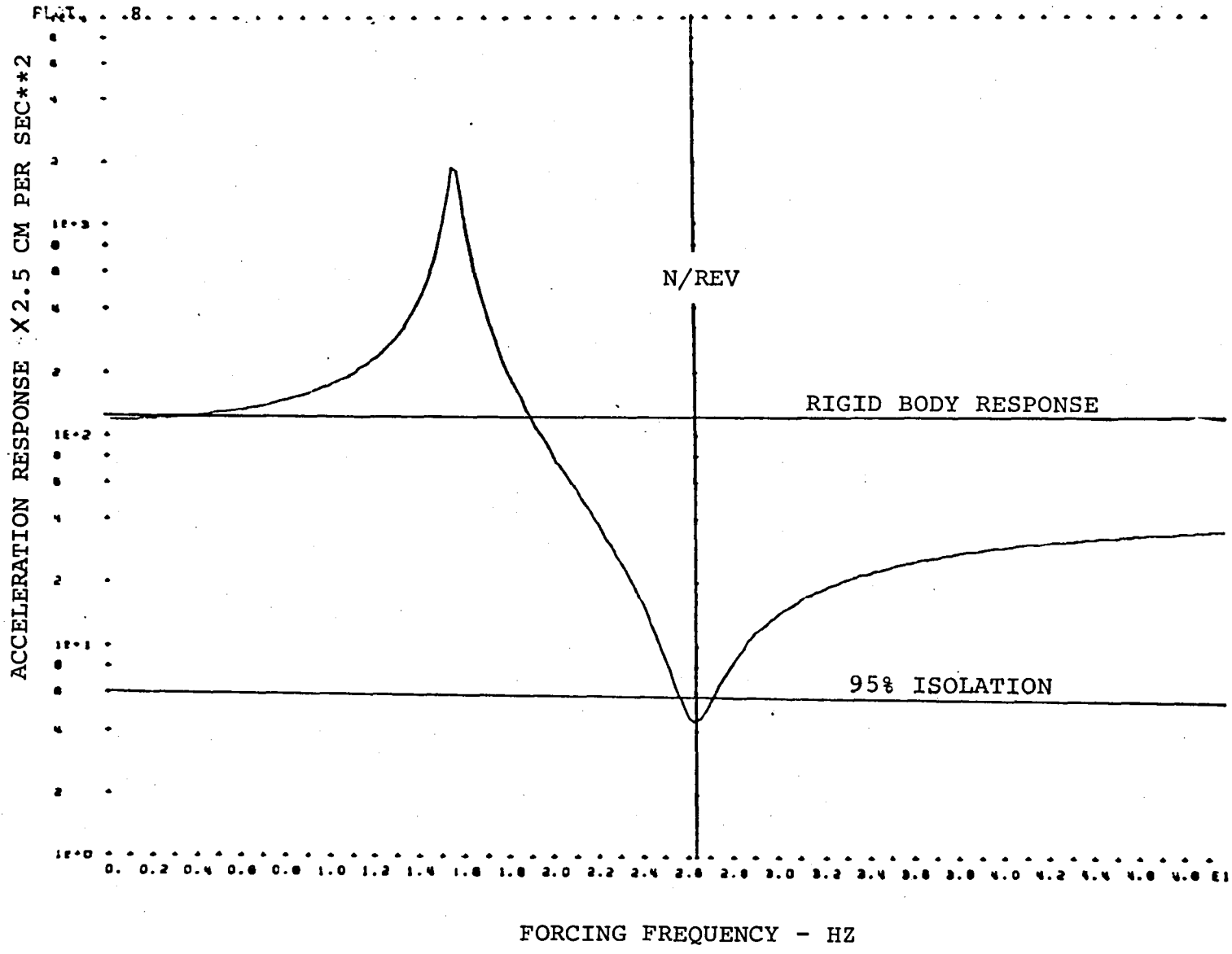


Figure 27. C.G. Vertical Response to a Vertical Shear

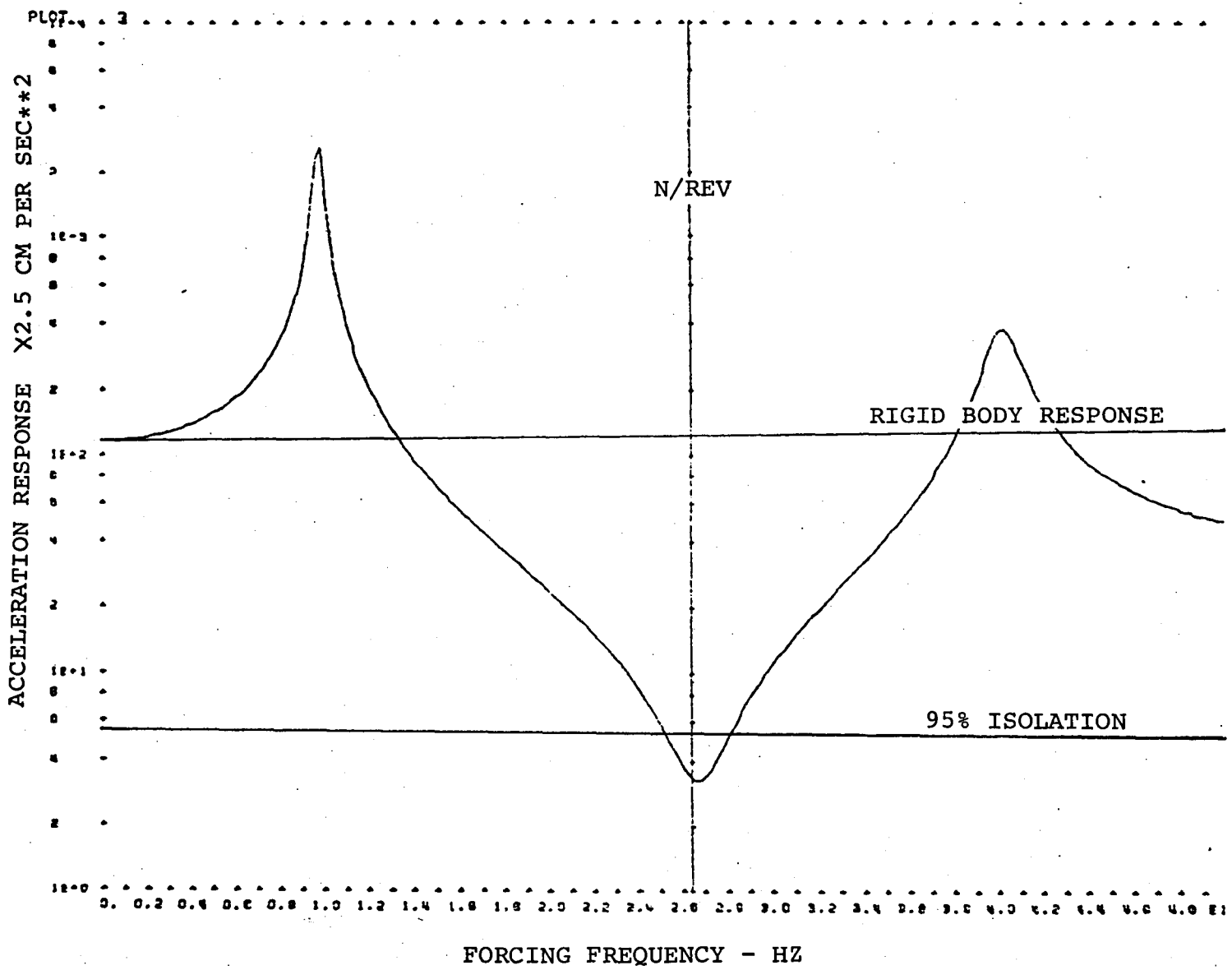


Figure 28. C.G. Longitudinal Response to a Pitch Moment and a Longitudinal Shear

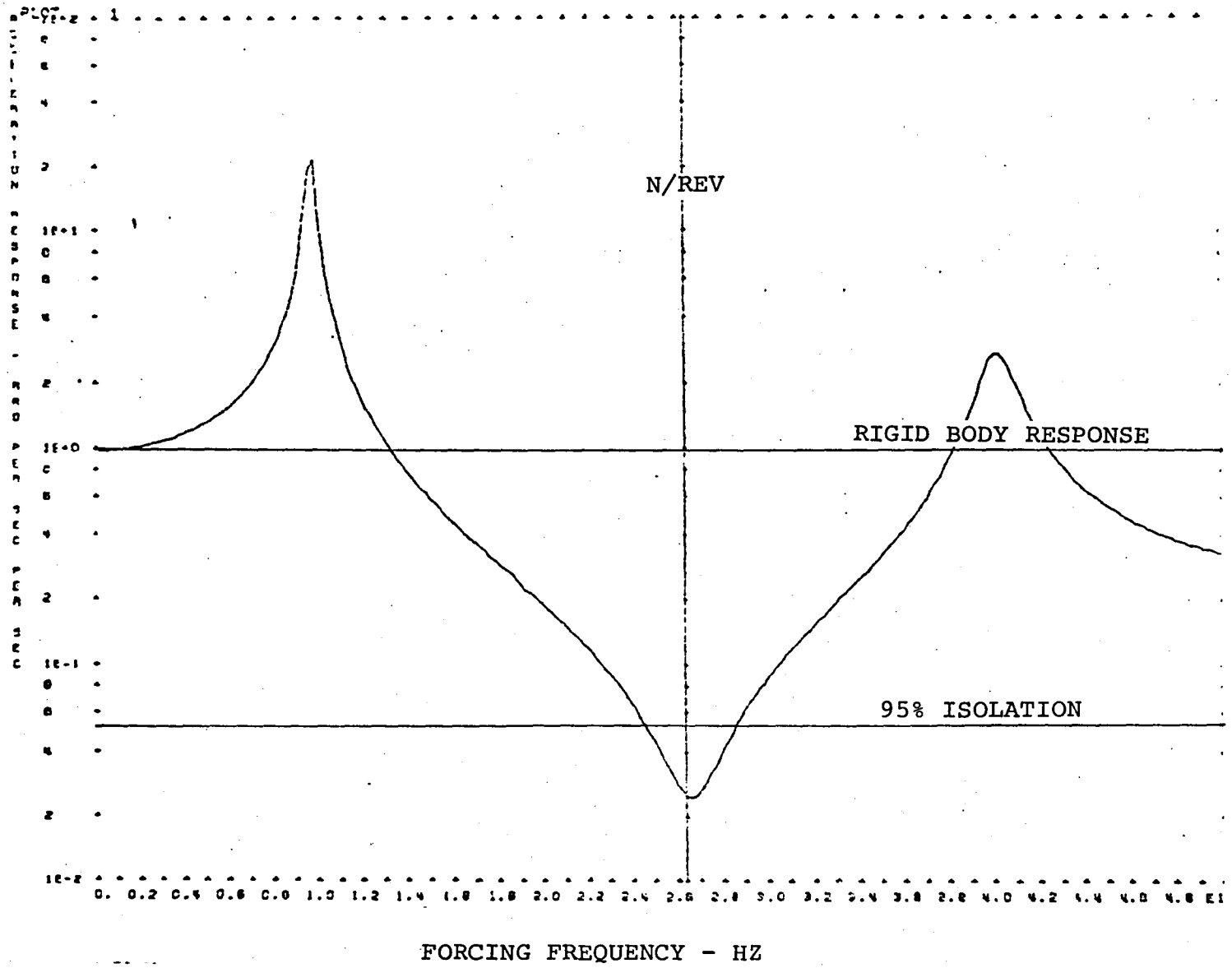


Figure 29. C.G. Pitch Response to a Pitch Moment and a Longitudinal Shear

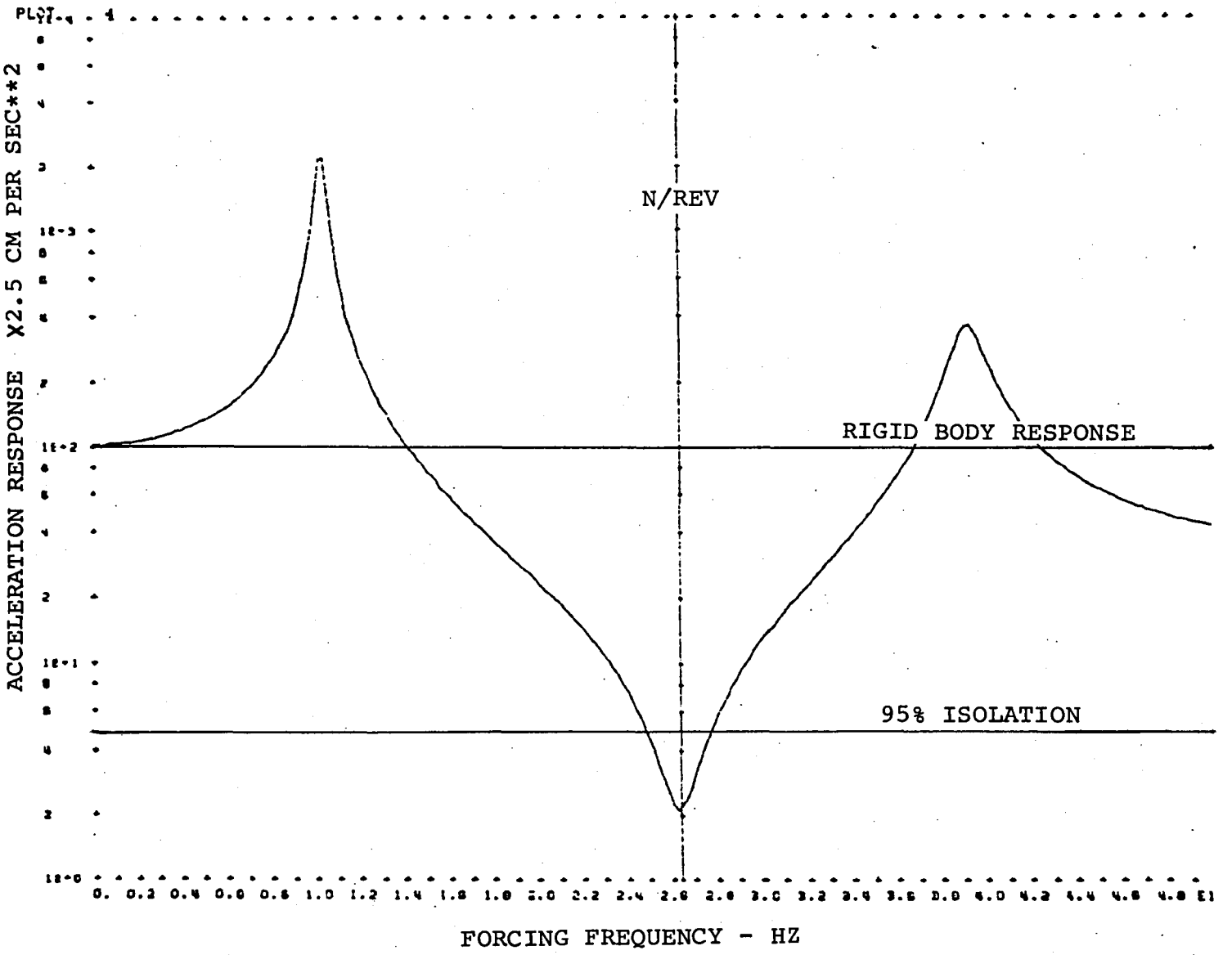


Figure 30. C.G. Lateral Response to a Roll Moment and a Lateral Shear

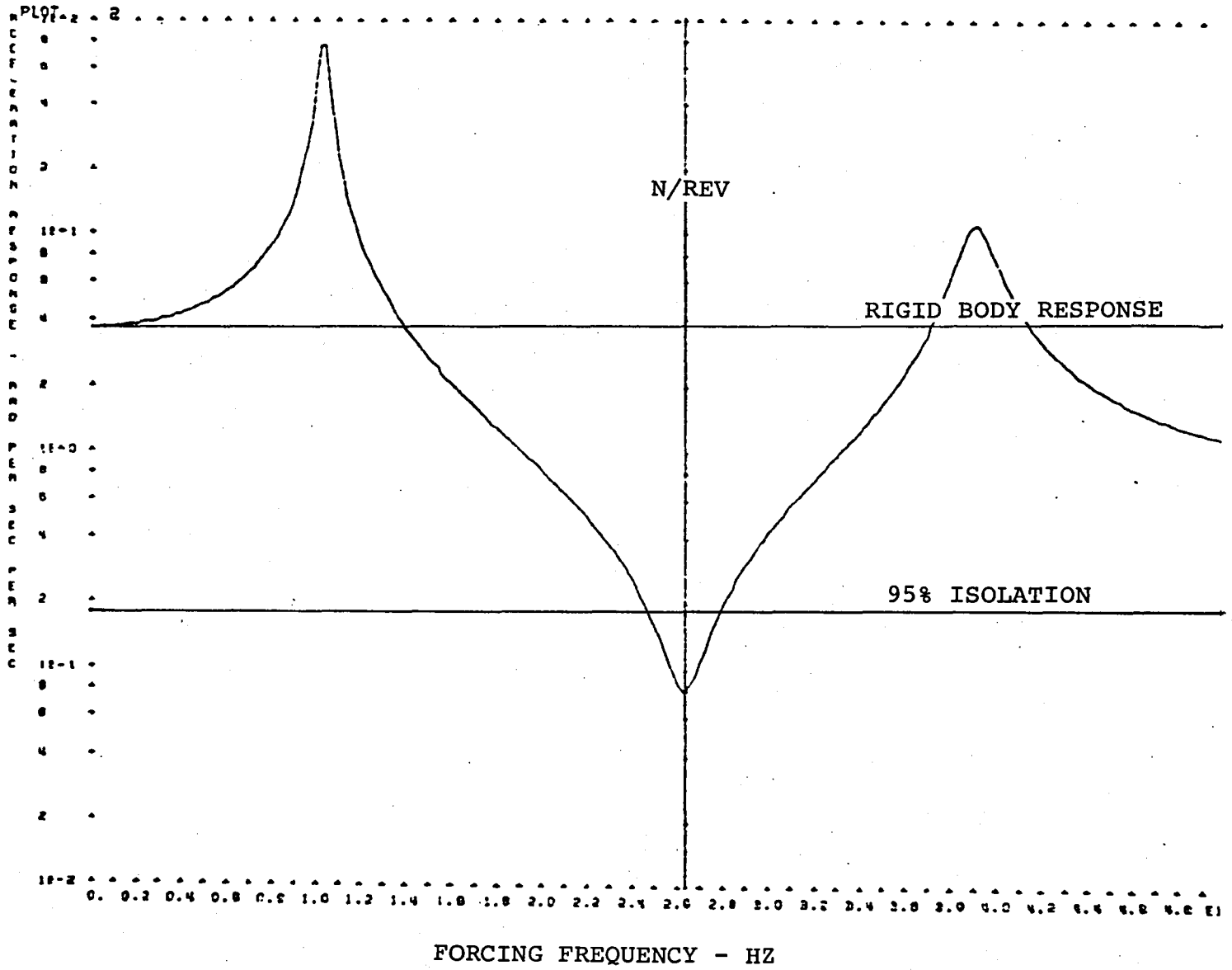


Figure 31. C.G. Roll Response to a Roll Moment and a Lateral Shear

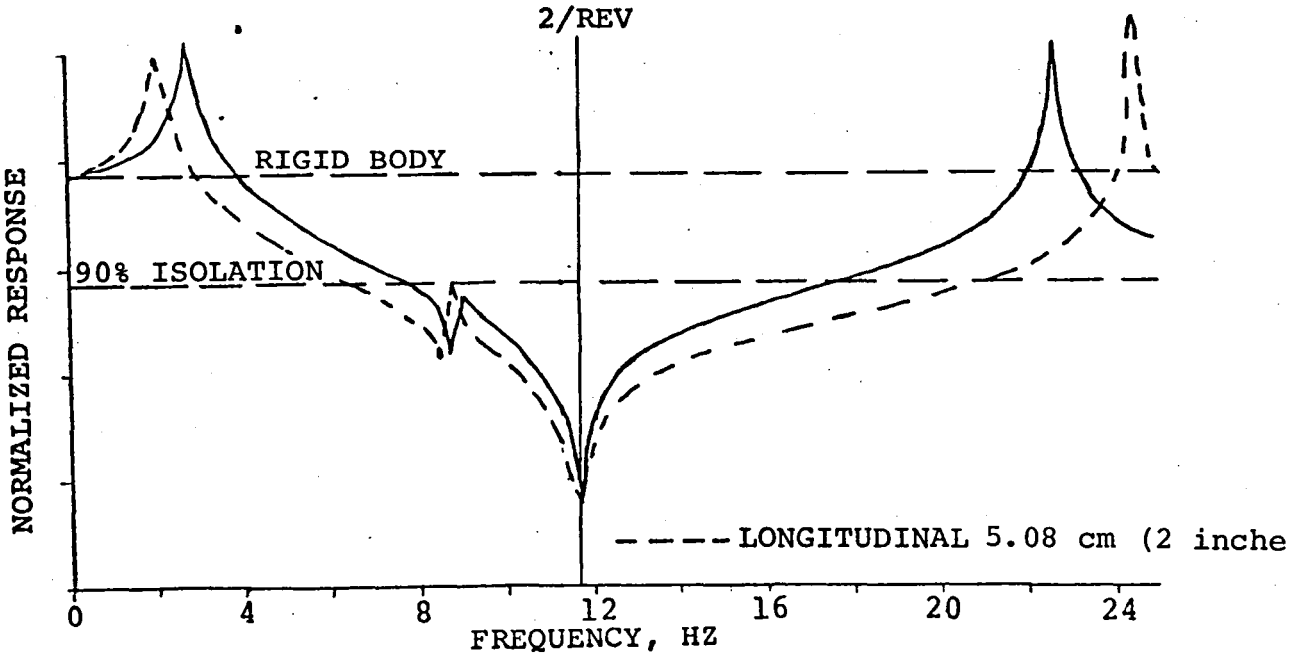


Figure 32. The Effect of Nodal Beam Attachment Stationline Upon Pitch Response To Longitudinal Excitation

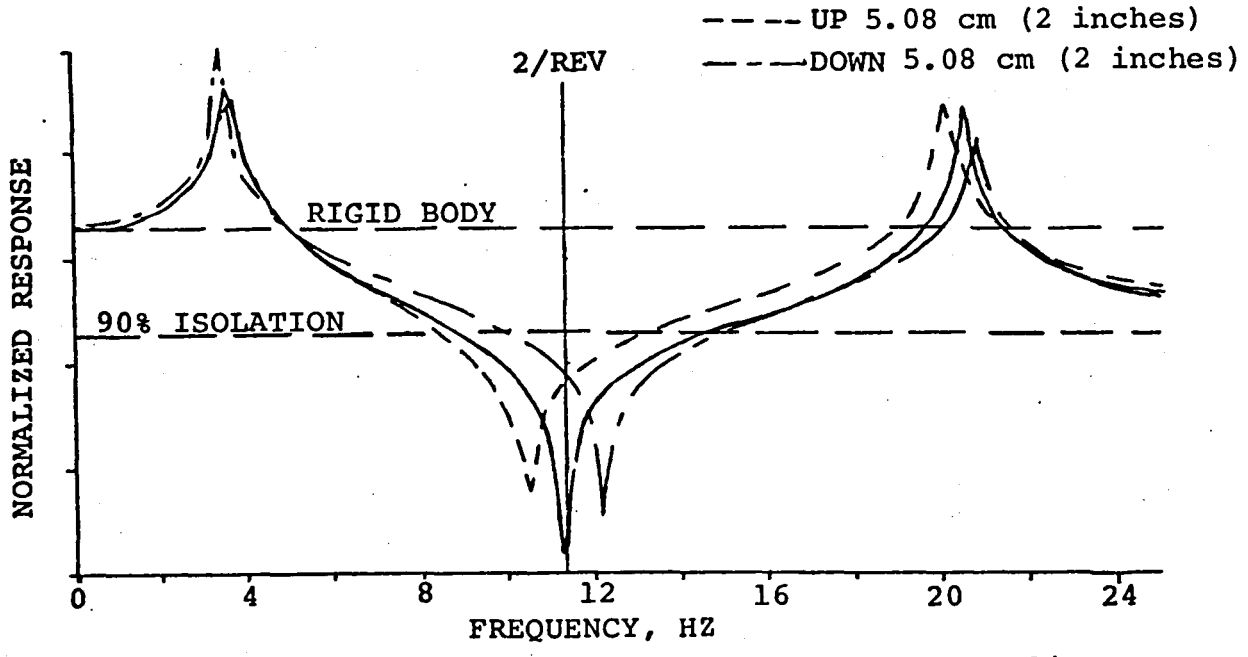


Figure 33. The Effect of Nodal Beam Attachment Waterline Upon Pitch Response To Longitudinal Excitation

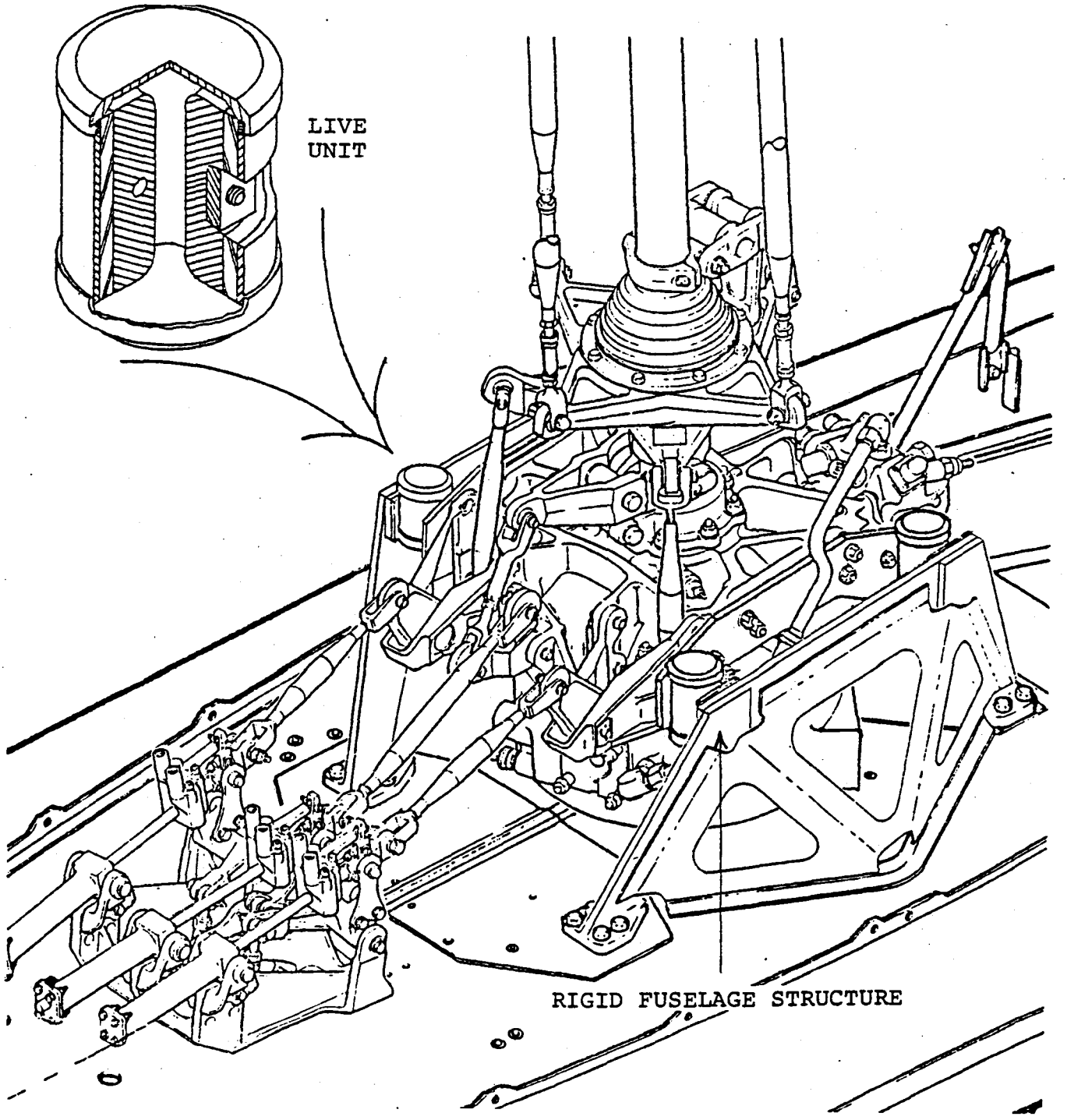


Figure 34. Four LIVE Plus Pylon Nodalization.

