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STUDY OF GROUND HANDLING CHARACTERISTICS OF A MARITIME PATROL AIRSHIP

FINAL REPORT

MARCH 1981

PREPARED UNDER CONTRACT NO. NAS2-10448

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GOODYEAR AEROSPACE CORPORATION

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16. Abstract

Mooring concepts appropriate for maritime patrol airship (MPA) vehicles are investigated.

The evolution of ground handling systems and procedures for all airship types is reviewed to ensure that appropriate consideration is given to past experiences. A tri-rotor maritime patrol airship is identified and described. Wind loads on a moored airship and the effects of these loads on vehicle design are analyzed. Several mooring concepts are assessed with respect to the airship design, wind loads, and mooring site considerations. Basing requirements and applicability of expeditionary mooring also are addressed.

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ABSTRACT

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The evolution of ground handling systems and procedures for all airship types is reviewed to ensure that appropriate consideration is given to past experiences. A tri-rotor maritime patrol airship is identified and described. Wind loads on a moored airship and the effects of these loads on vehicle design are analyzed. Several mooring concepts are assessed with respect to the airship design, wind loads, and mooring site considerations. Basing requirements and applicability of expeditionary mooring also are addressed.

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FOREWORD

With the recent advent of the Coast Guard's 200-mile coastal patrol zone, a renewed interest has developed in applying lighter-than-air (LTA) technology to developing high-performance and fuel-efficient maritime patrol vehicles (MPA's). The U.S. Coast Guard and U.S. Navy launched a joint effort to investigate their feasibility. As part of this on-going program, it was concluded that modern hybrid airships may be cost-effective and fuel-efficient vehicles capable of carrying out many maritime patrol missions.

One area identified as requiring in-depth technical study was the ground handling characteristics and associated equipment for this new class of vehicles. Historically, ground handling has been a severe problem for lighter-than-air vehicles due to their inherent lack of low-speed controllability. Even if modern hybrid airships exhibit a substantial increase in available control power, ground handling is still a concern.

In 1980, NASA and the U.S. Coast Guard signed a memorandum of agreement to coordinate development efforts in LTA technology. Based on this agreement, a timely decision was made to augment an on-going NASA-sponsored ground handling study contract (specifically aimed at the hybrid heavy lift airship) in order to analyze ground handling problems associated with maritime patrol airship configurations. Funds were made available by the U.S. Coast Guard. The original contracted study was carried out by Goodyear Aerospace Corporation (GAC) between December 1, 1979 and July 31, 1980. The augmented portion of the contract (for MPA vehicles) also was performed by Goodyear Aerospace and covered October 1, 1980 through February 28, 1981. The contractor's report number is GER-16948.

The objective of this ground handling study is to define several ground handling systems appropriate for MPA vehicles and to assess their impact on vehicle design and mooring operations. This report is the result of additional study performed under NASA-Ames Contract NAS2-10448. Accordingly, several portions of the NASA's Contractor Report CR-166130, "Preliminary Study of Ground Handling Characteristics of Buoyant Quad Rotor Vehicles," are repeated within this report.

Dr. H. Miura served as the NASA technical monitor for the augmented MPA ground handling study. Cognizant technical personnel for the U.S. Coast Guard were Commander K. Williams and Mr. L. Nivert. Within Goodyear Aerospace, Mr. Dale E. Williams, LTA program manager, and Mr. Donald B. Block, chief LTA engineer, provided overall program guidance. Mr. Ronald G. E. Browning was the project engineer. Prime contributors were Mr. F. Bloetscher, Mr. W. Trumpold, Mr. A. Ahart, Mr. L. Cermak, and Mr. P. Jacobs.

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SECTION I - HISTORICAL REVIEW

1. EARLY APPROACHES

a. General

The evolution of ground handling systems has, by necessity, paralleled the advancement of airship design and operational capabilities (References 1-11). Early craft, due to their limited size, were easily ground handled to and from mooring sheds by small groups of men. However, as envelope size increased, more effective and efficient ground support became necessary.

b. Floating Hangar

Not unexpectedly, Von Zeppelin extended his innovative skills to airship mooring. The use of a floating hangar on Lake Constance was the culmination of his assessment of how to satisfy three main requirements for airship mooring operations:

1. Provide a flat surface
2. Provide unobstructed approaches
3. Enable the airship always to carry out docking procedures in line with the prevailing wind direction.