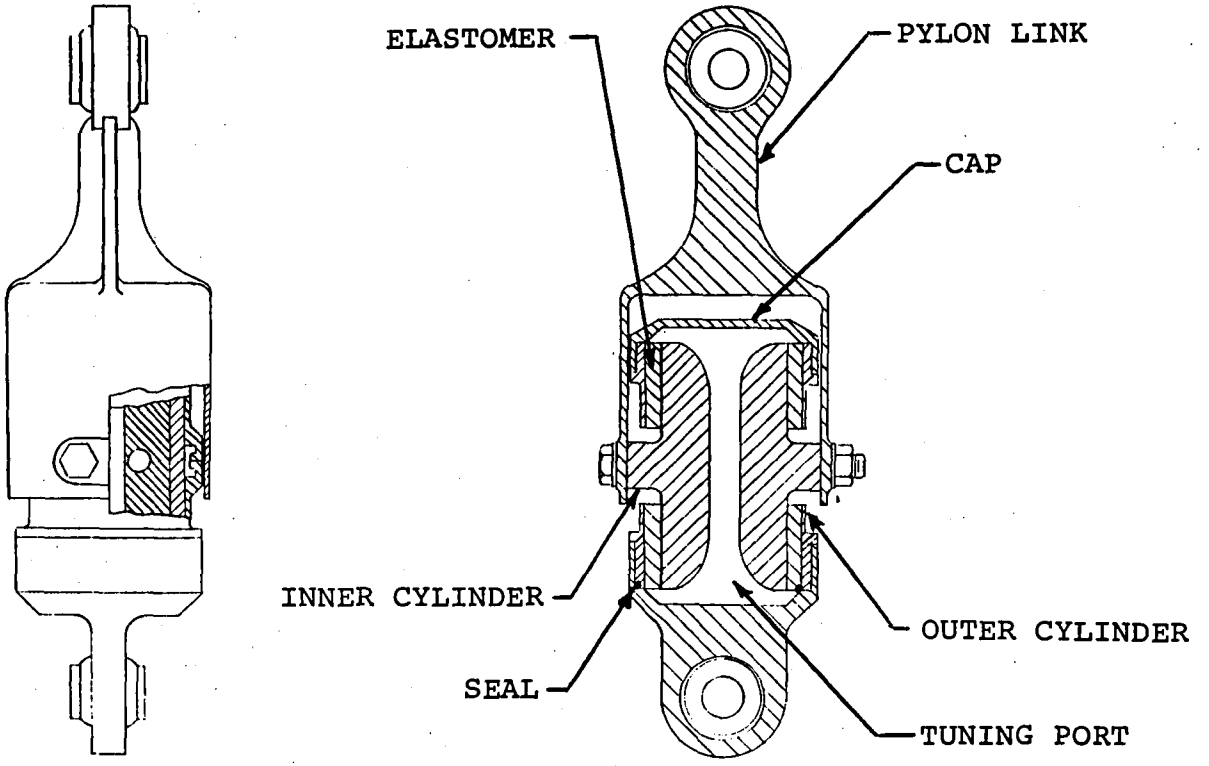


Figure 35. LIVE Isolator in a Pinned-Pinned Link.

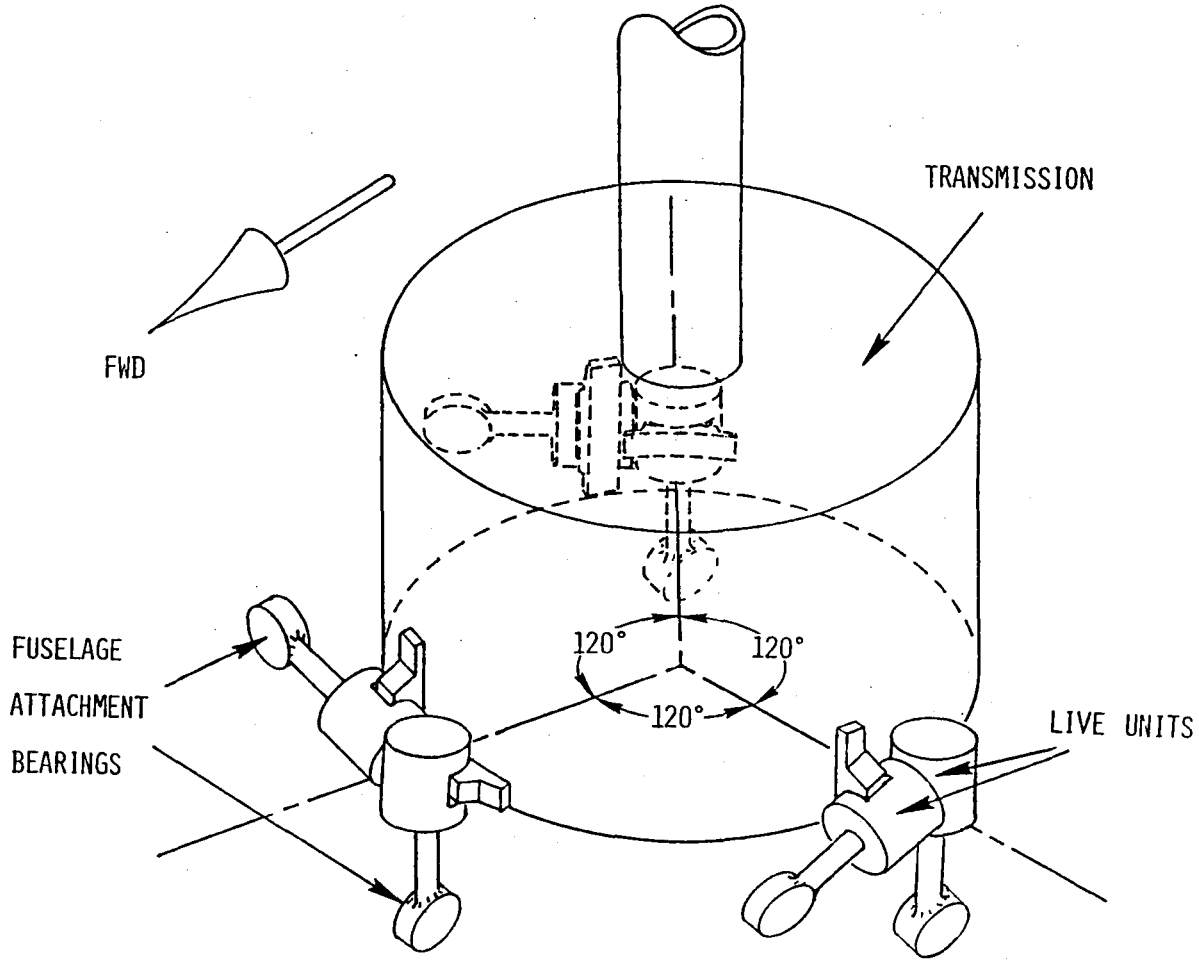


Figure 36. Total Main Rotor Isolation System Using Six LIVE Units for Pylons Having High Nodal Points

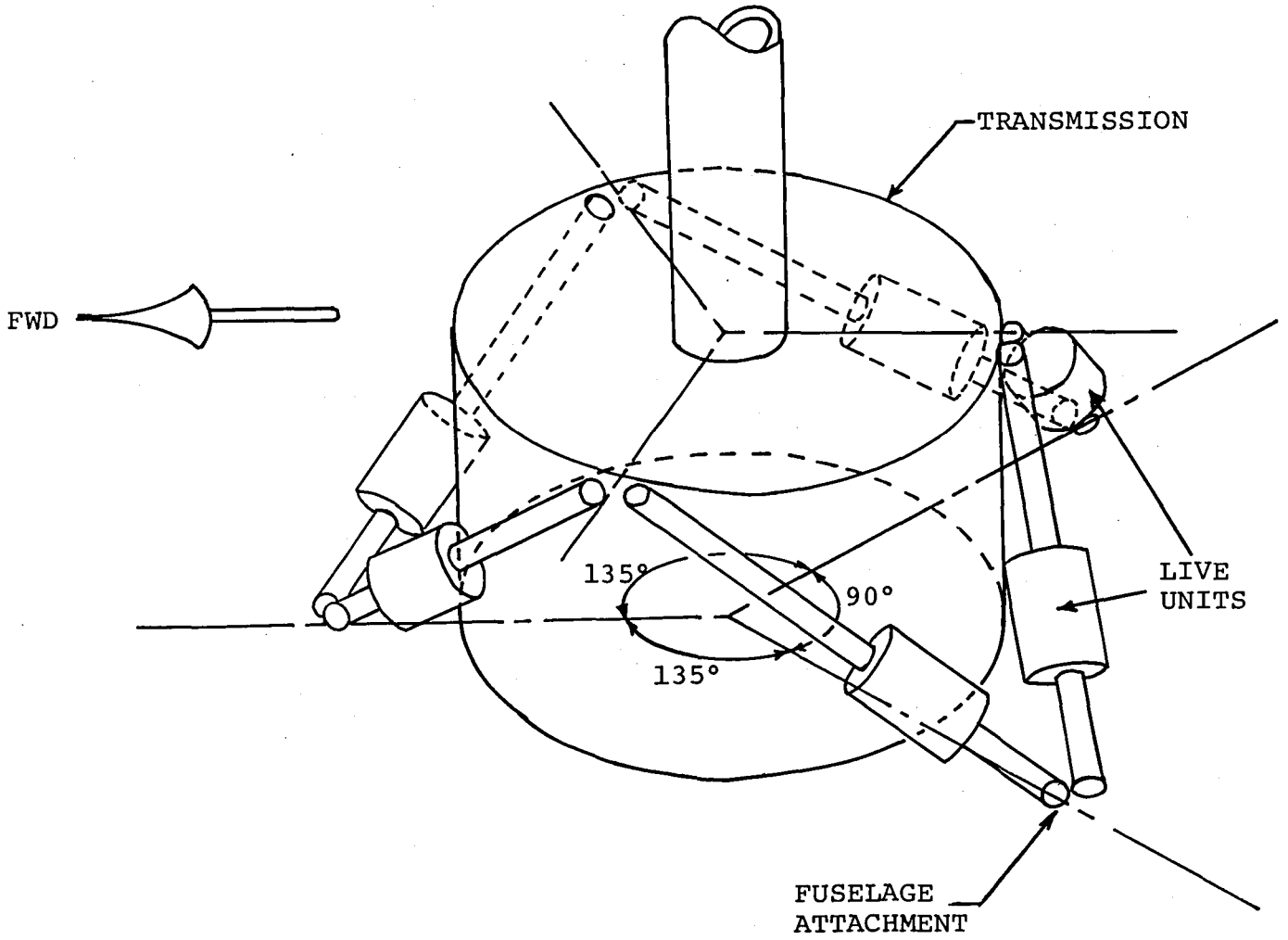


Figure 37. Total Main Rotor Isolation System Using Six LIVE Units for Pylons Having High Nodal Points

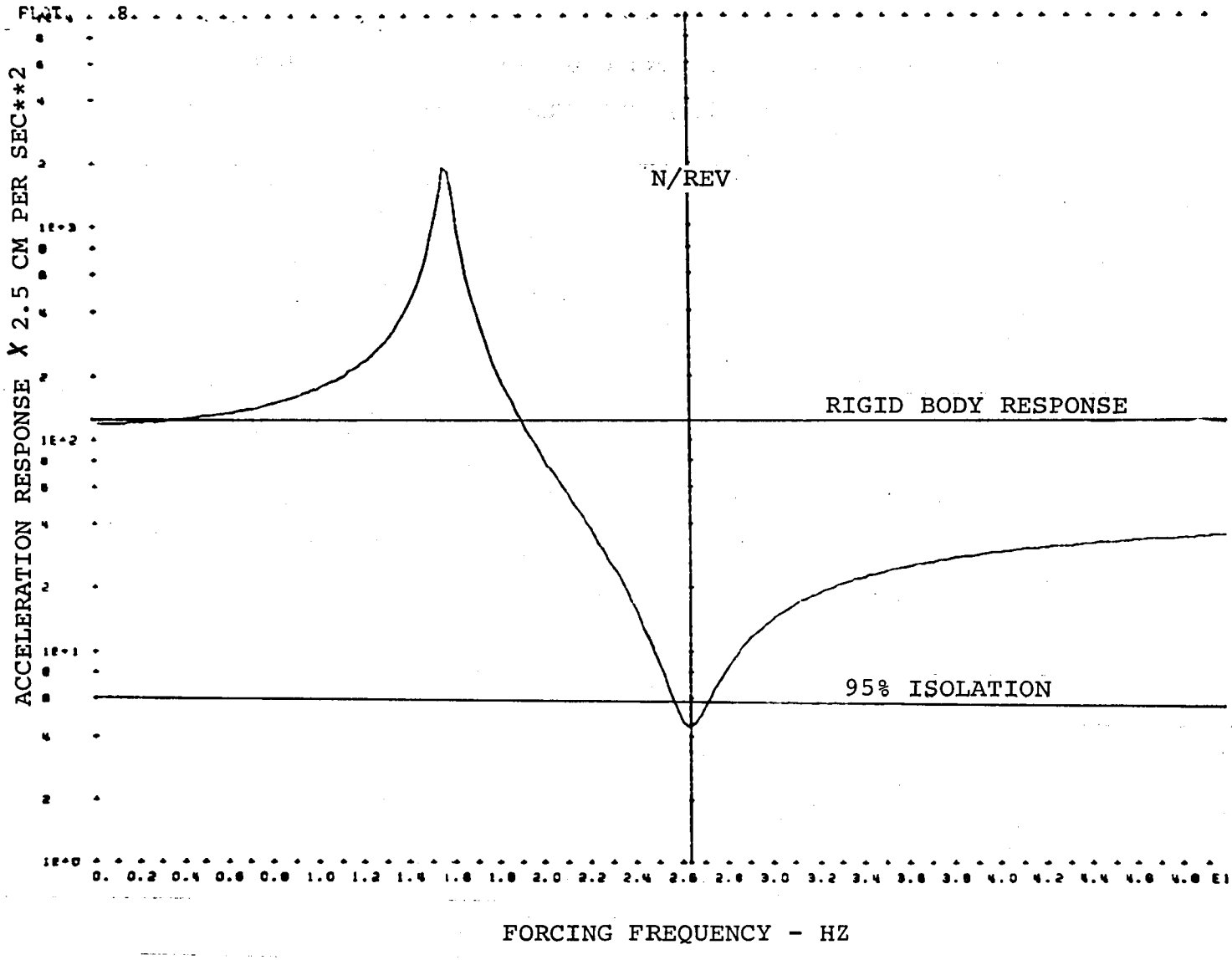


Figure 38. C.G. Vertical Response to a Hub Vertical Shear.

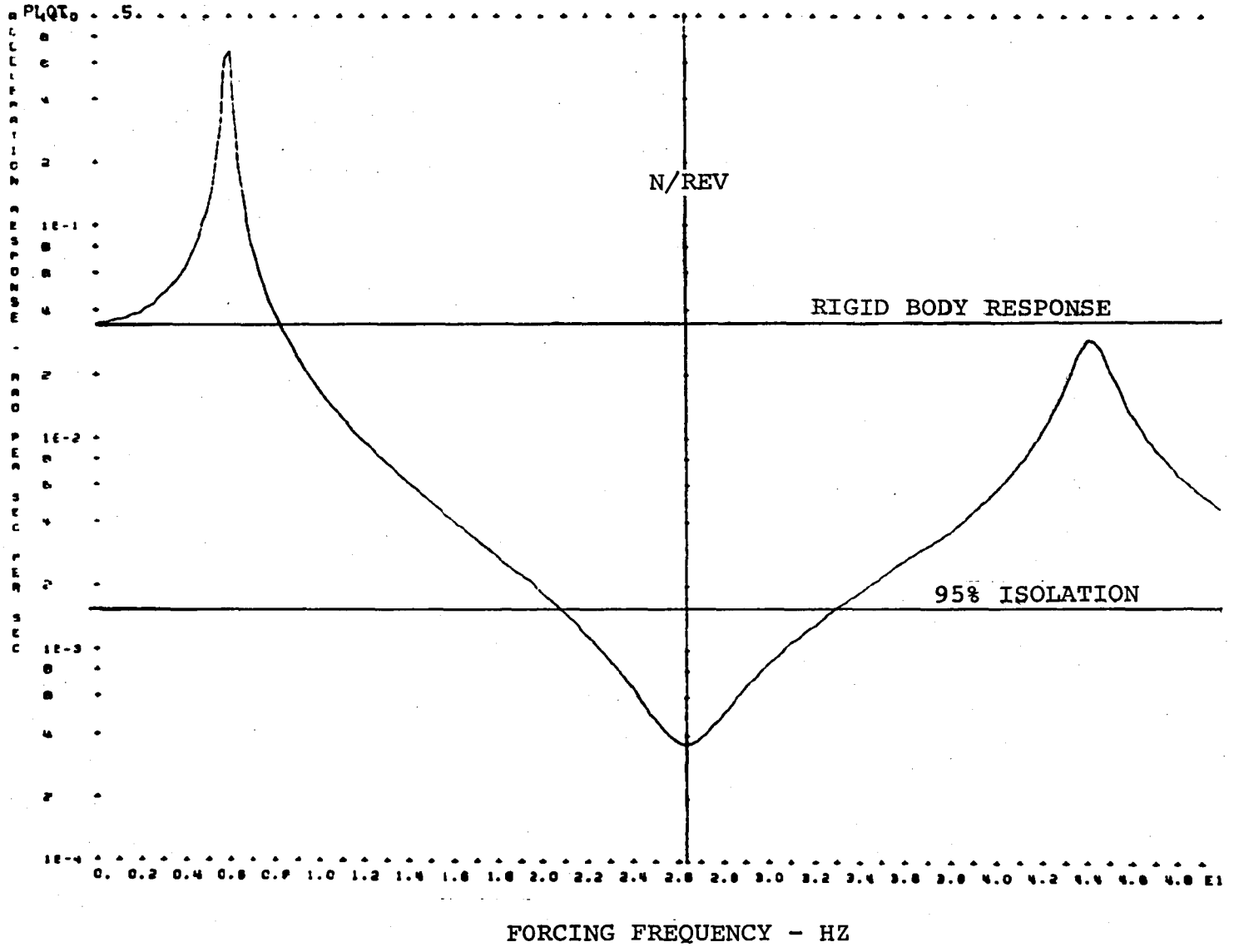


Figure 39. C.G. Yaw Response to a Hub YAW Moment.

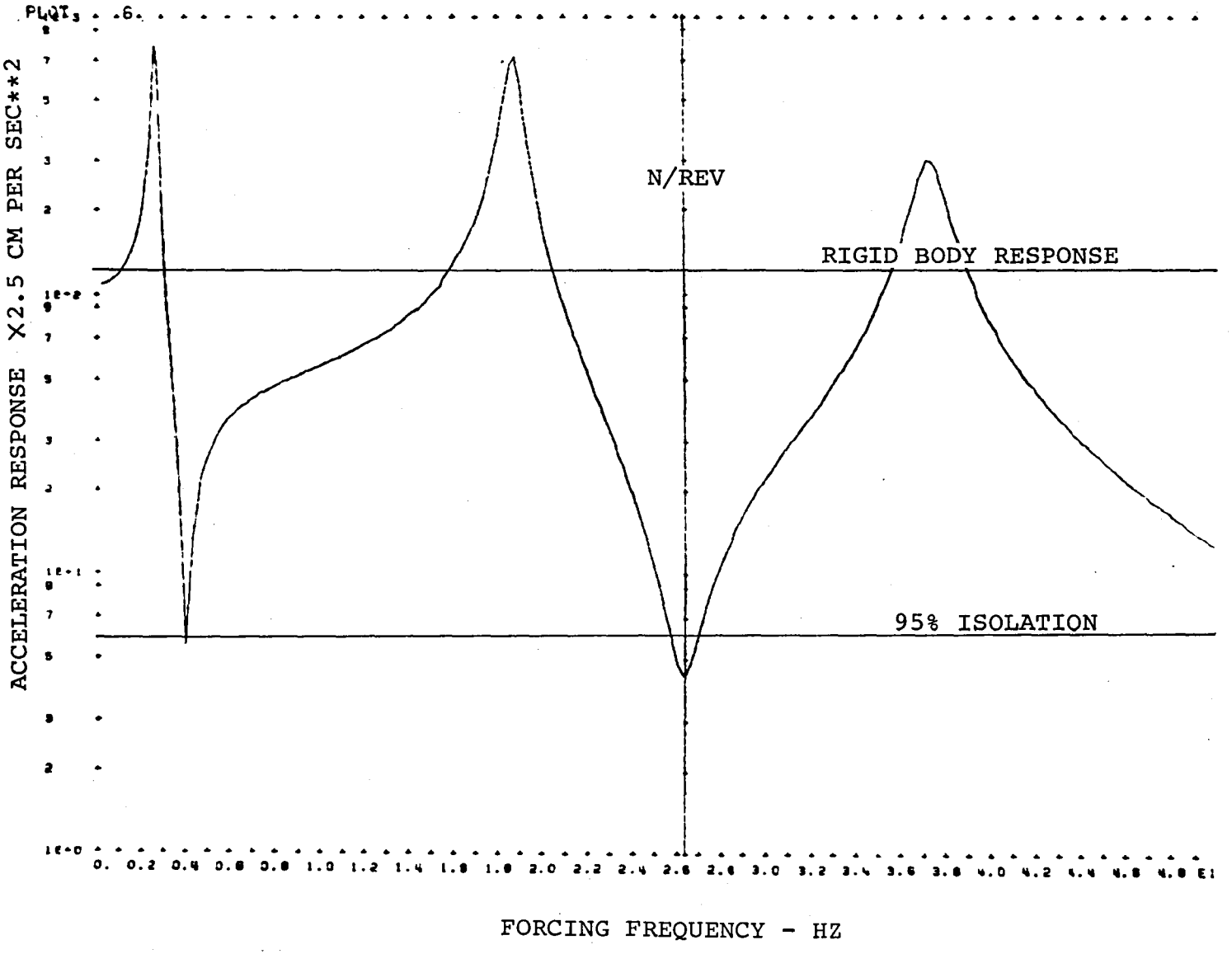


Figure 40. C.G. Longitudinal Response to a Hub Longitudinal Shear.

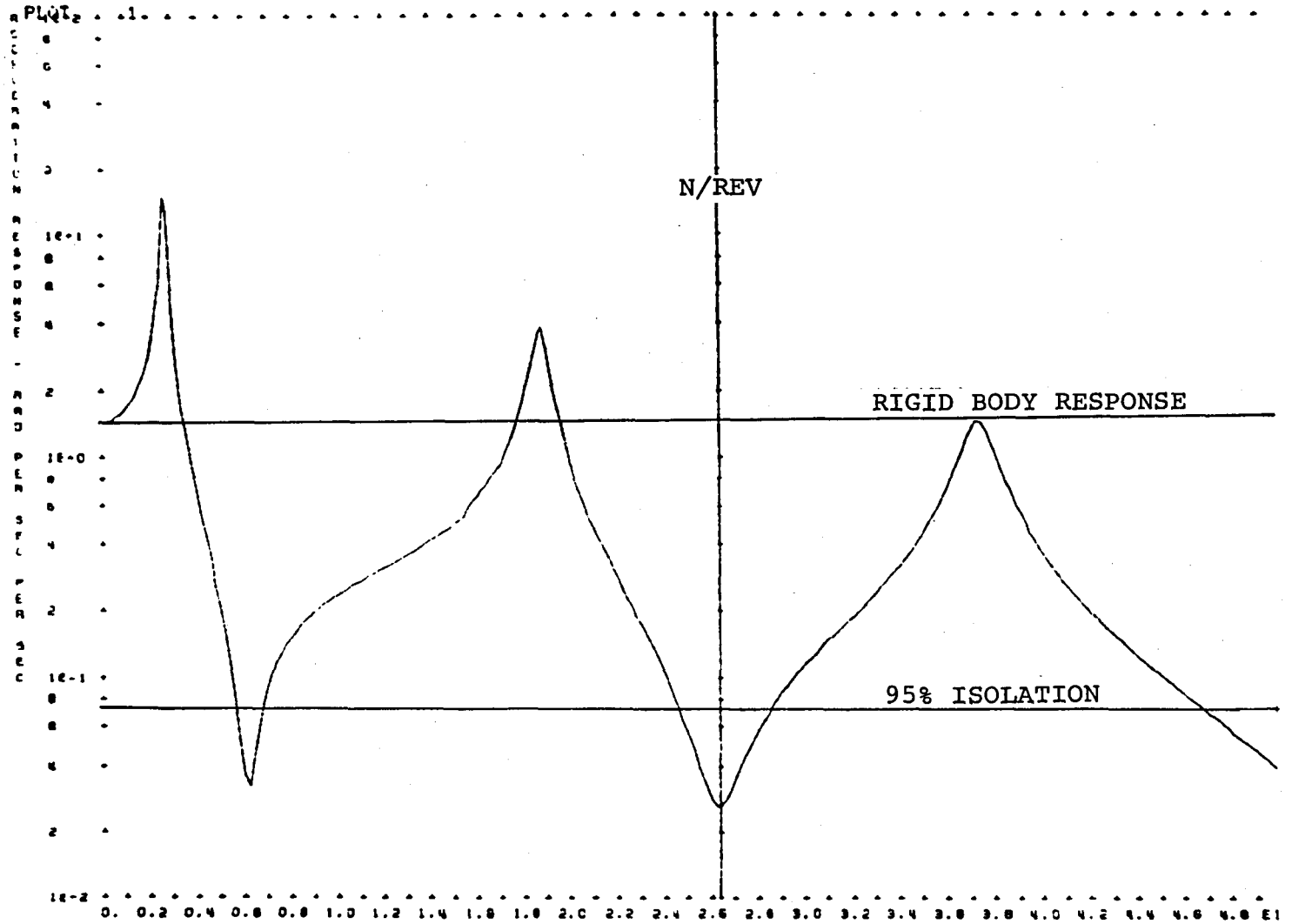


Figure 41. C.G. Pitch Response to a Hub Longitudinal Shear.

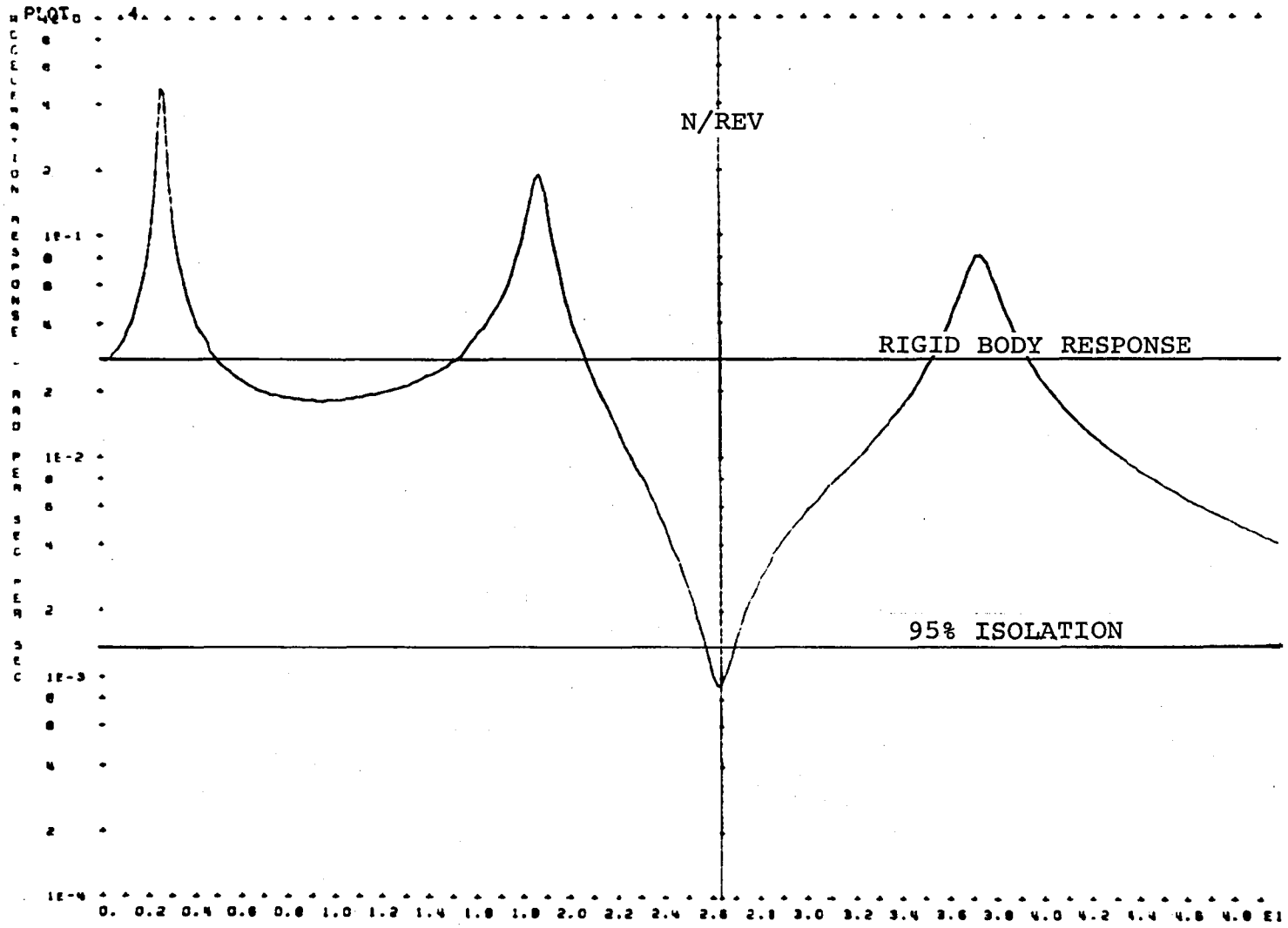


Figure 42. C.G. Pitch Response to a Hub Pitch Moment.

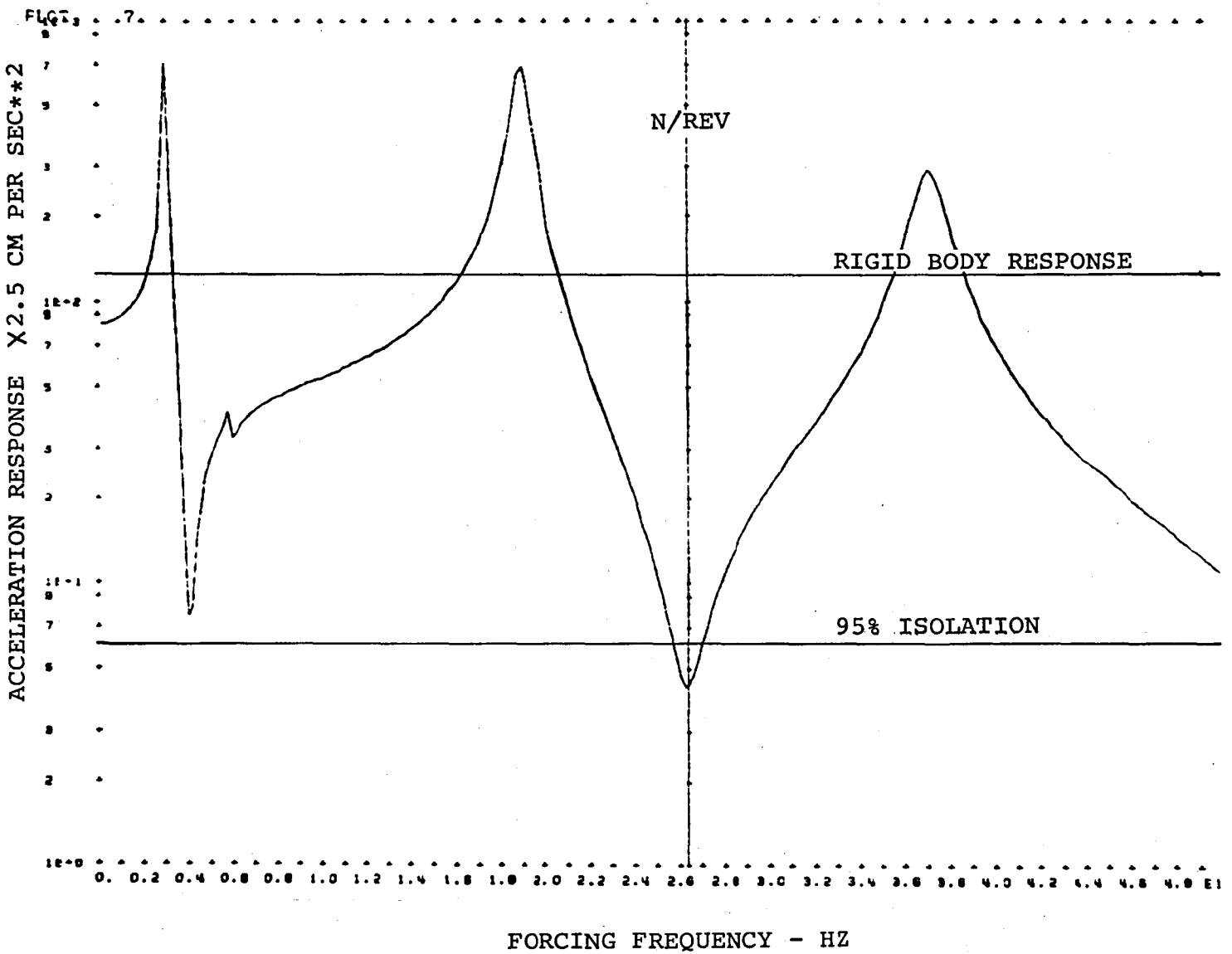


Figure 43. C.G. Lateral Response to a Hub Lateral Shear.

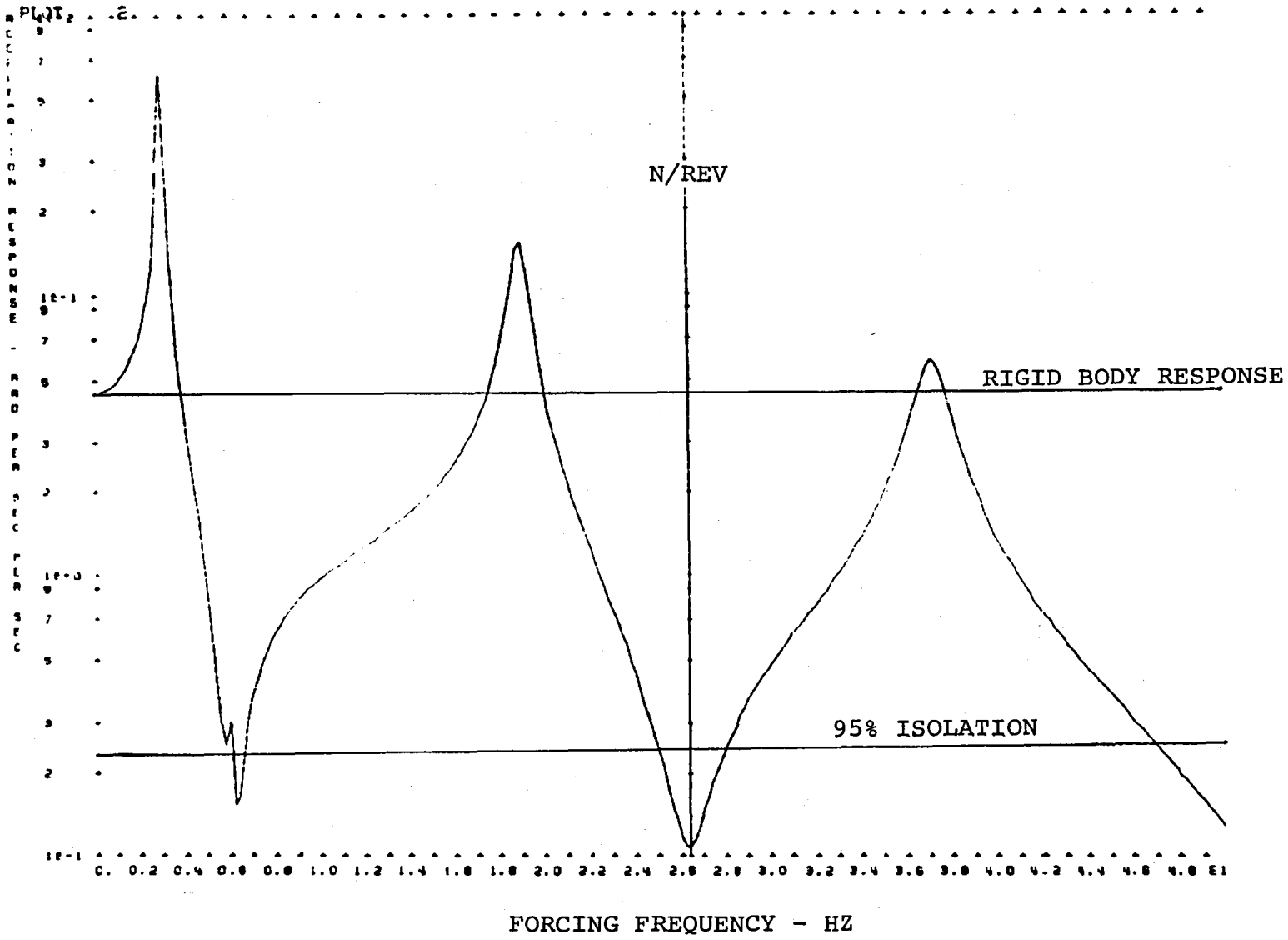


Figure 44. C.G. Roll Response to a Hub Lateral Shear.

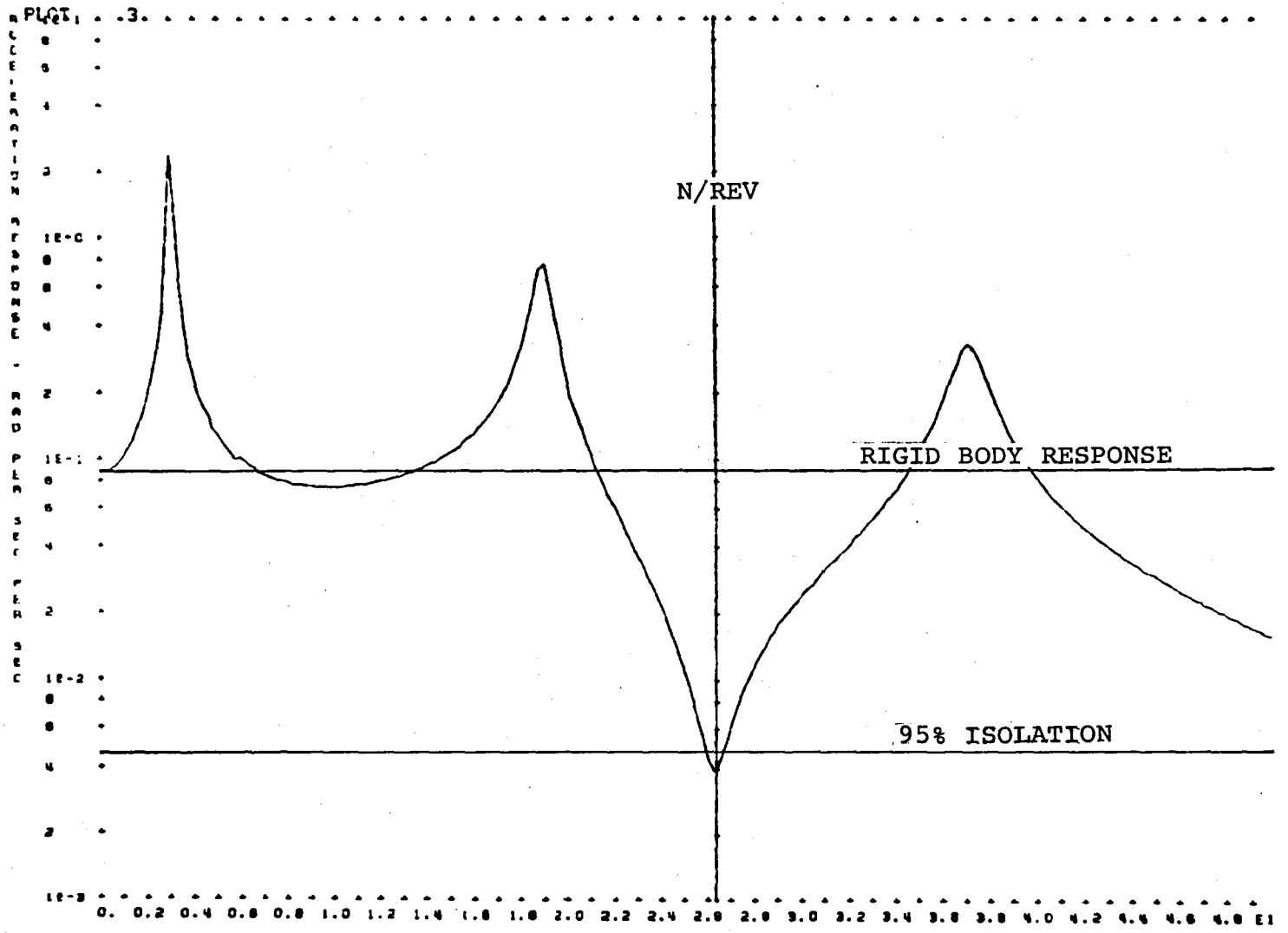


Figure 45. C.G. Roll Response to a Hub Roll Moment.

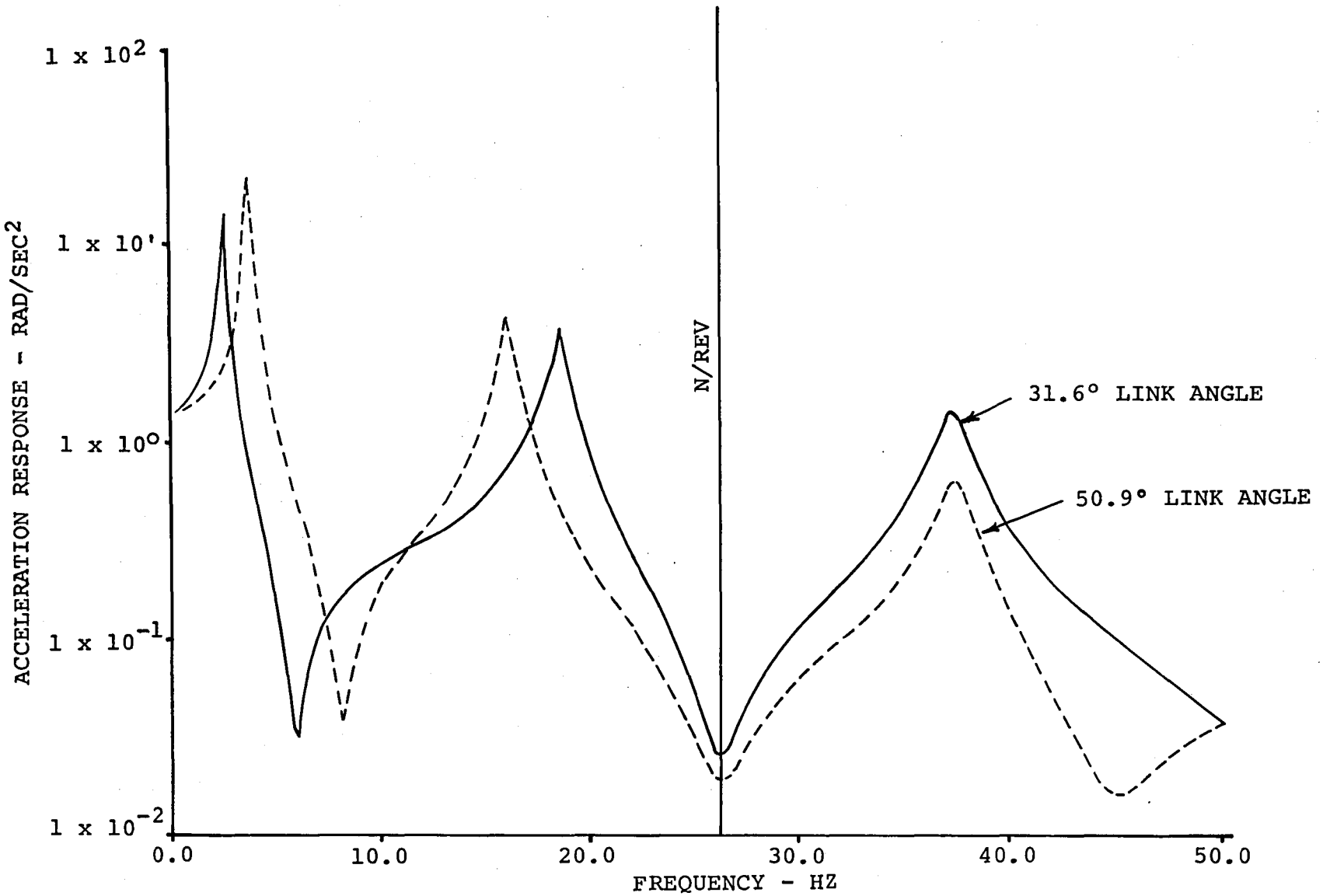


Figure 46. Effect of Link Angle Change on Natural Modes and Isolation.

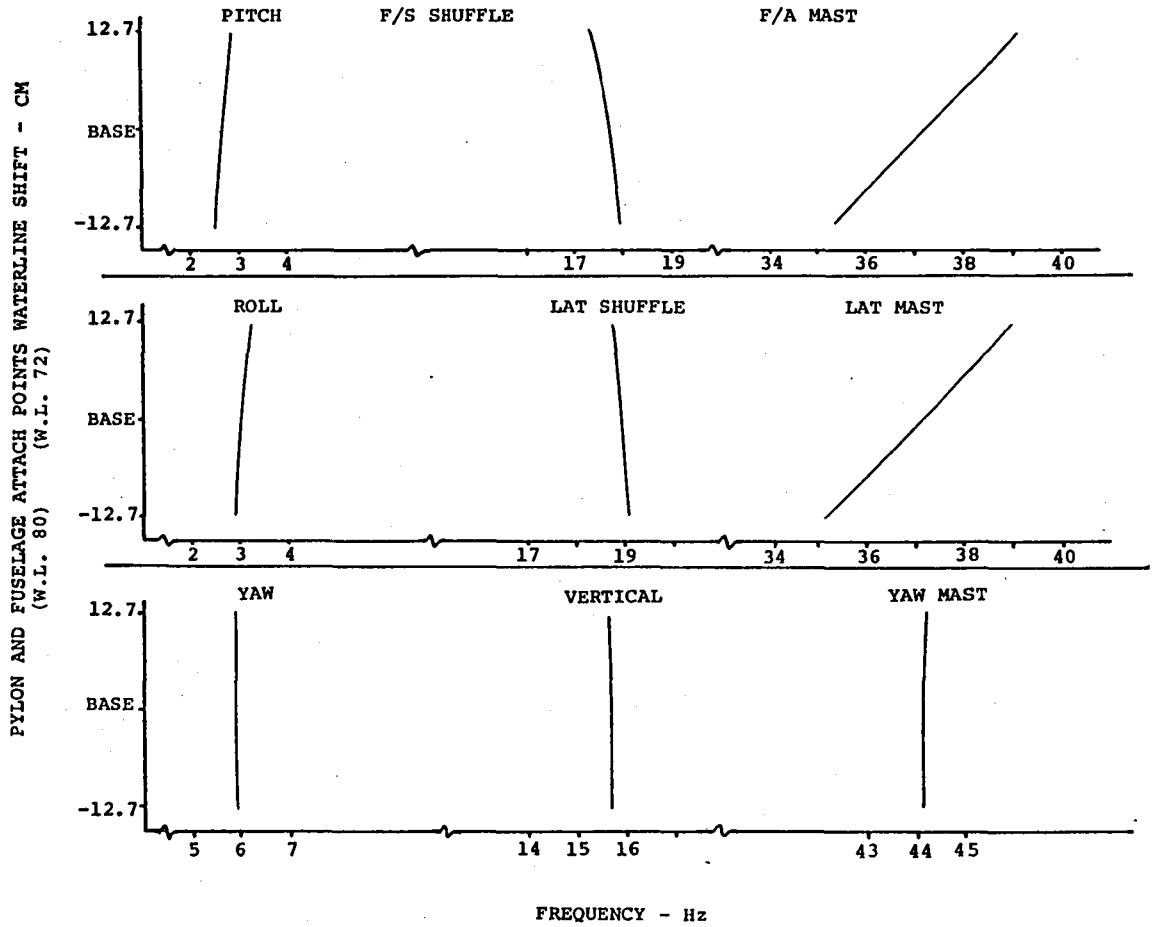


Figure 47. Pylon and Fuselage Attach Points Vertical Location Effects on Frequency.