This also marked the inception of mechanical handling systems through the use of small boats acting as tugs.

The downfall of this approach was its sensitivity to stormy weather. Due to this, the concept was eventually abandoned and a return to land facilities was implemented. Two early examples are shown in Figure 1-1.

c. Manpower

For several years, no attempt was made to change the operation of walking an airship to and from its protective hangar. Since most airship flights during this period (World War I) were conducted by the military, a sufficiently large contingent of personnel was always available for ground handling. This system remained, however, closely dependent on wind conditions. Numerous flights either were cancelled or extended due to incompatible winds at the scheduled undocking or docking times, respectively.

d. Docking Rails and Trolleys

In keeping with the philosophy of providing hangar space for an airship when it was not in flight, early attempts at ground handling were aimed

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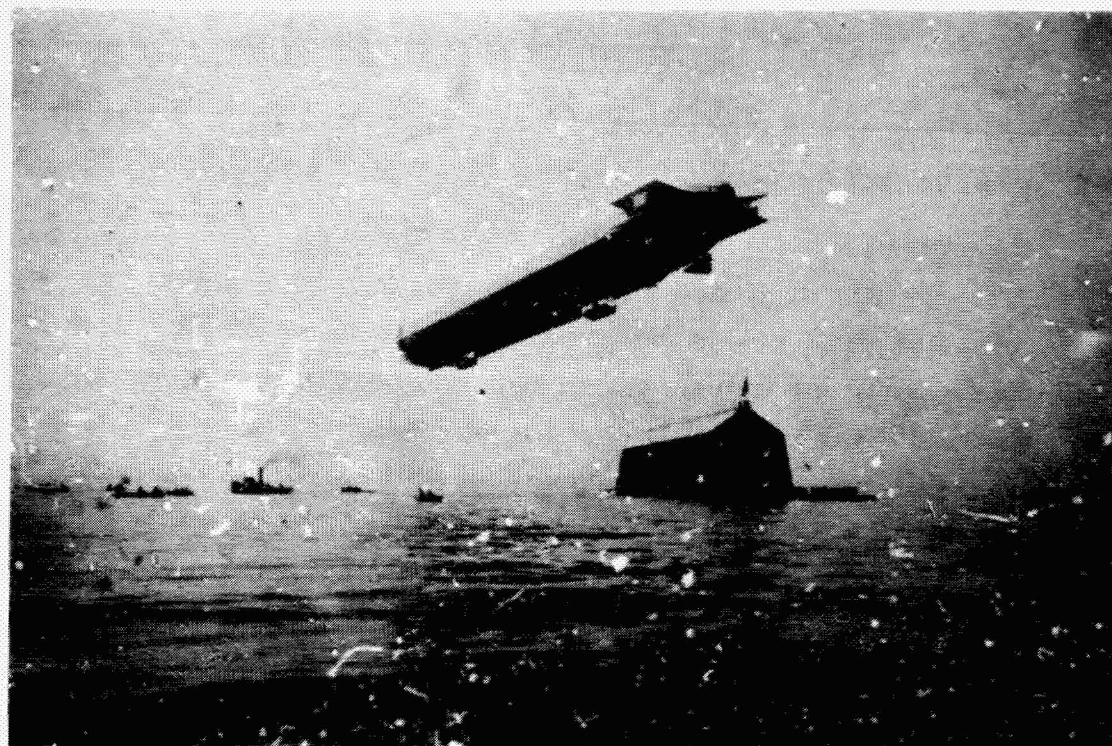