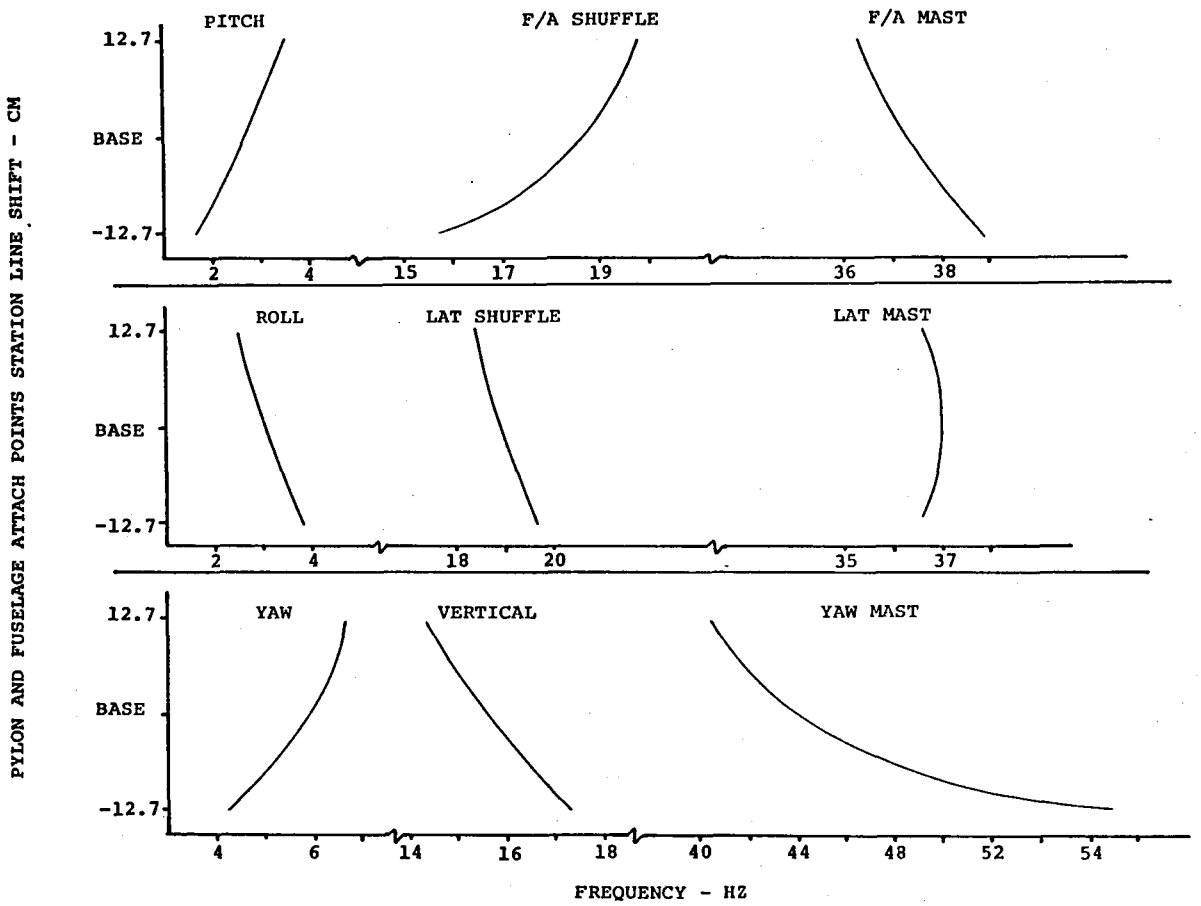


Figure 48. Fuselage Station Location of Pylon and Fuselage Attach Points Effect on Frequency.

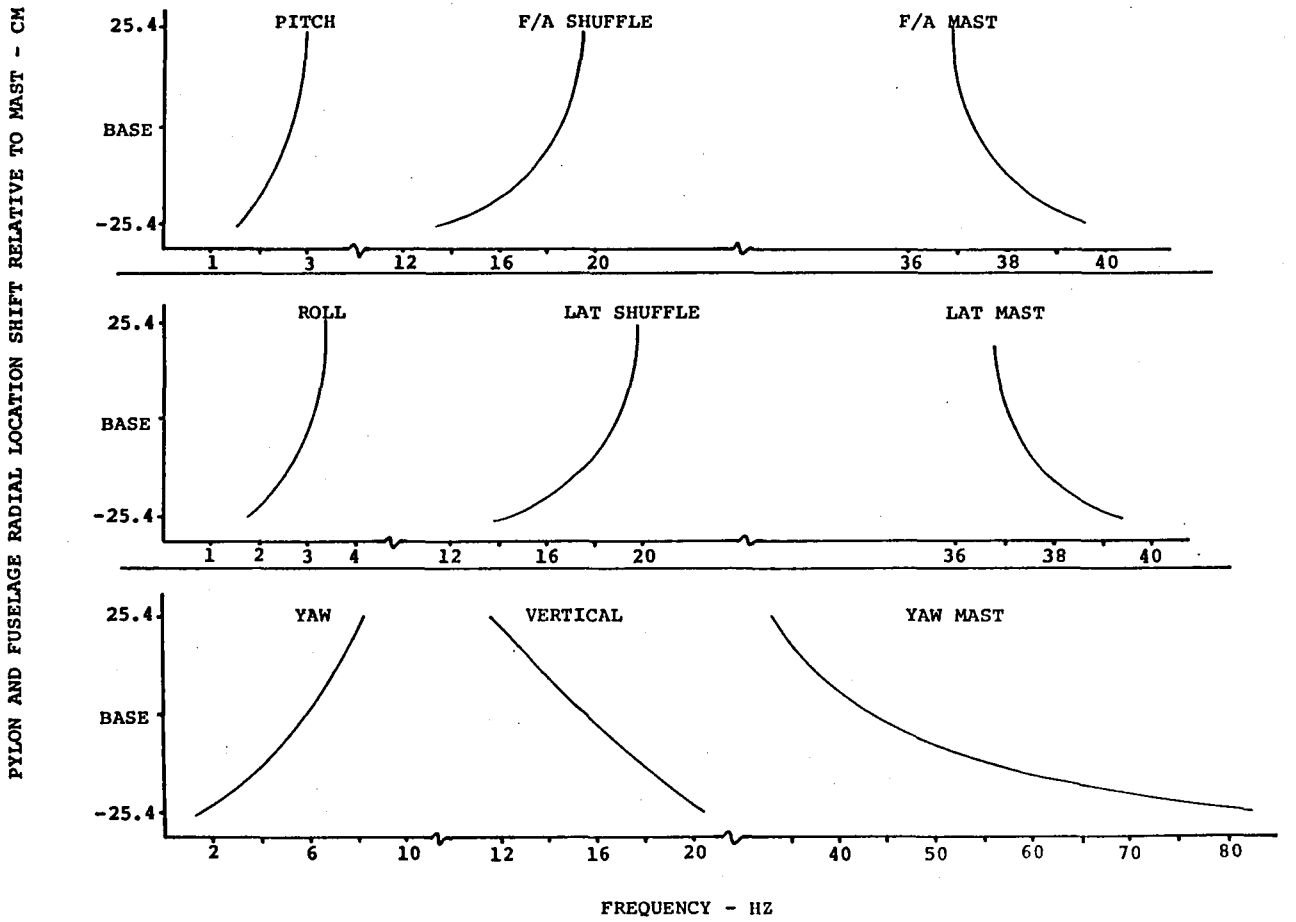


Figure 49. Pylon and Fuselage Attach Points Moved Radially Effect on Frequency.

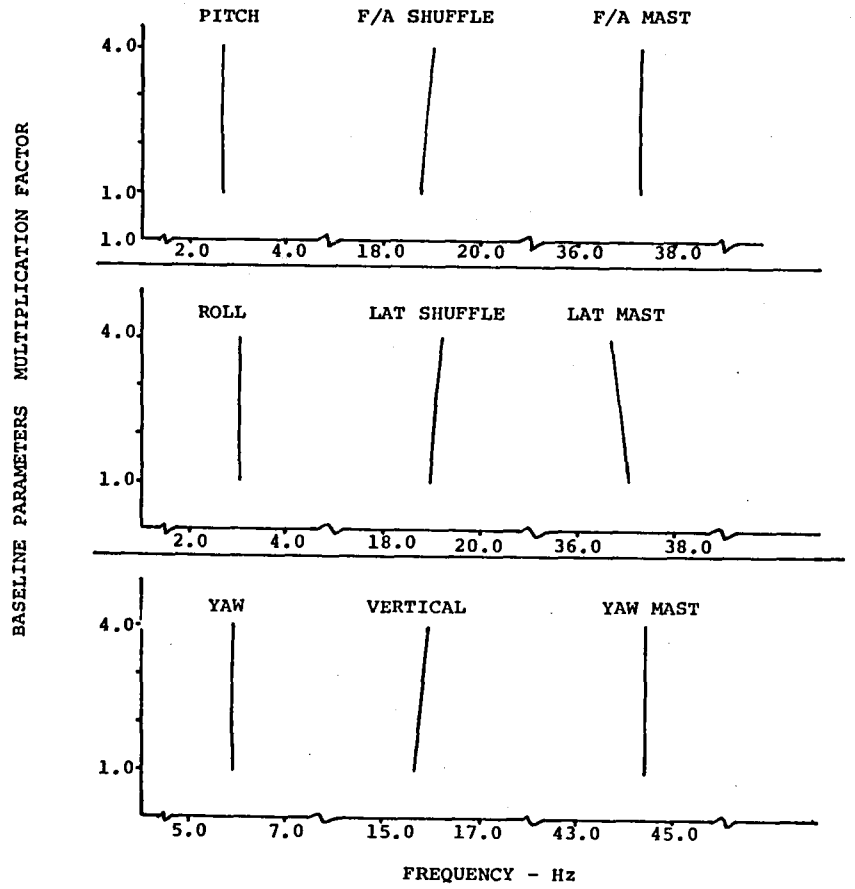


Figure 50. Baseline Mass, Inertias, Stiffnesses Effect on Frequecy.

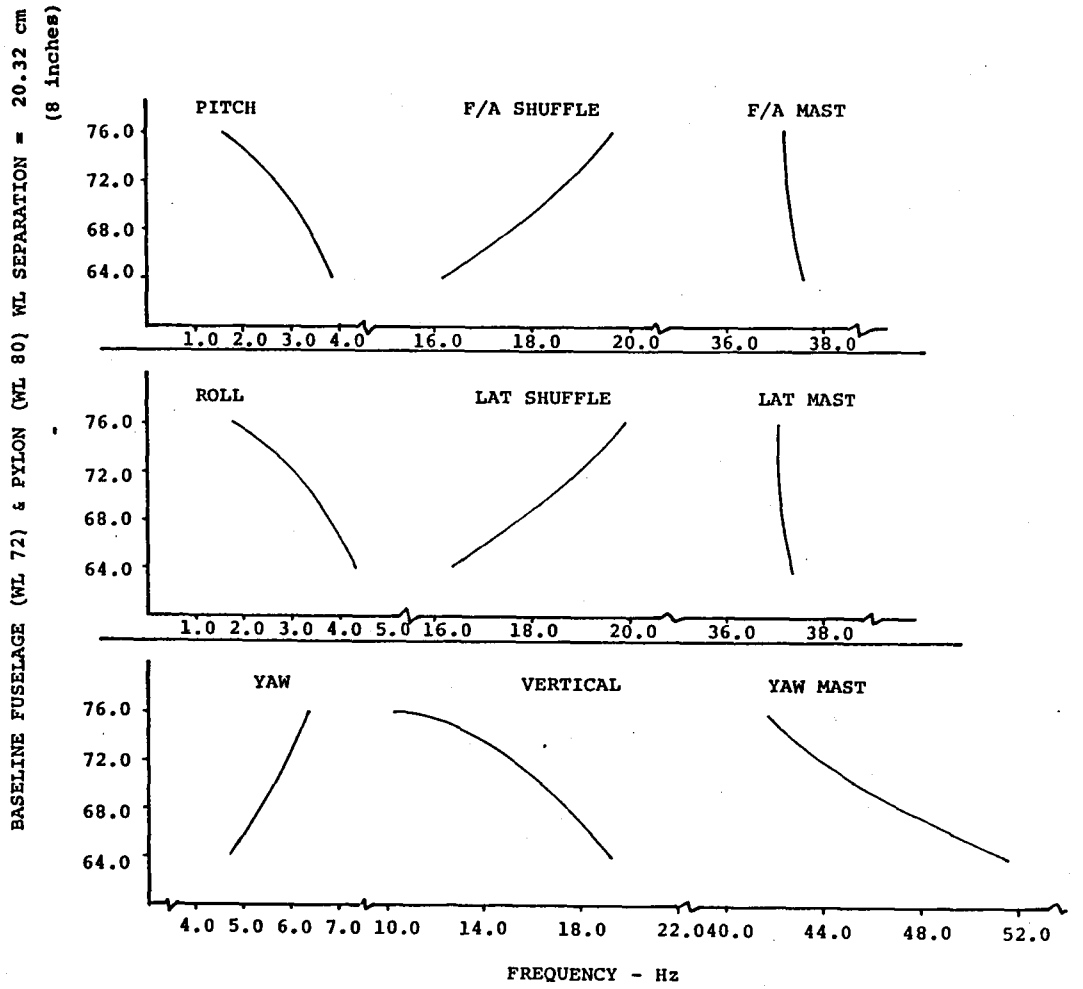


Figure 51. Fuselage Attach Points Vertical Location Effects on Frequency.

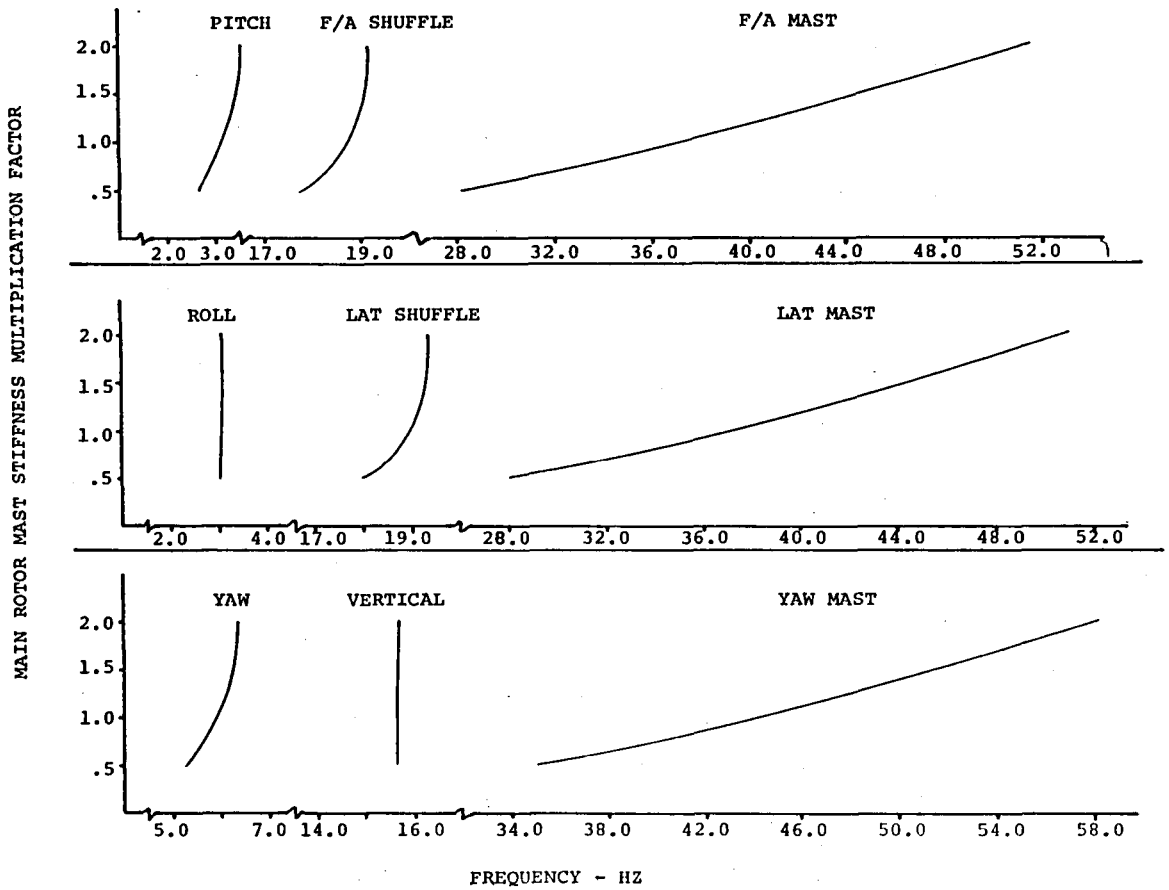


Figure 52. Main Rotor Mast Stiffness Effects on Frequency.

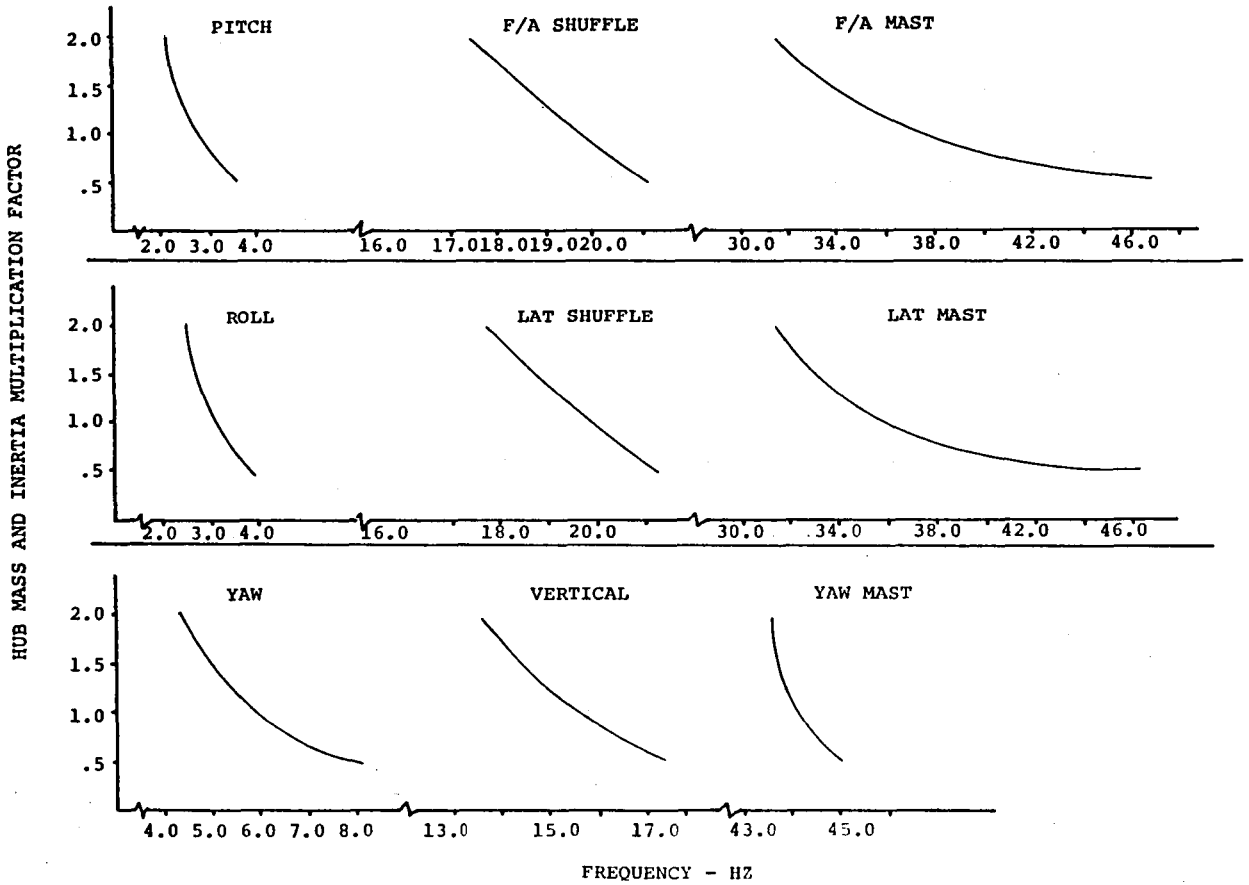


Figure 53. Hub Mass and Inertia Effects on Frequency.

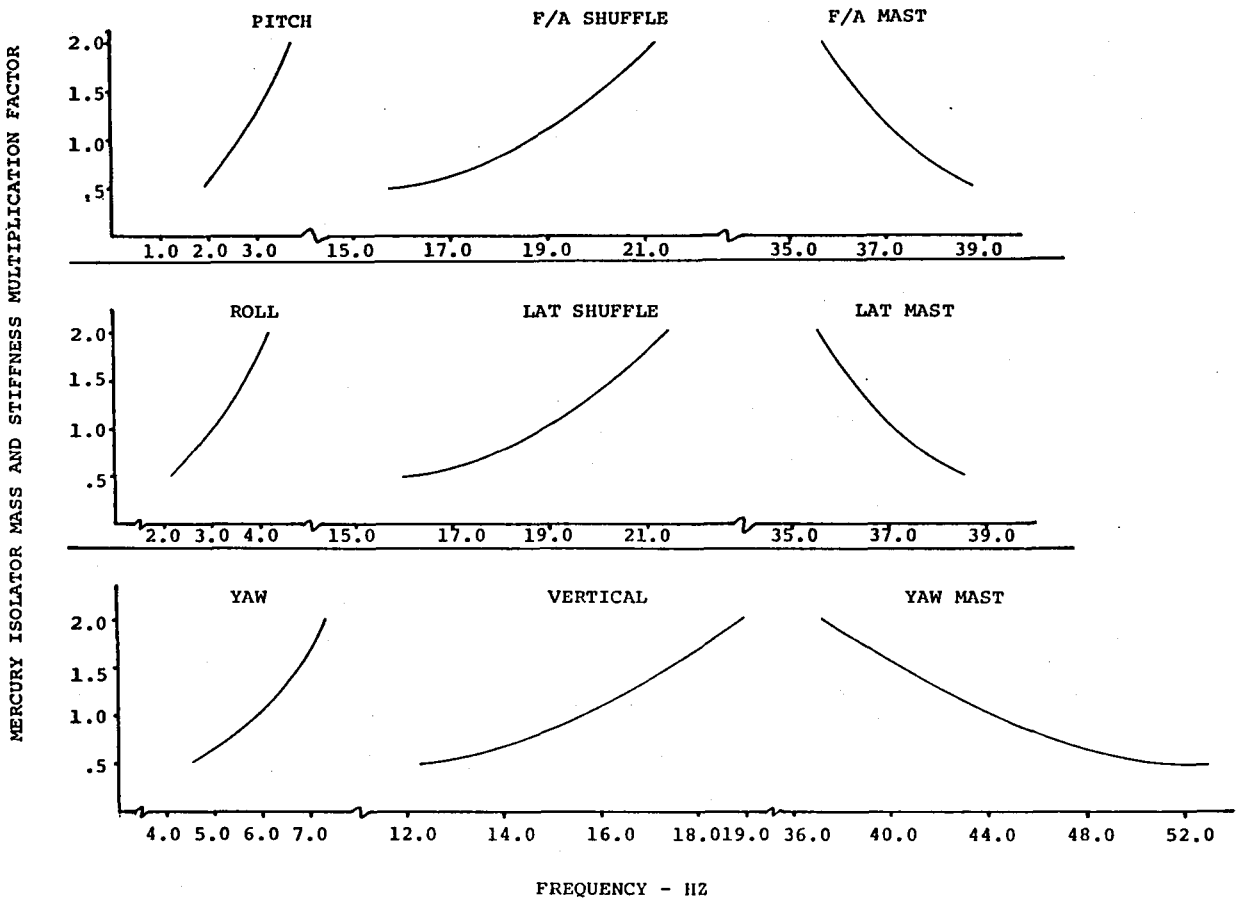


Figure 54. Mercury Isolator Mass and Stiffness Effects on Frequency.

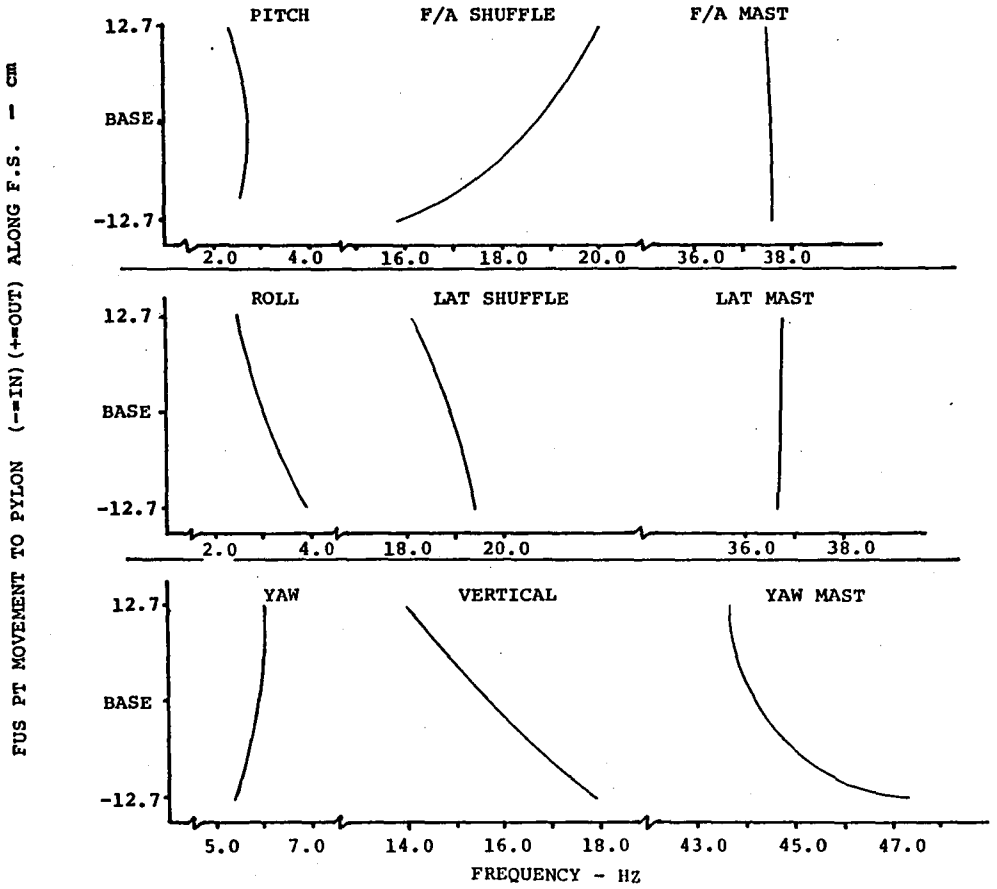


Figure 55. Fuselage Station Location of Fuselage Attach Point Effects on Frequency.

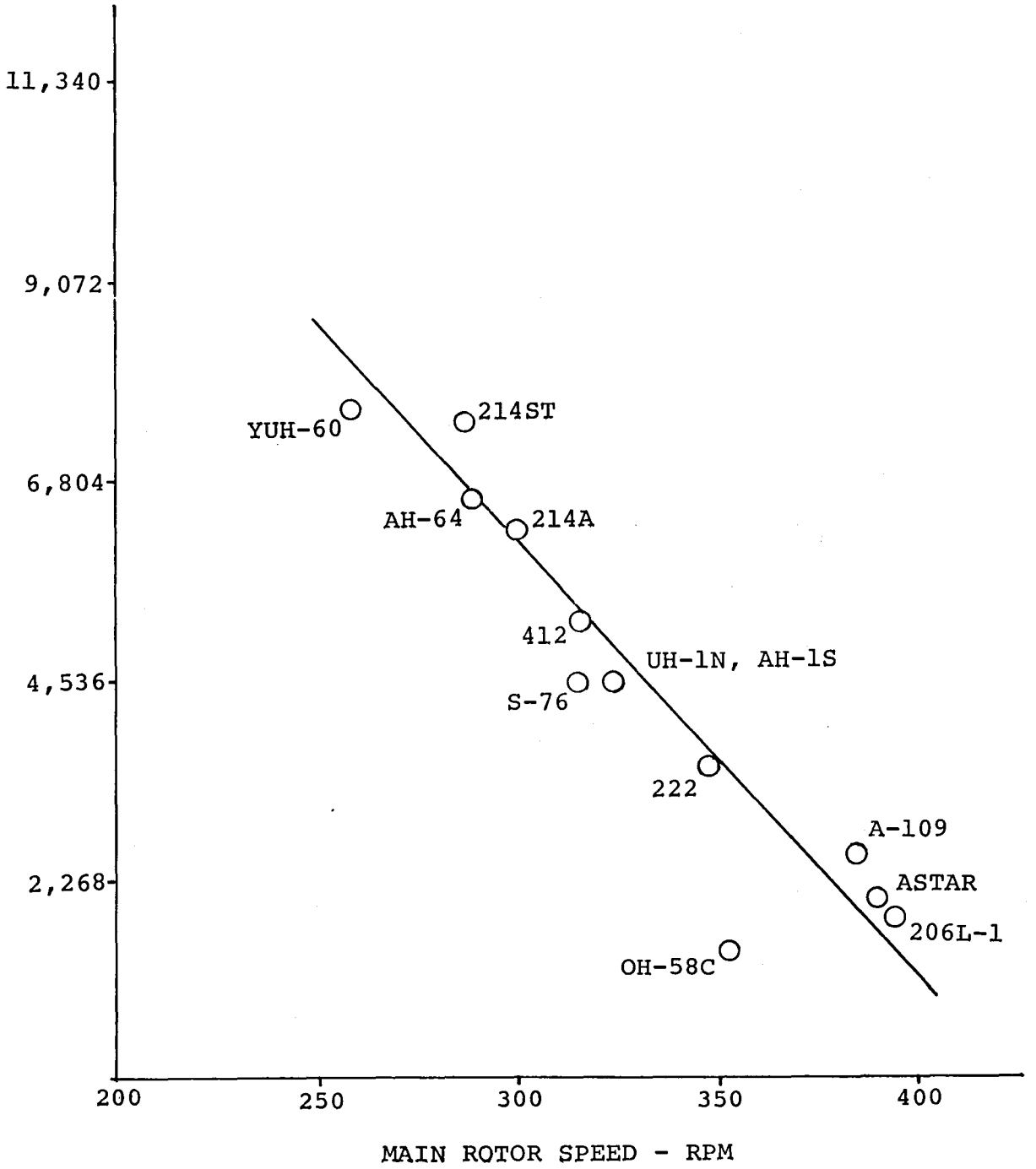


Figure 56. Effects of Helicopter Size on RPM

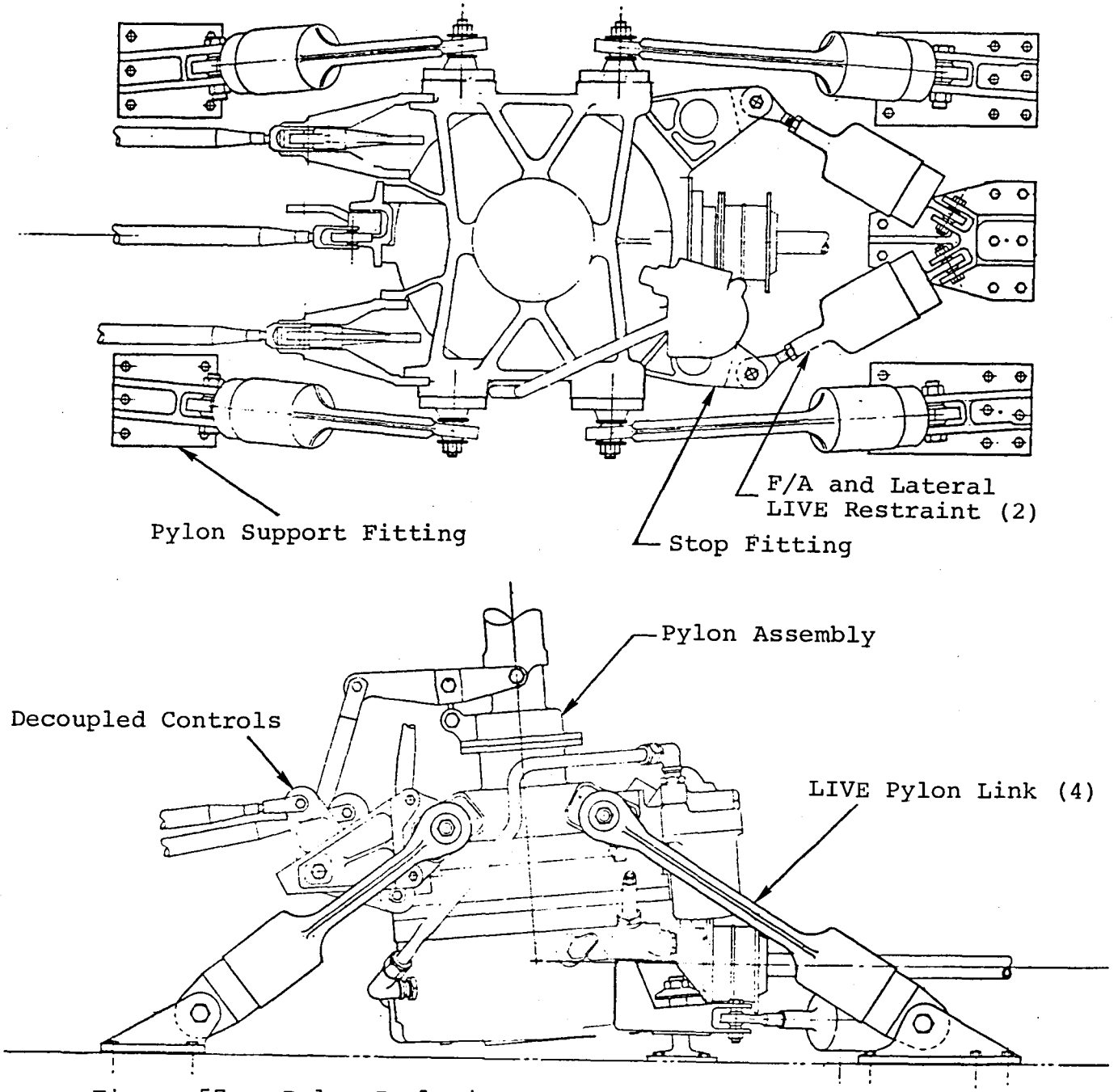


Figure 57. Pylon Isolation System - LIVE Link, Model 206L.

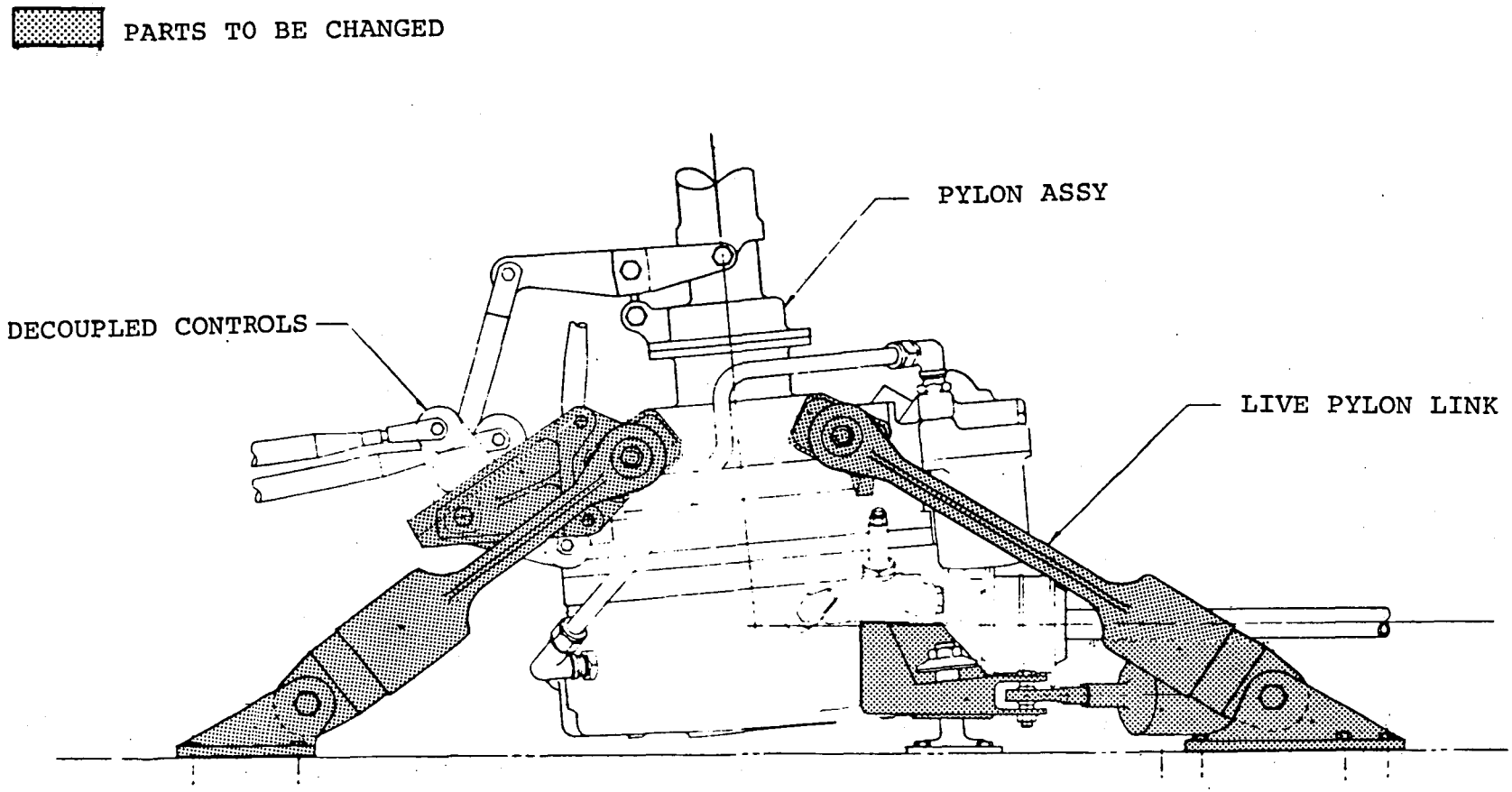


Figure 58. Hardware Changes Necessary for Incorporation of the Six LIVE Link Isolation System on the 206LM

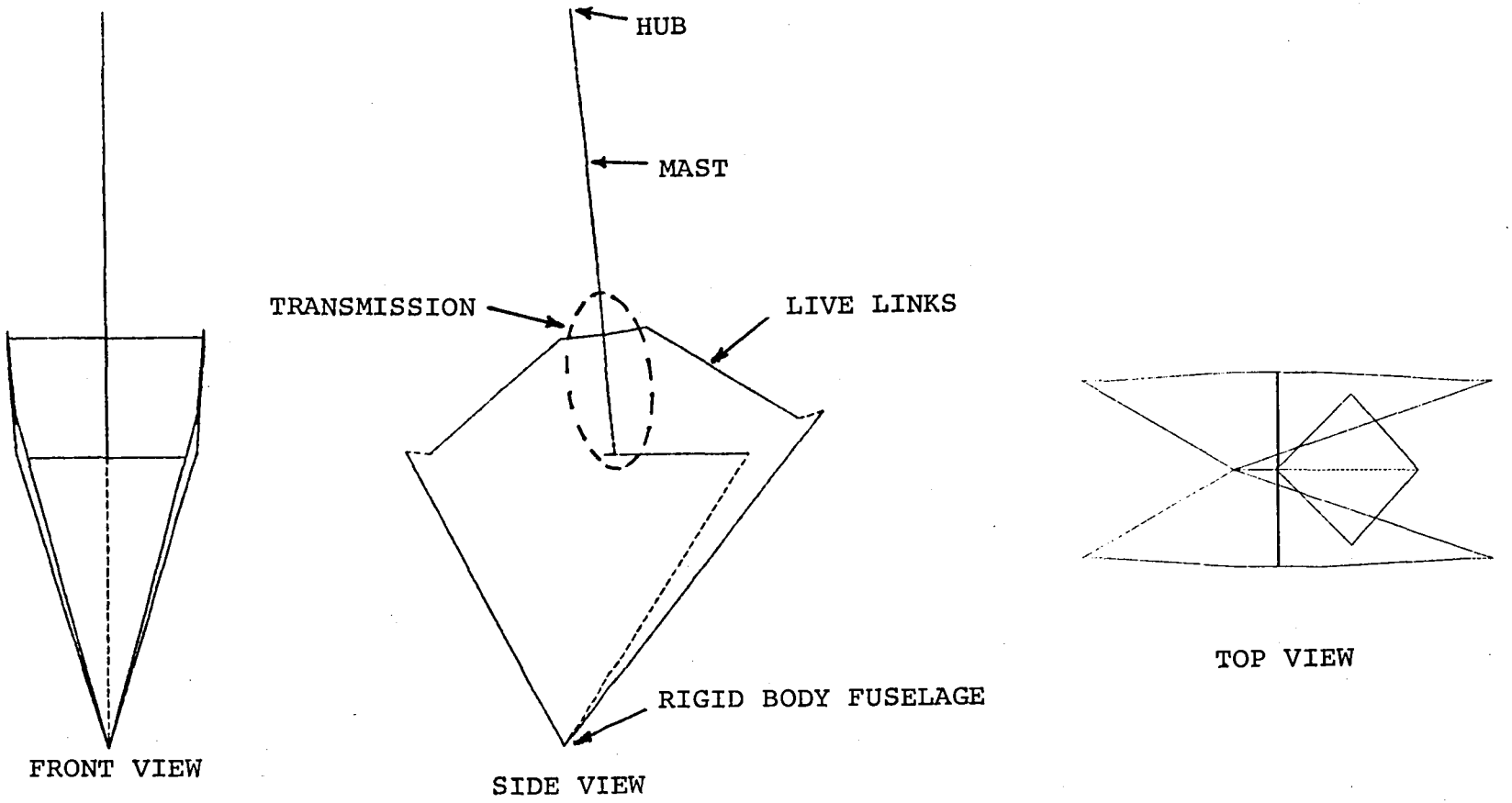
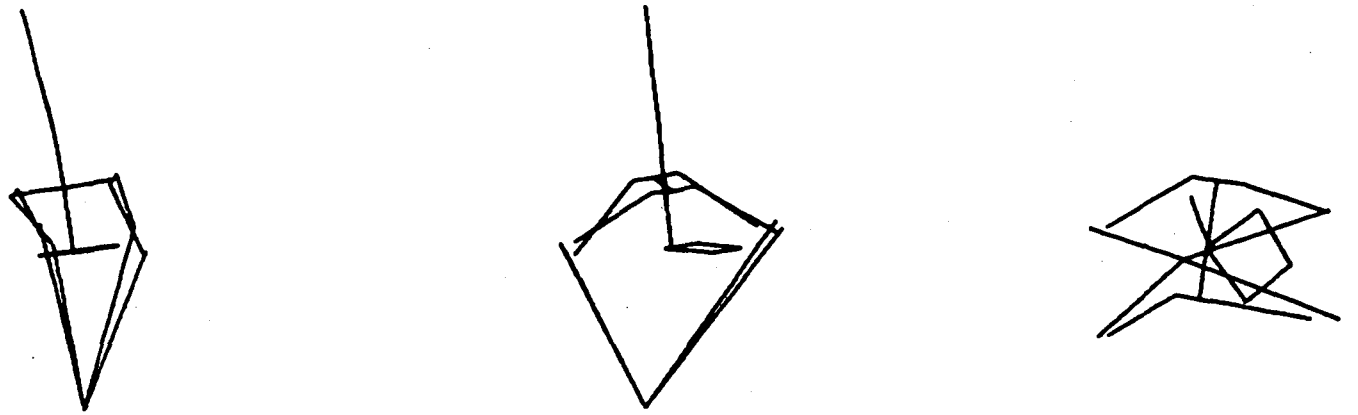
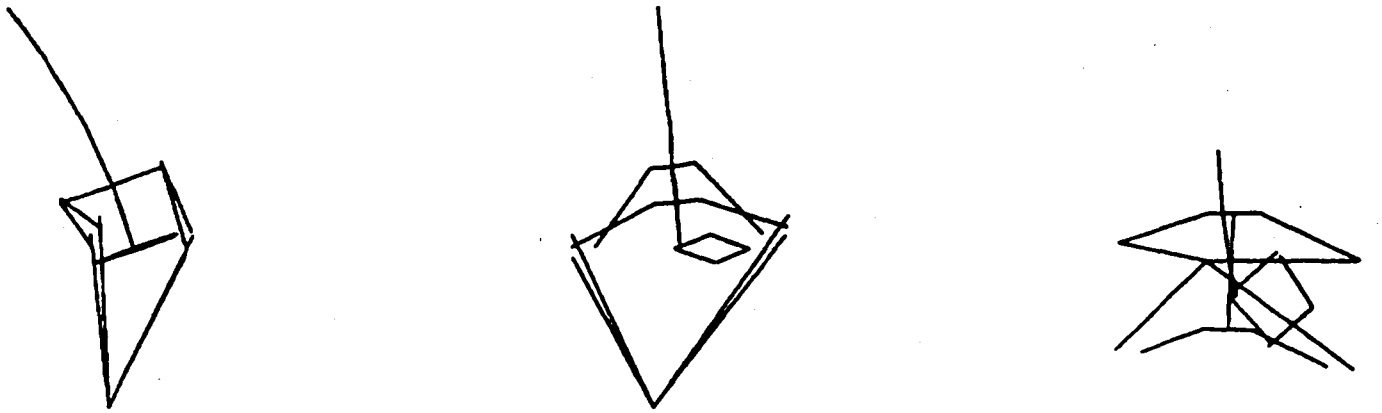


Figure 59. NASTRAN Model of Six LIVE Isolation System Installed on the 206LM.

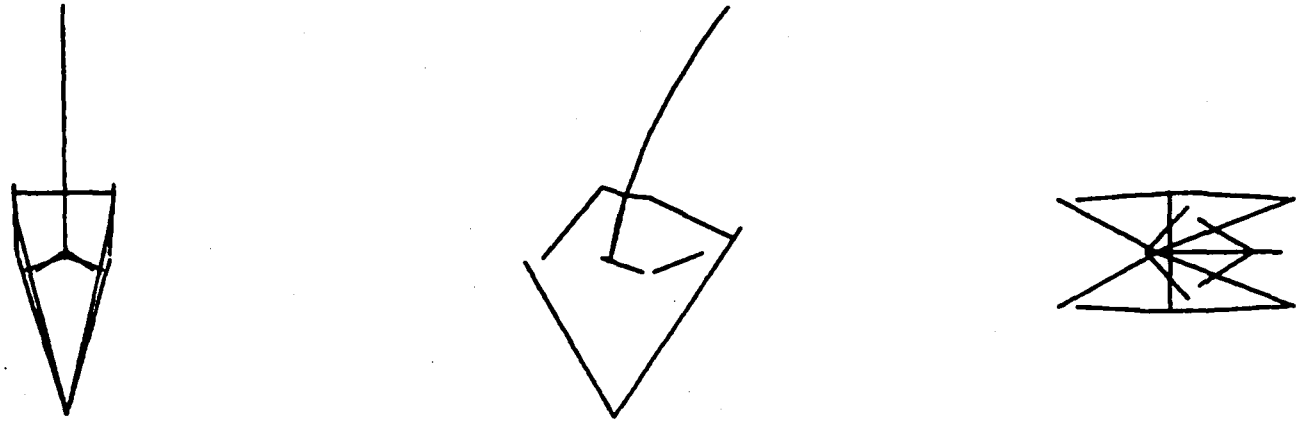


First Pylon Yaw Mode 2.58 Hz

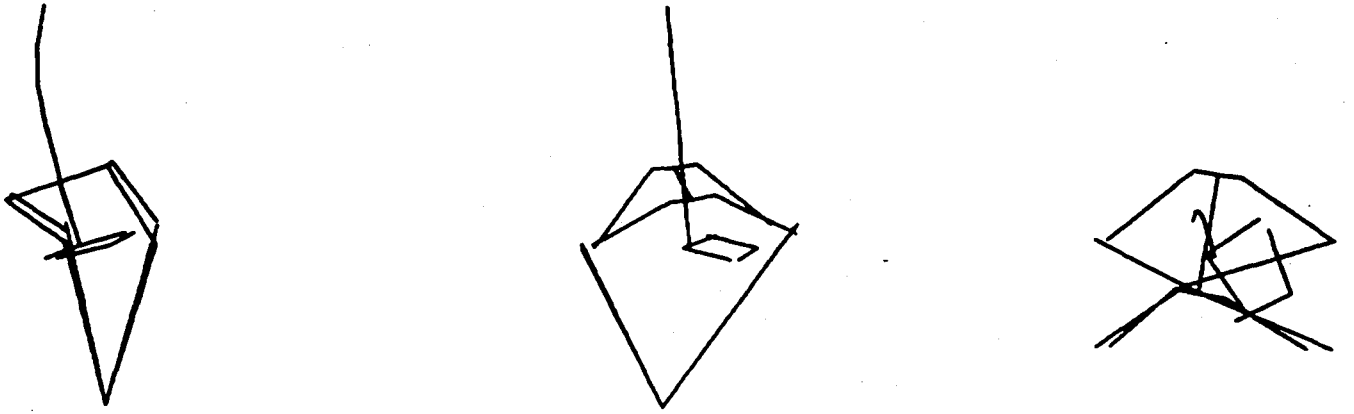


First Pylon Roll Mode - 2.91 Hz

Figure 60a. Baseline Helicopter NASTRAN Mode Shapes.