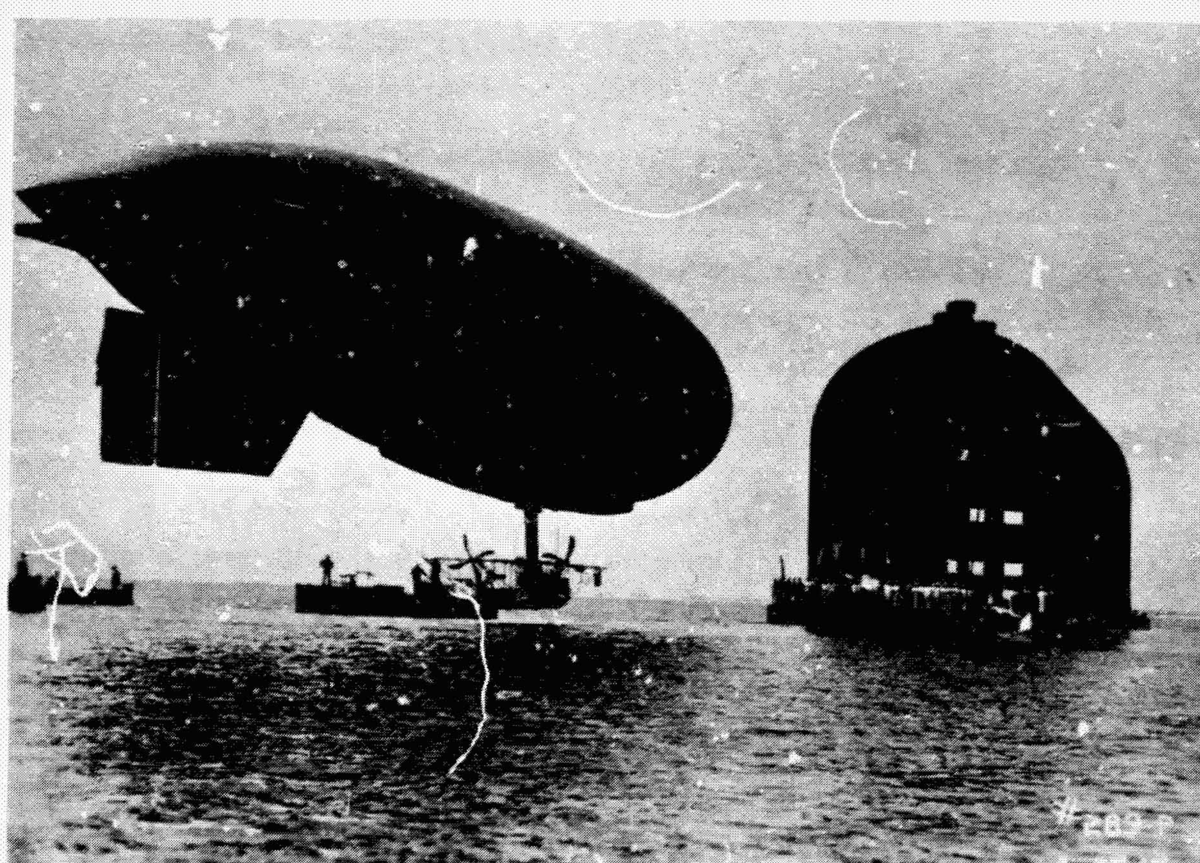

Figure 1-1 - Early Examples of Floating Airdocks at improving the efficiency of moving the airship to and from the hangar, rather than providing an exterior mooring system. The result was the development of docking rails and trolleys (see Figures 1-2 and 1-3). Initial design and use of this equipment was undertaken by the Germans and Italians. System refinements were instituted at a later date in both the United States and England.

Docking rails were built along the inside of each hangar wall and extended some distance out onto the airfield (see Figure 1-4). These rails provided a rigid base along which mobile trolleys could run, thereby establishing a control system for the critical portion of the airship undocking/docking sequence.

A typical docking operation utilizing the rail/trolley system is:

1. The airship lands and is walked to the external rail end by the ground crew.
2. A rope tackle is attached from the left and right trolleys to bow mooring points on the airship.
3. The airship is walked forward until trolleys can be attached in the same manner to stern mooring points.
4. The airship, now secured fore and aft, is walked into the hangar.