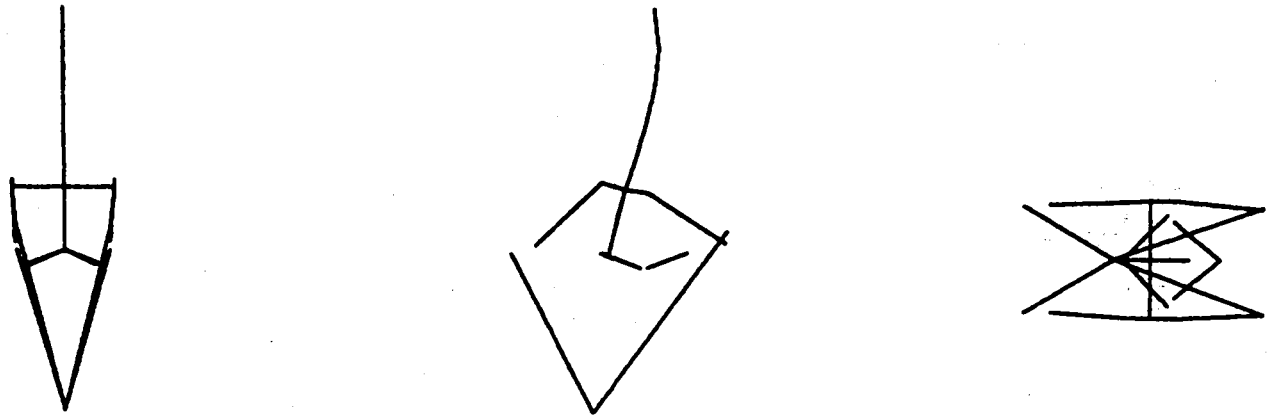


First Pylon Pitch Mode - 3.02 Hz

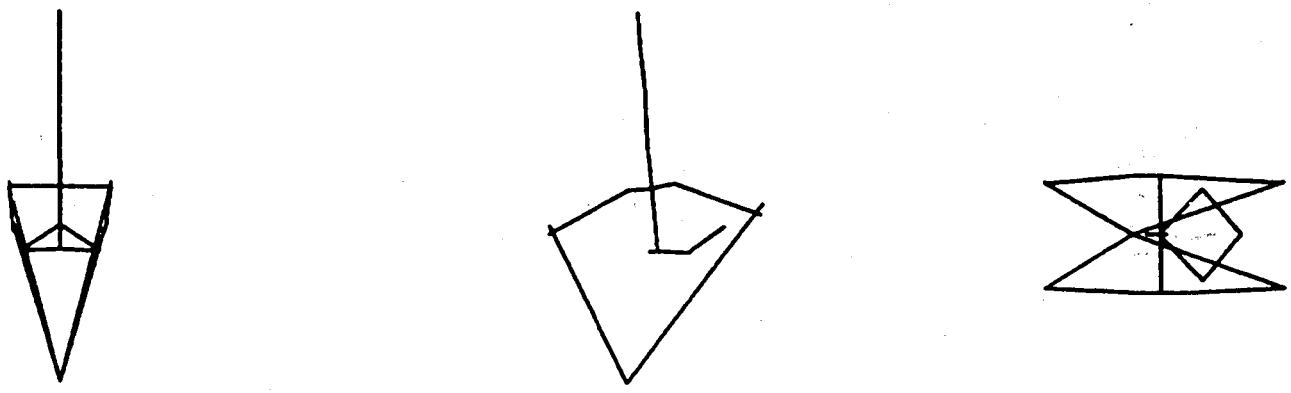


First Pylon Lateral Translation Mode - 8.42 Hz

Figure 60b. Baseline Helicopter NASTRAN Mode Shapes.

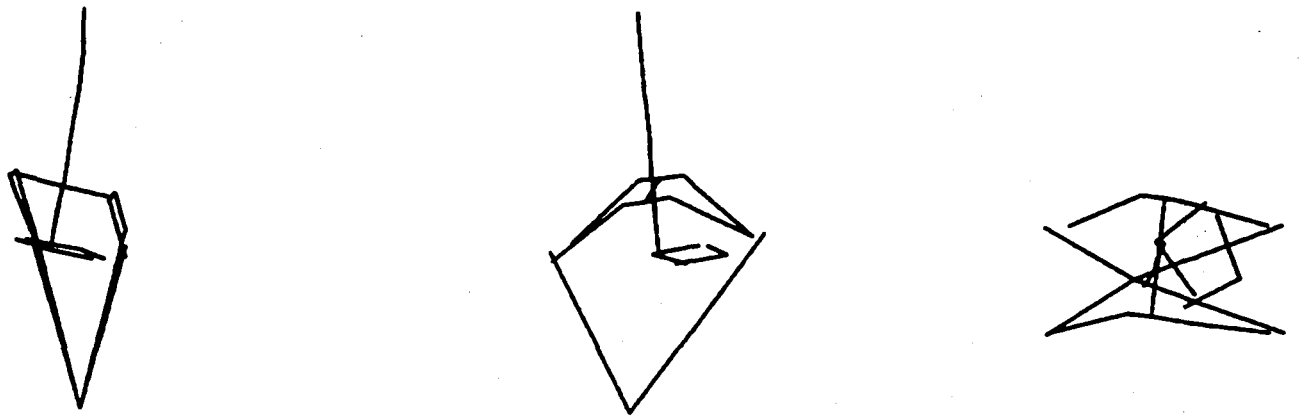


First Pylon Longitudinal Translation Mode - 12.53 Hz

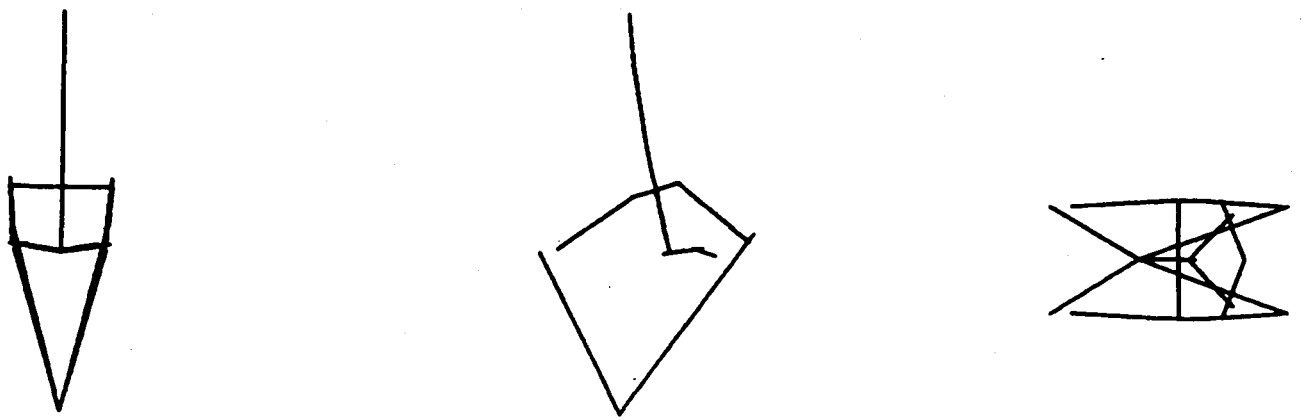


First Pylon Vertical Translation Mode - 14.14 Hz

Figure 60c. Baseline Helicopter NASTRAN Mode Shapes.

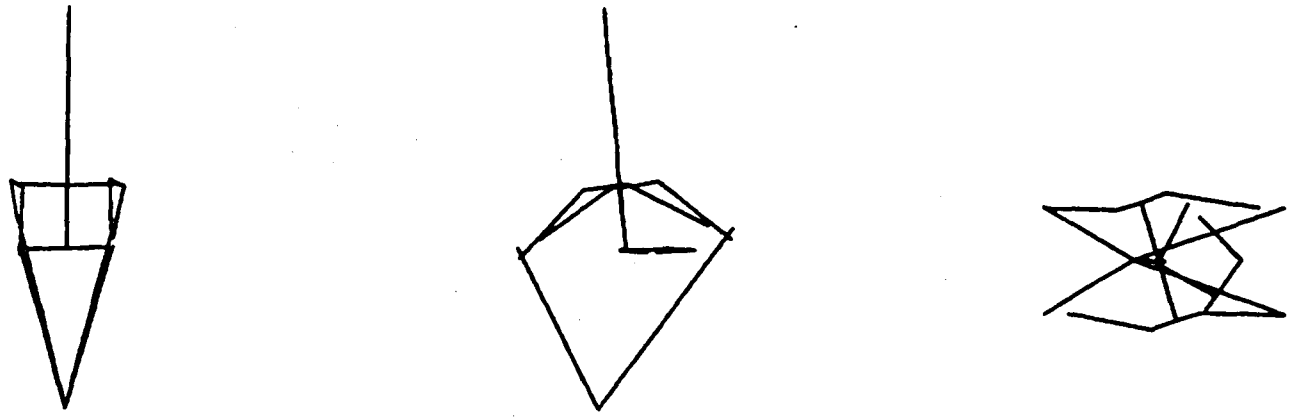


First LIVE Isolator Lateral Mode - 20.84 Hz

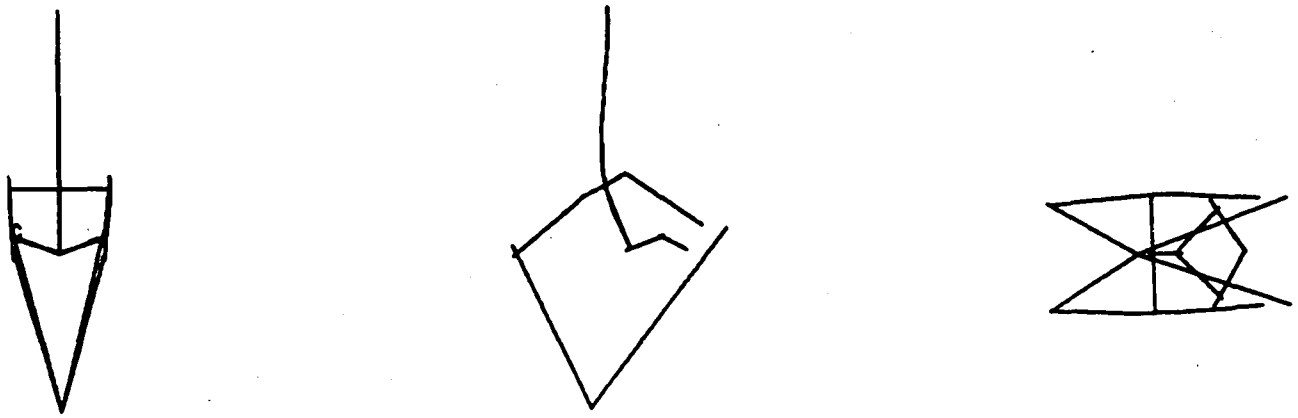


First LIVE Isolator Longitudinal Mode - 22.01 Hz

Figure 60d. Baseline Helicopter NASTRAN Mode Shapes.



First LIVE Yaw Mode - 25.97 Hz



Longitudinal Mast Bending Mode - 36.66 Hz

Figure 60e. Baseline Helicopter NASTRAN Mode Shapes.

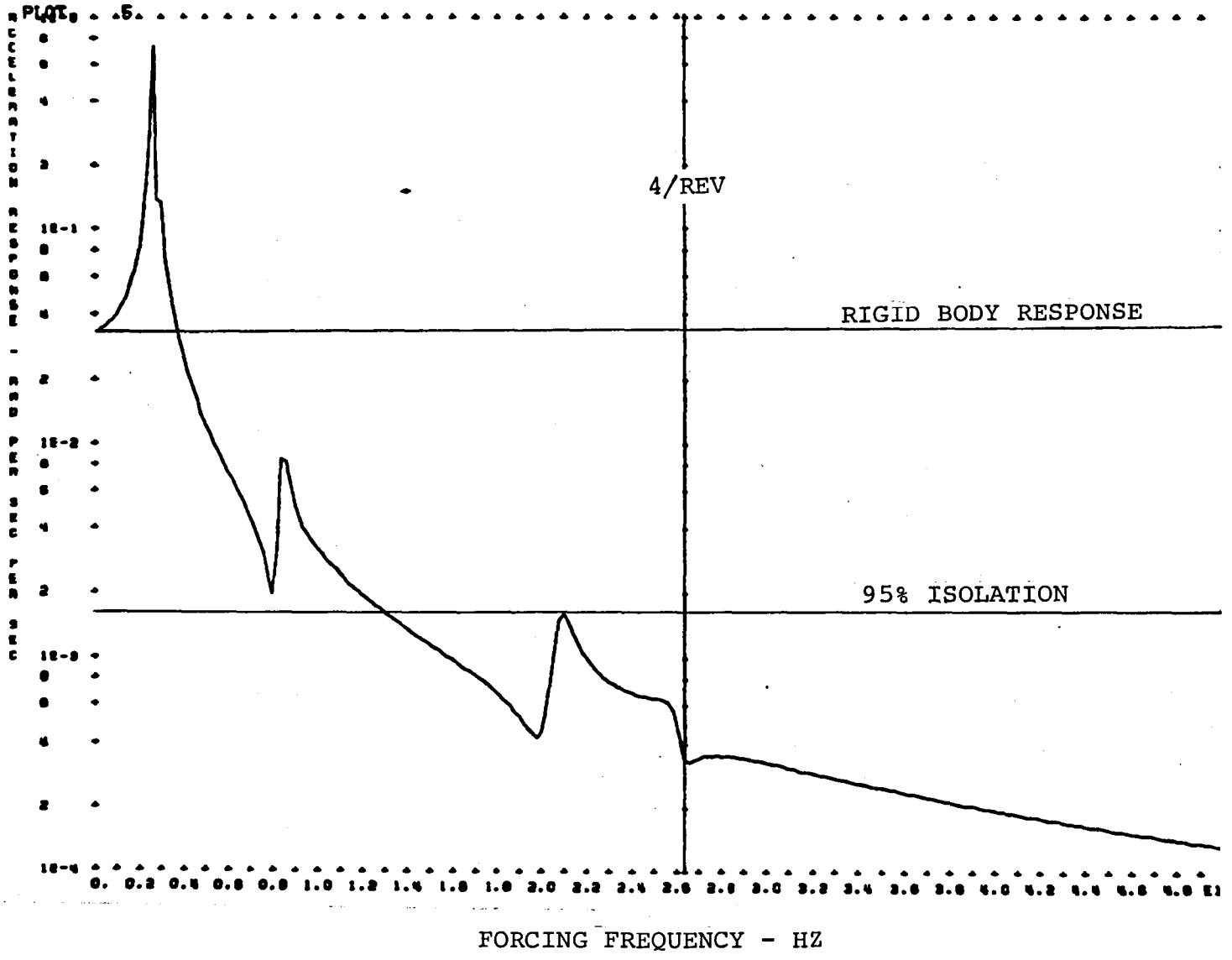


Figure 61. Baseline Helicopter C.G. Yaw Response to a 11300 cm-N (1000 in-lb) Yaw Hub Moment

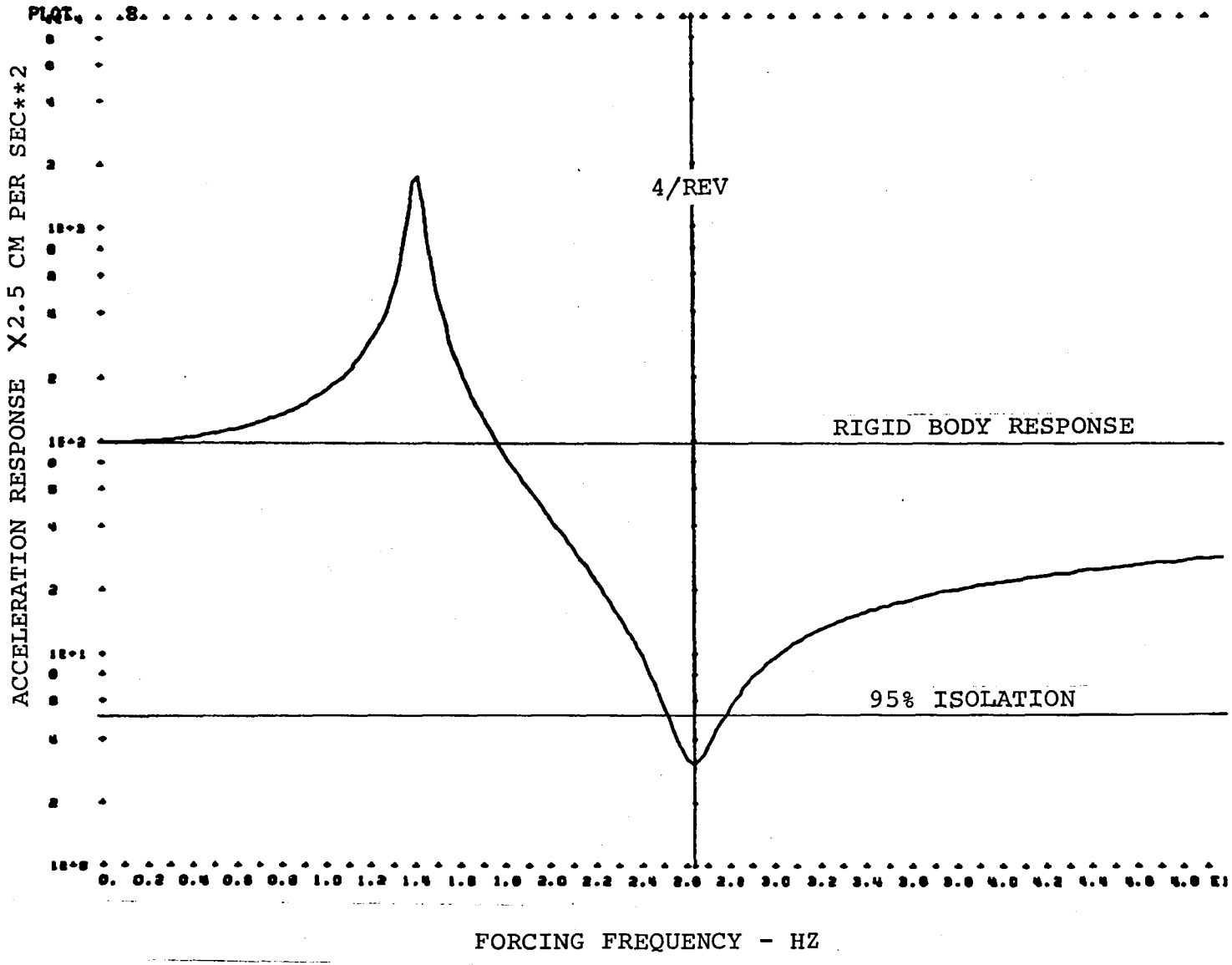


Figure 62. Baseline Helicopter C.G. Vertical Response to a 4448N (1000 Lb) Vertical Hub Force

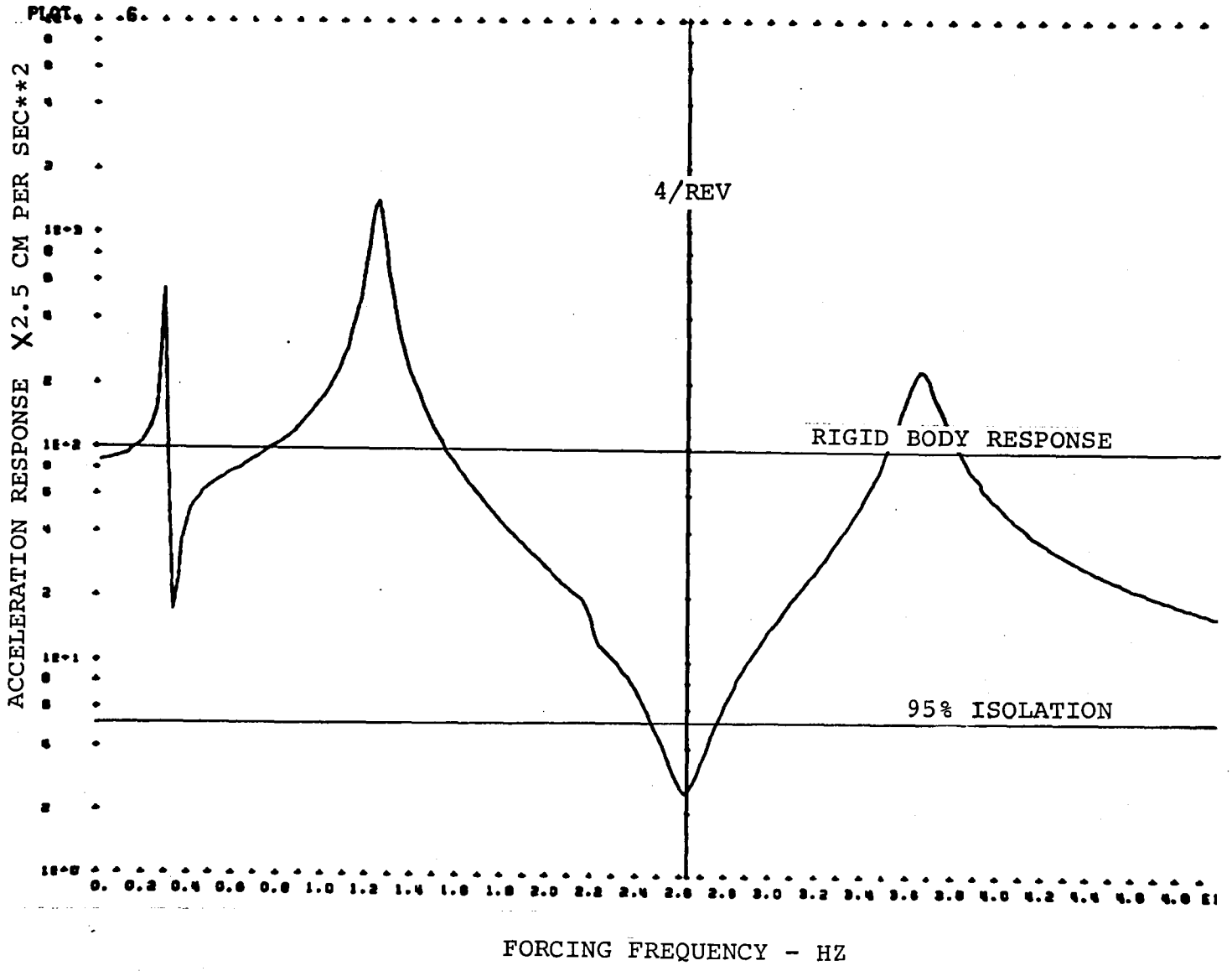
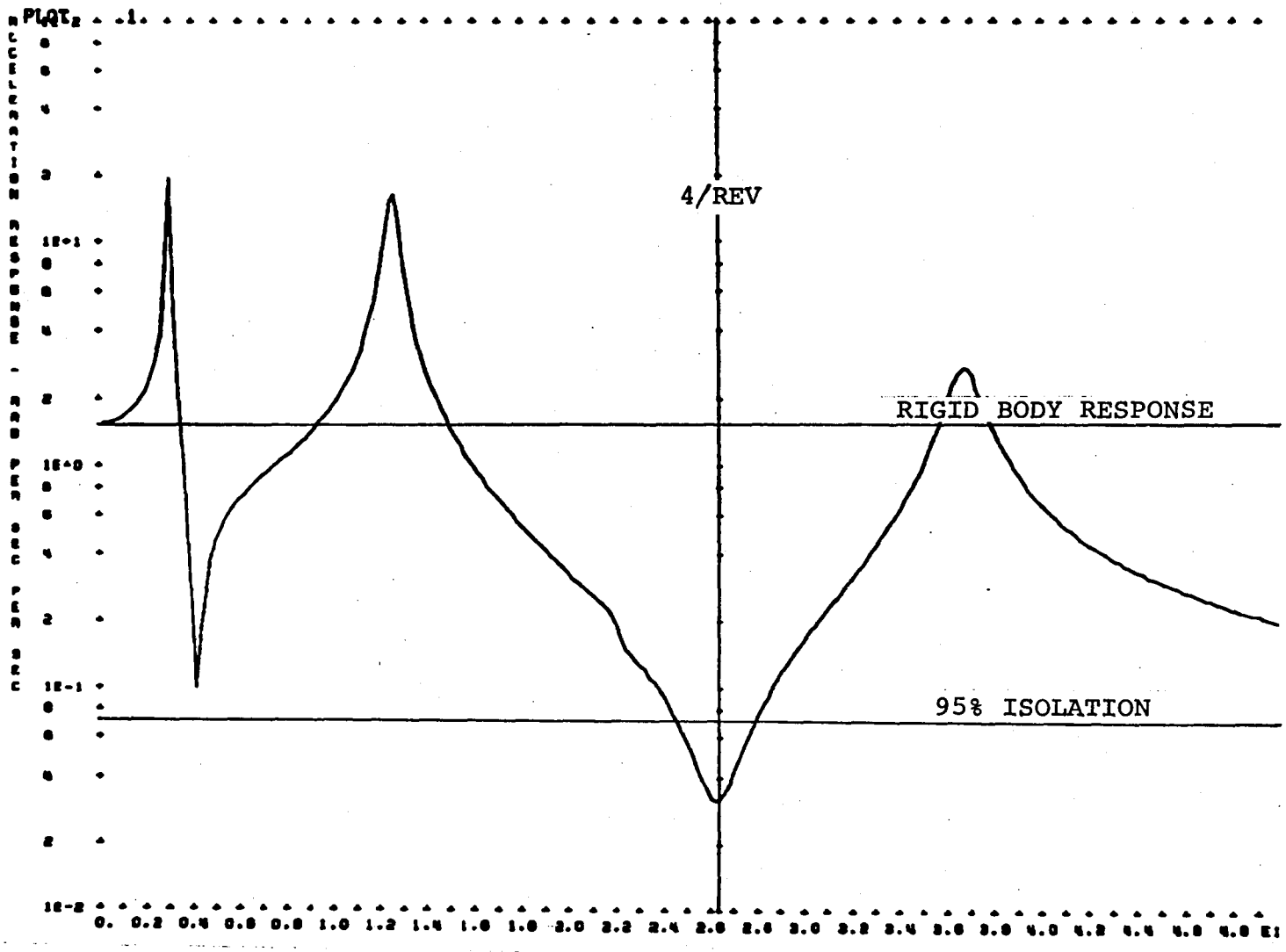


Figure 63. Baseline Helicopter C.G. Longitudinal Response to a 4448N (1000 Lb) Longitudinal Hub Force



FORCING FREQUENCY - HZ

Figure 64. Baseline Helicopter C.G. Pitch Response to a 4448N (1000 Lb) Longitudinal Hub Force

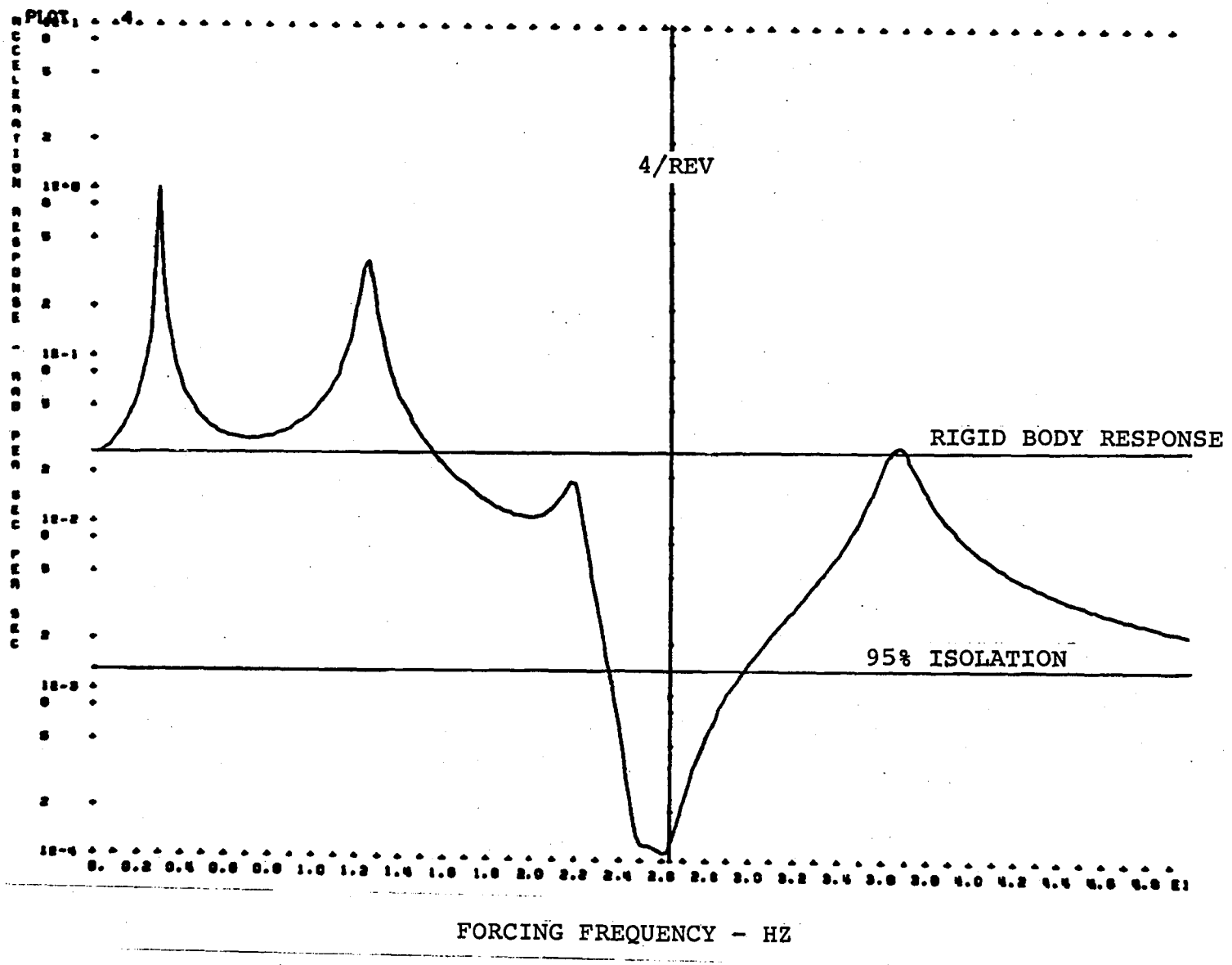


Figure 65. Baseline Helicopter C.G. Pitch Response to a 11300 cm-N (1000 in-lb) Pitch Hub Moment

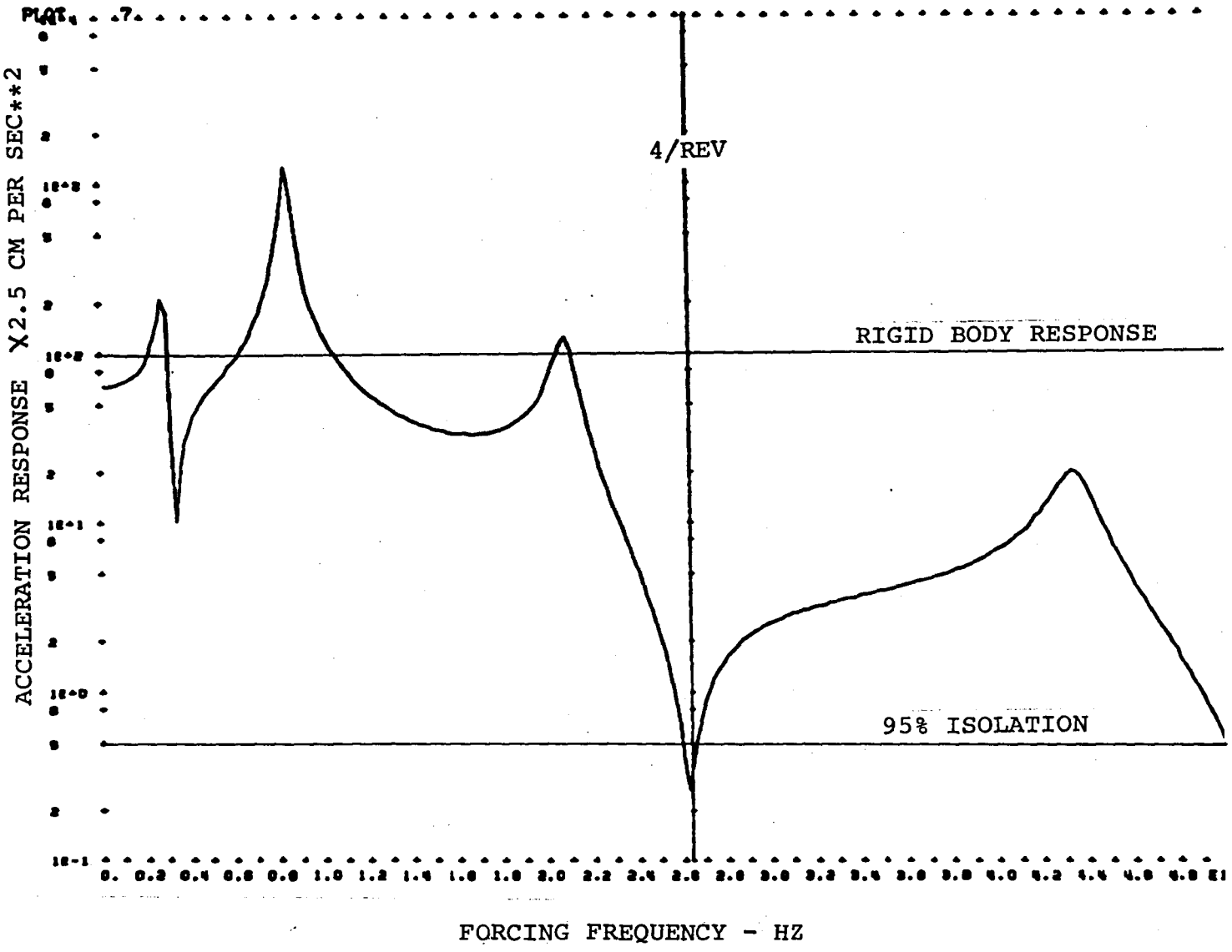


Figure 66. Baseline Helicopter C.G. Lateral Response to a 4448N (1000 Lb) Lateral Hub Force

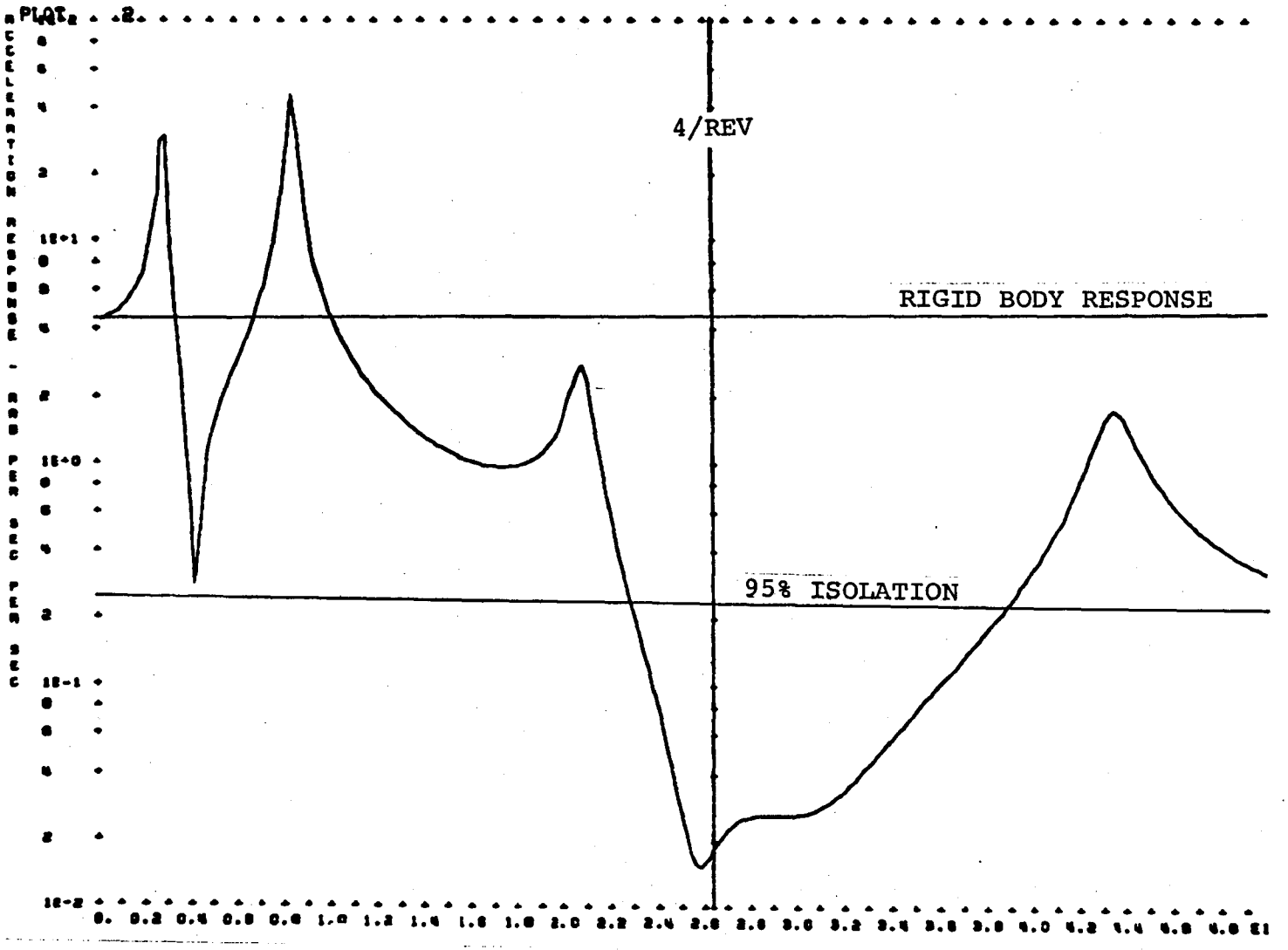
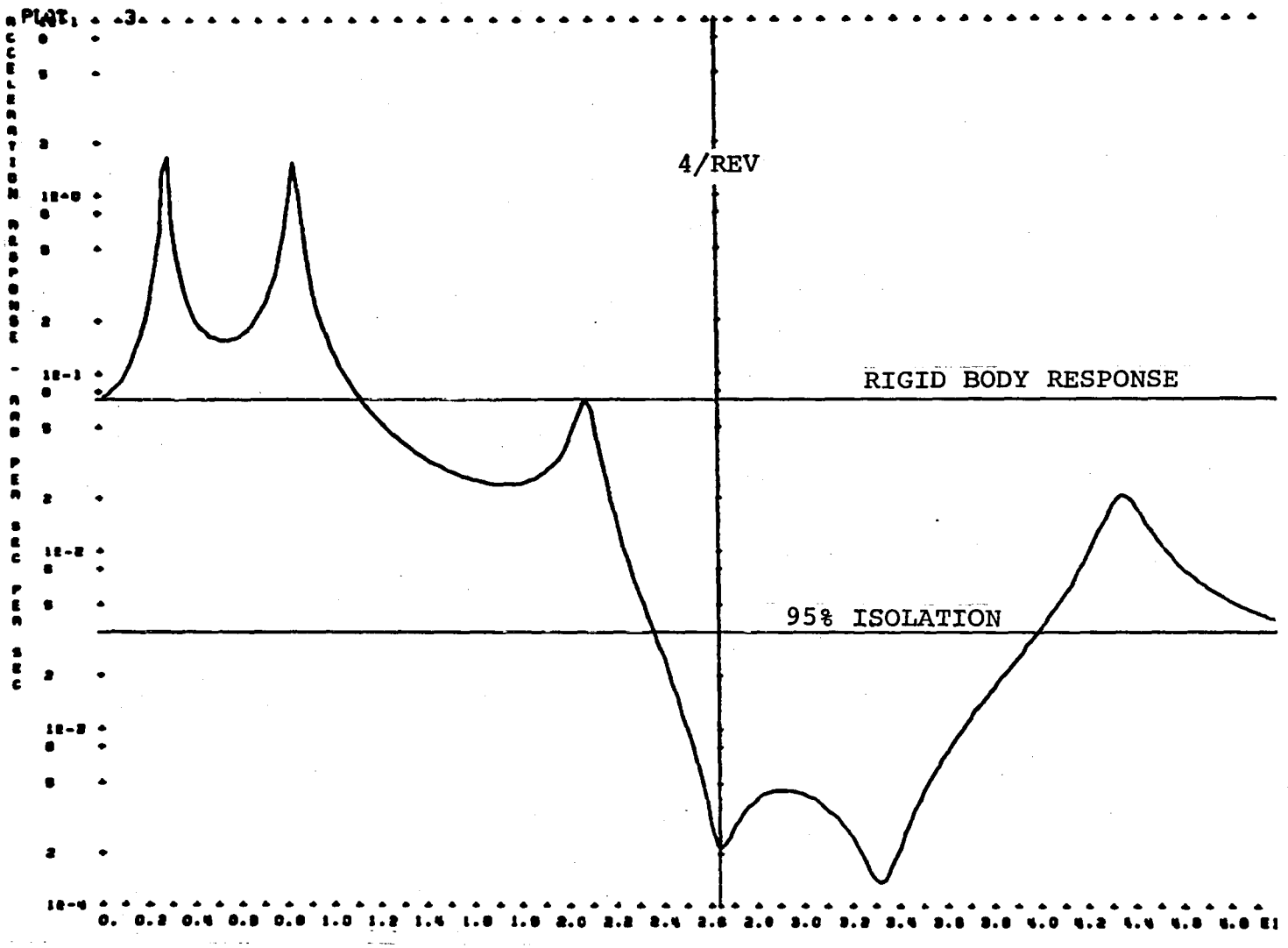


Figure 67. Baseline Helicopter C.G. Roll Response to a 4448N (1000 Lb) Lateral Hub Force



FORCING FREQUENCY - HZ

Figure 68. Baseline Helicopter C.G. Roll Response to a 11300 cm-N (1000 in-lb) Roll Hub Moment

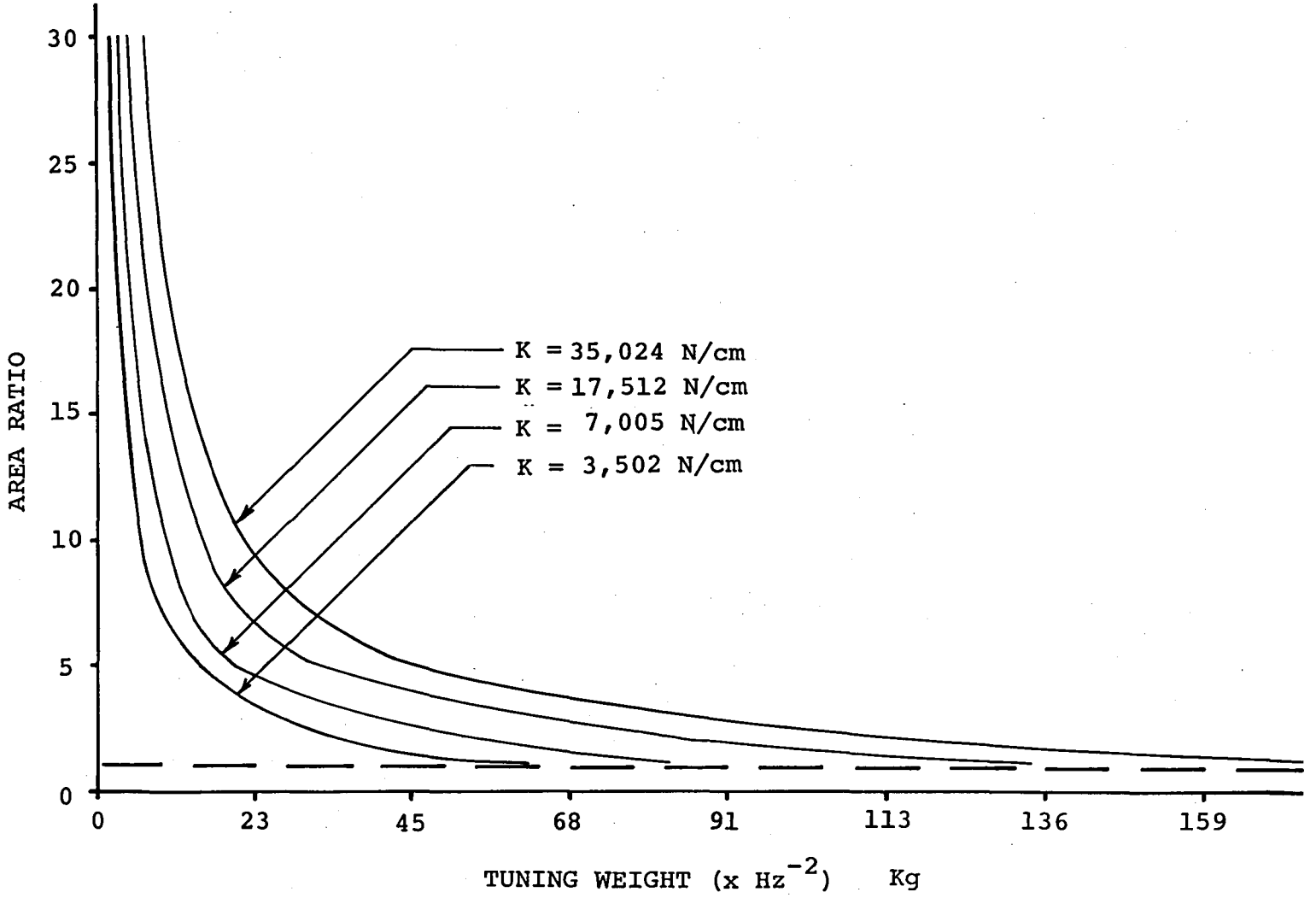


Figure 69. Effect of Area Ratio on Tuning Weight

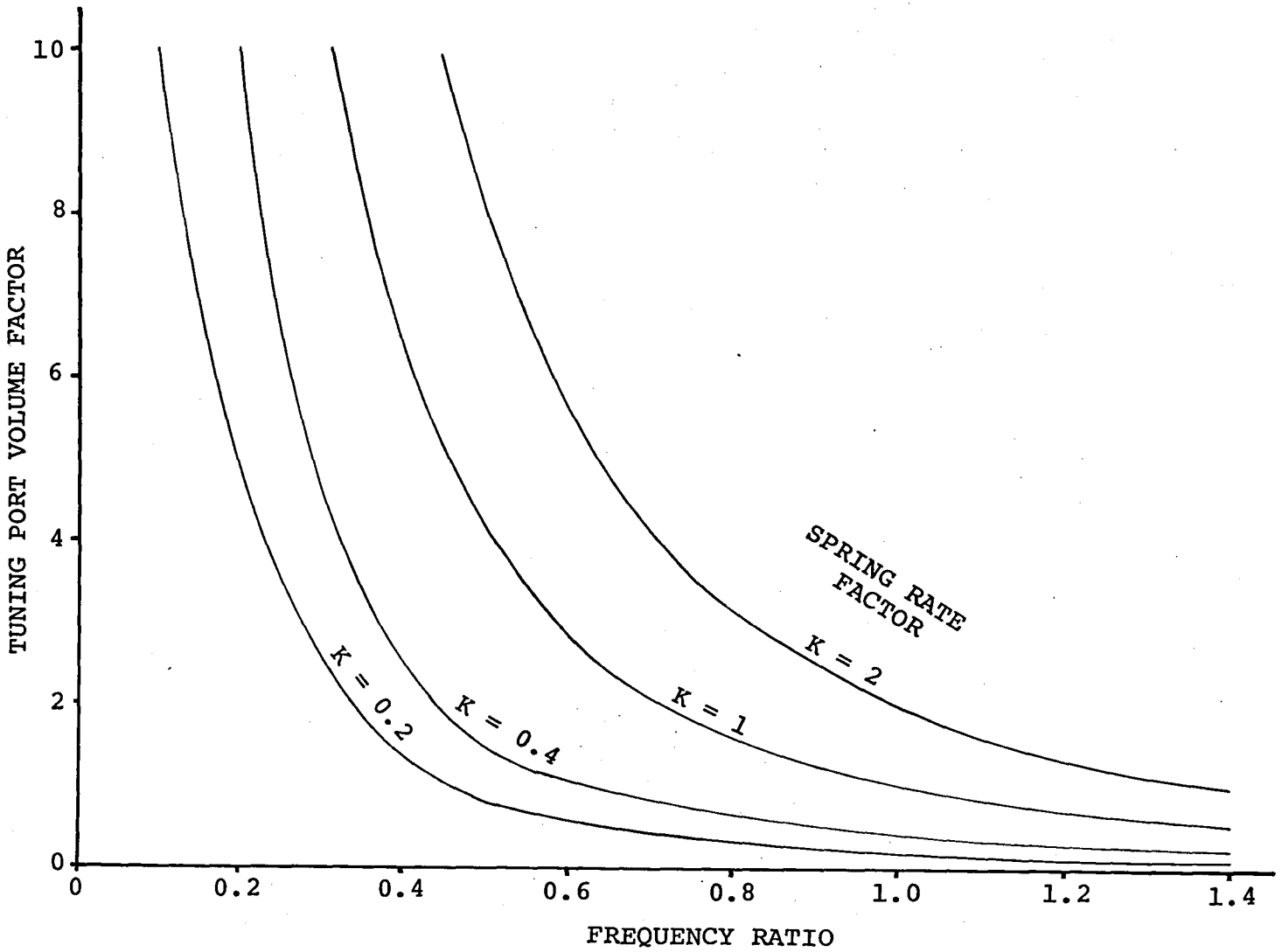


Figure 70. Effect of Frequency and Spring Rate on Tuning Port Volume.