Eight crewmen were used on each trolley. The remaining available personnel were assigned to the bow hauling rope to ease the airship forward and underneath the car to keep it from contacting the ground.

e. Ground Cable Landing System

Another early attempt at minimizing ground crew personnel requirements was the ground cable landing. The end points of a long cable were secured, through springs, to ground anchor points. The airship's objective was to engage the cable with a suspended grappling hook while flying overhead. The results of this experiment were unsuccessful.

f. Mooring-by-Wire

Several variations of a mooring by wire system were suggested and tried (see Figure 1-5). Although experiences with these systems were not totally unsatisfactory, some significant drawbacks made them impractical.

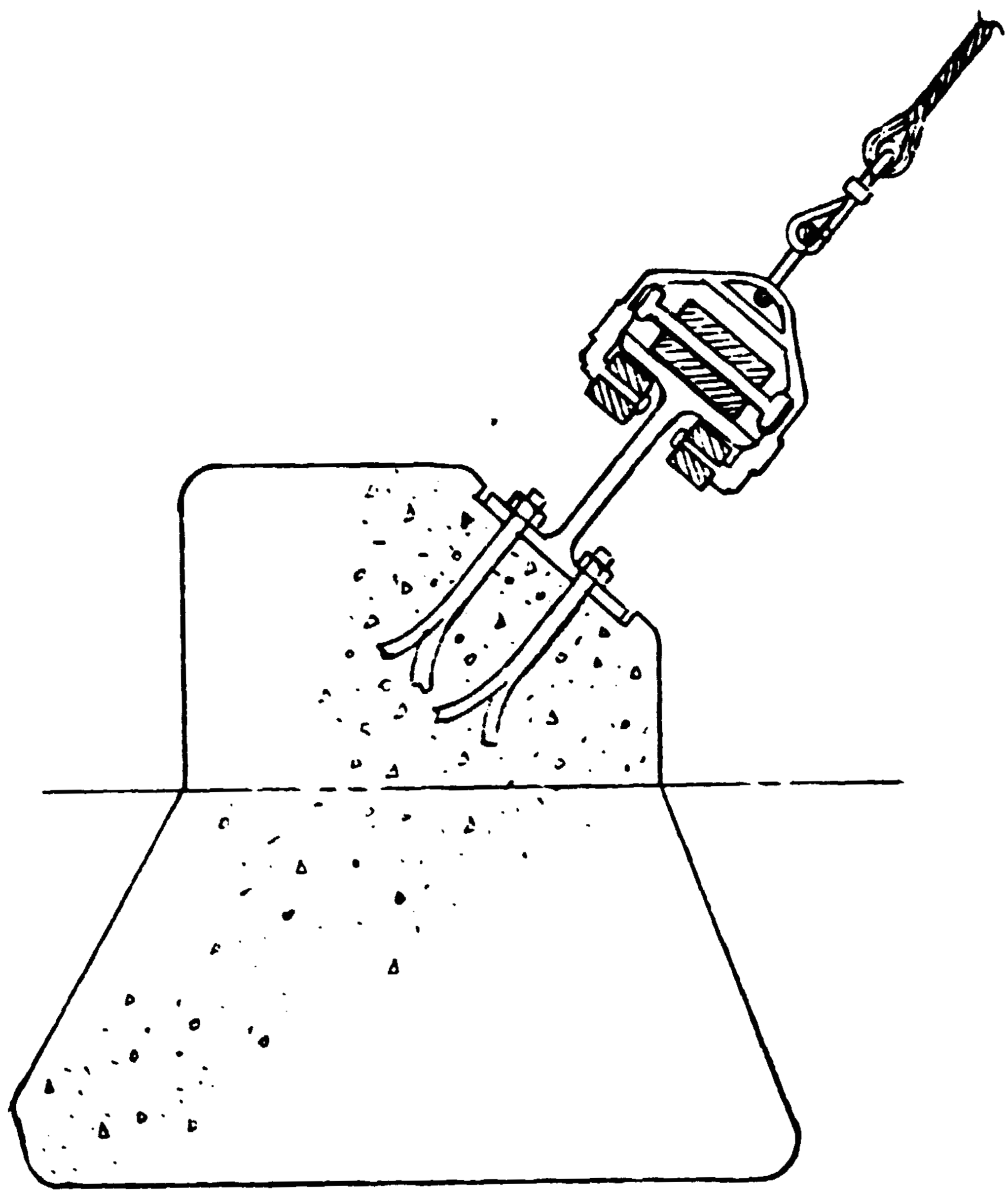

Figure 1-2 - Italian Docking Rail and Trolley (1923)