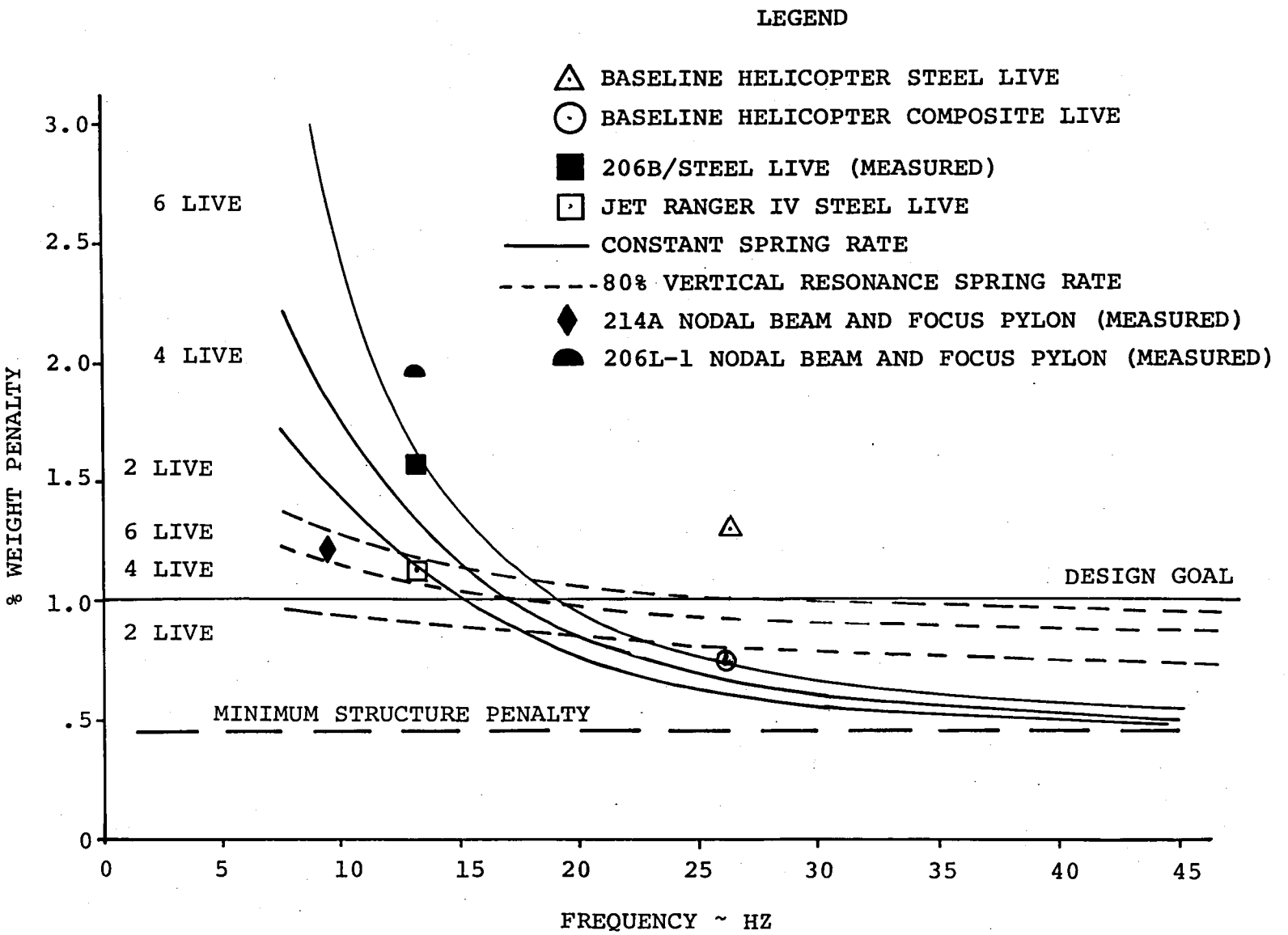


Figure 71. Weight Penalty of LIVE Total Isolation Systems.

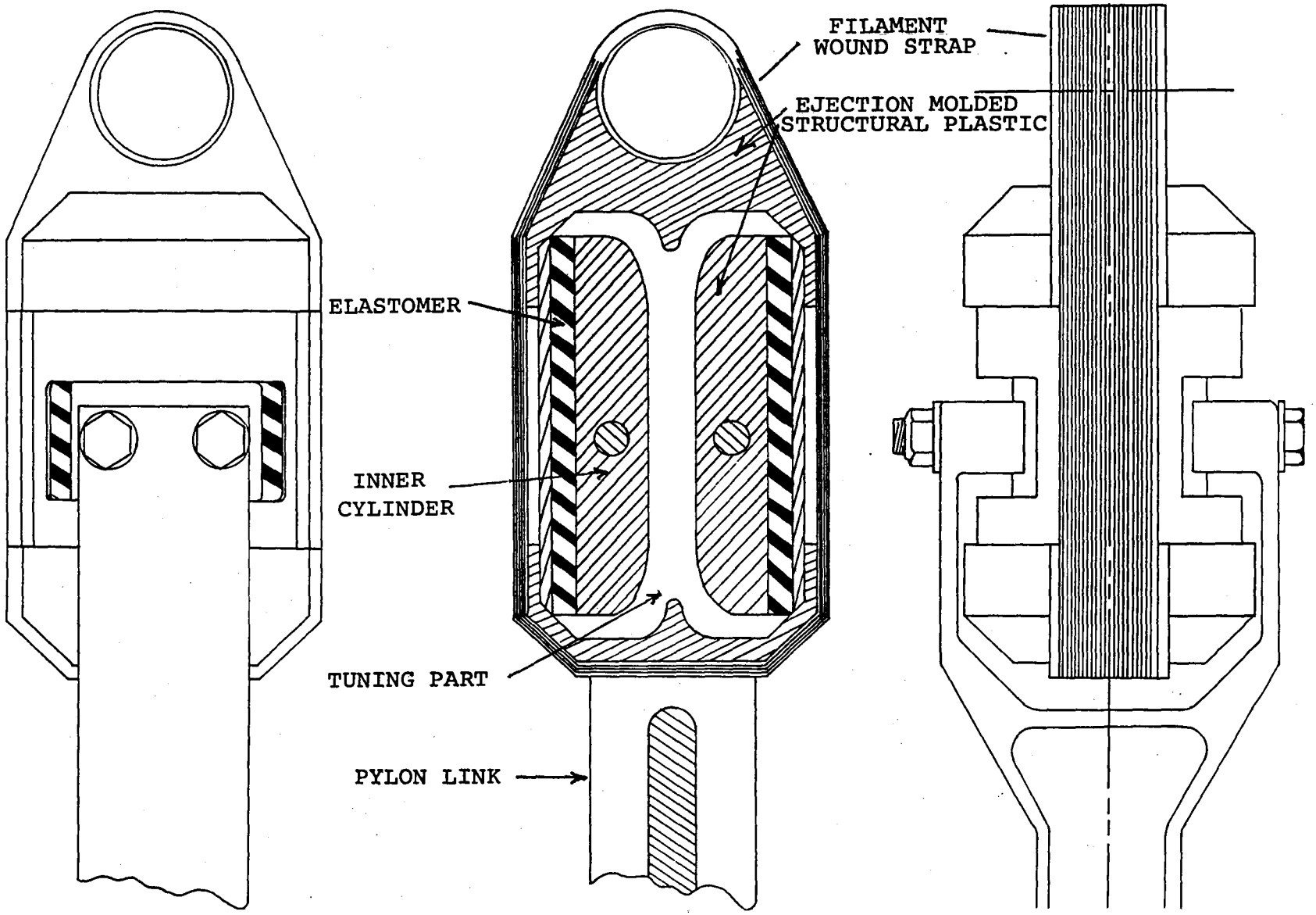


Figure 72. Construction for Composite LIVE Link

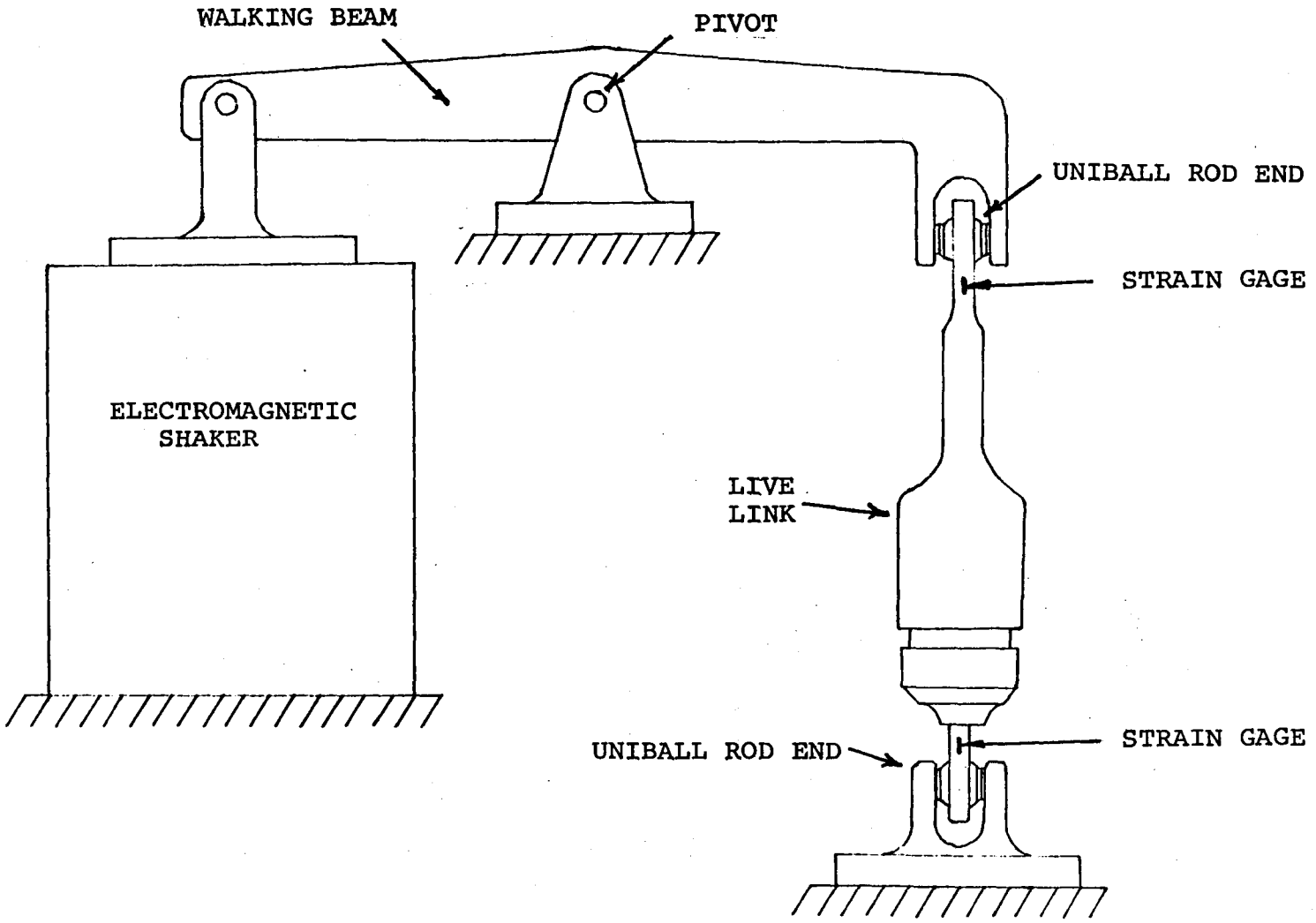


Figure 73. LIVE Link Test Installation

Use or disclosure of data on this page is subject to the restriction on the title page.

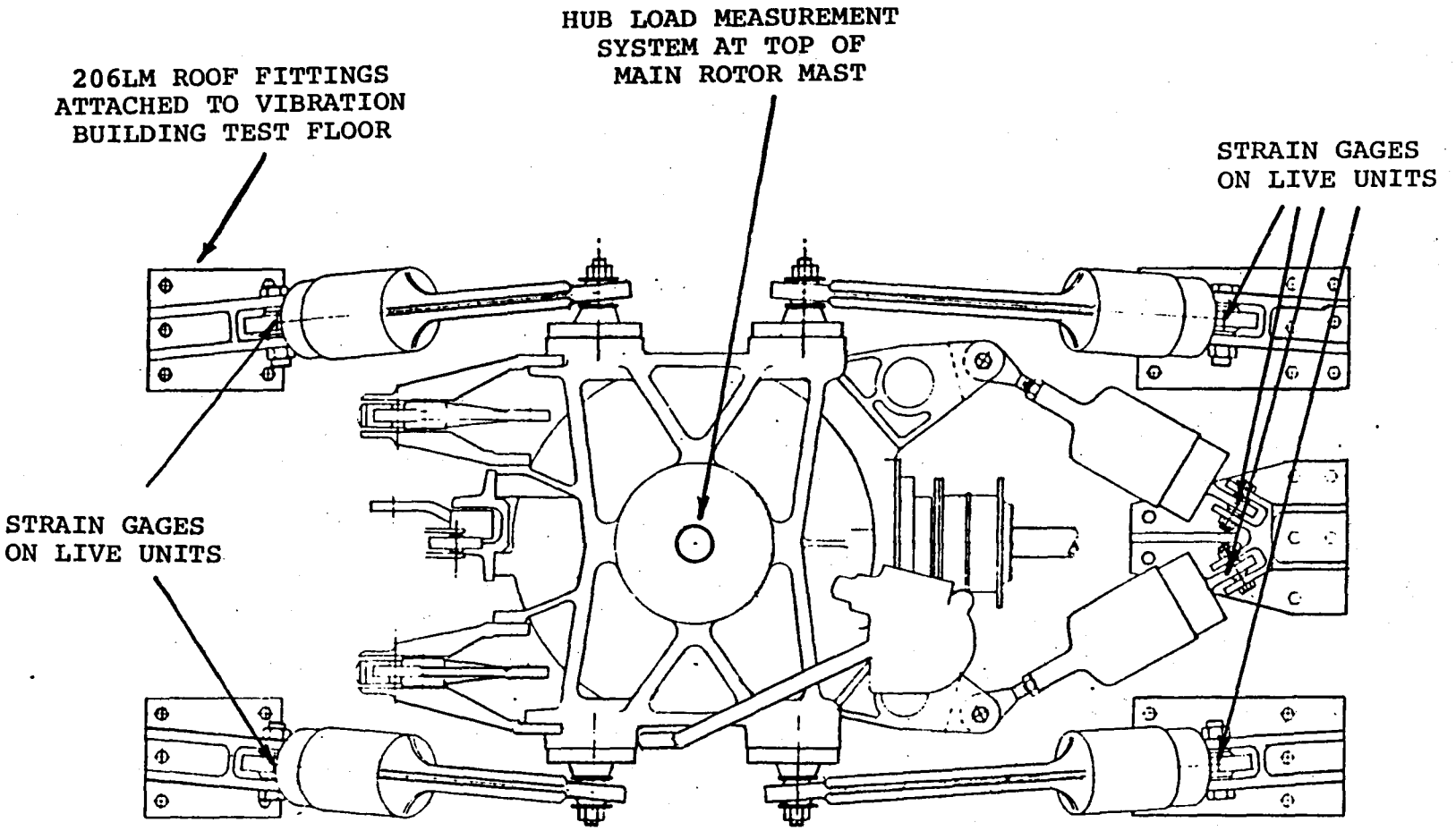


Figure 74. Six LIVE System Pylon Isolation Test Installed on Test Floor.

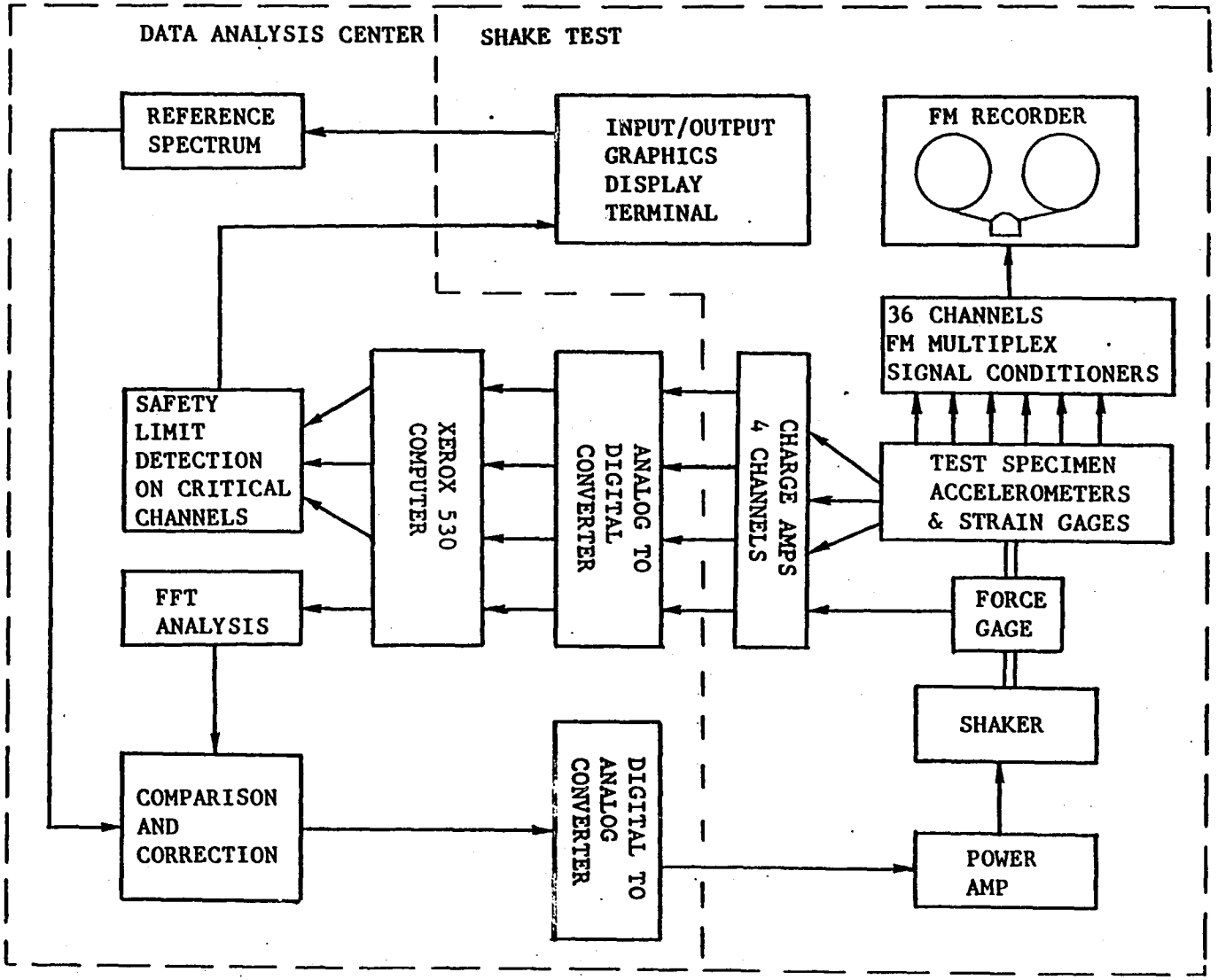


Figure 75. Block Diagram of Computer Control, Data Acquisition, and Analysis System.

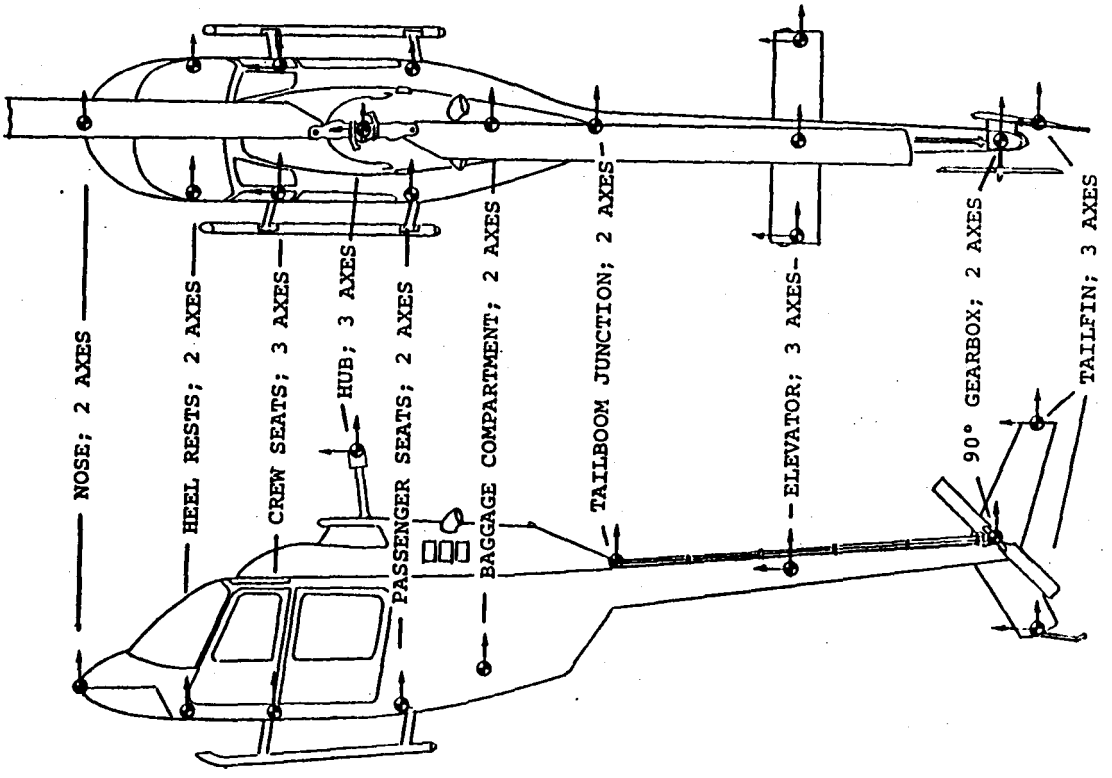


Figure 76. Accelerometer Locations for Vibration Test and Shake Test

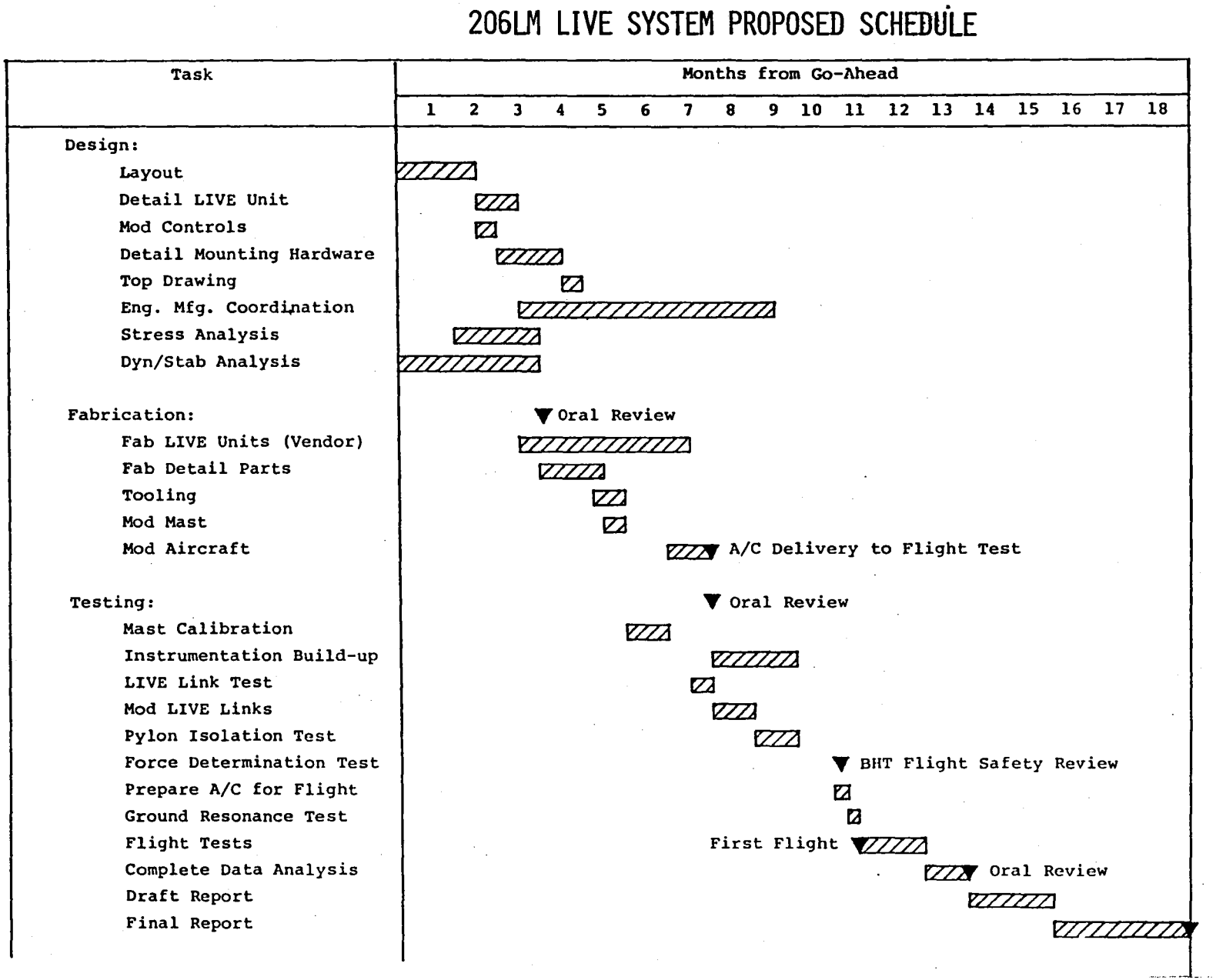


Figure 77. 206LM LIVE System Proposed Schedule.

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4 Title and Subtitle	5 Report Date
Total Main Rotor Isolation System	June 1981
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15 Supplementary Notes

16 Abstract

The requirements for a preliminary design study and verification procedure for a total main rotor isolation system at n/rev are established. The system is developed and analyzed, and predesign drawings are created for an isolation system that achieves over 95 percent isolation of all six degrees of freedom.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
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