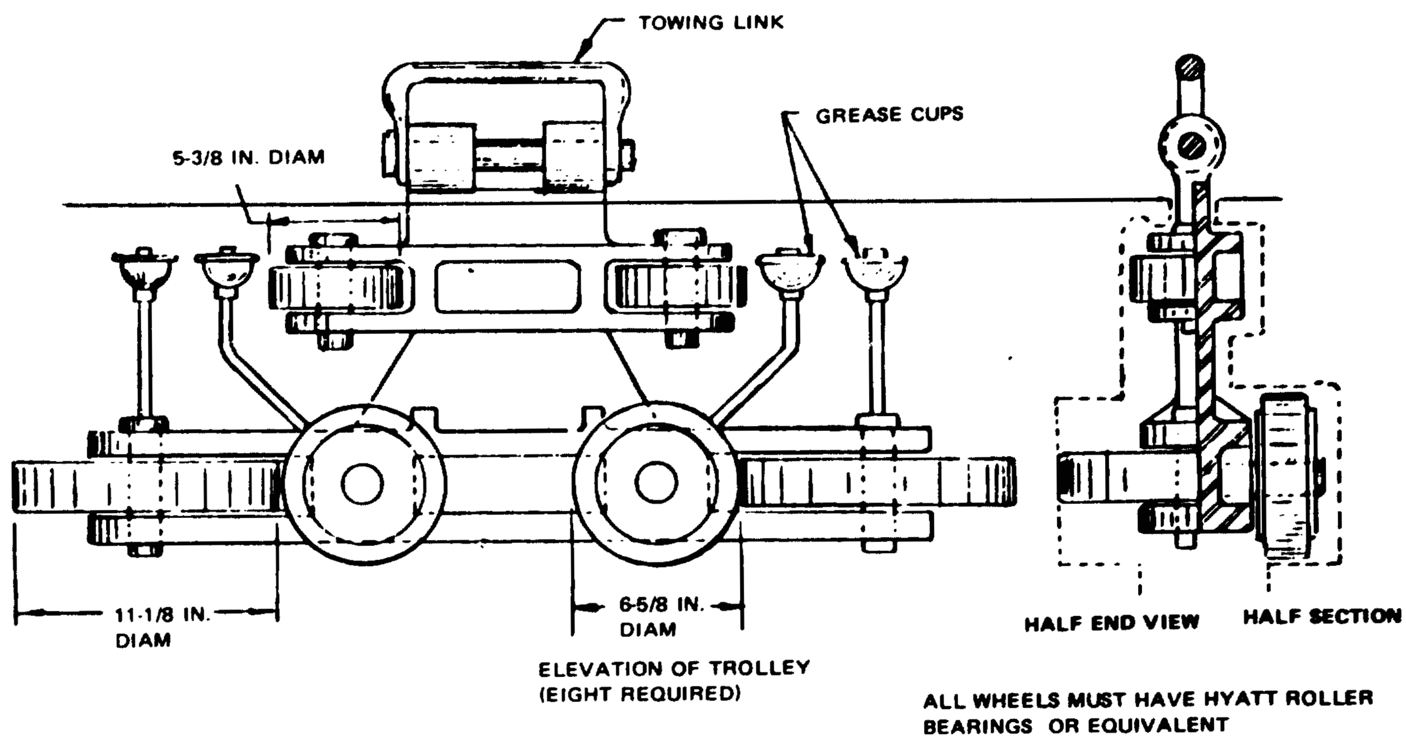

Figure 1-3 - Docking Rail Trolley (1923)

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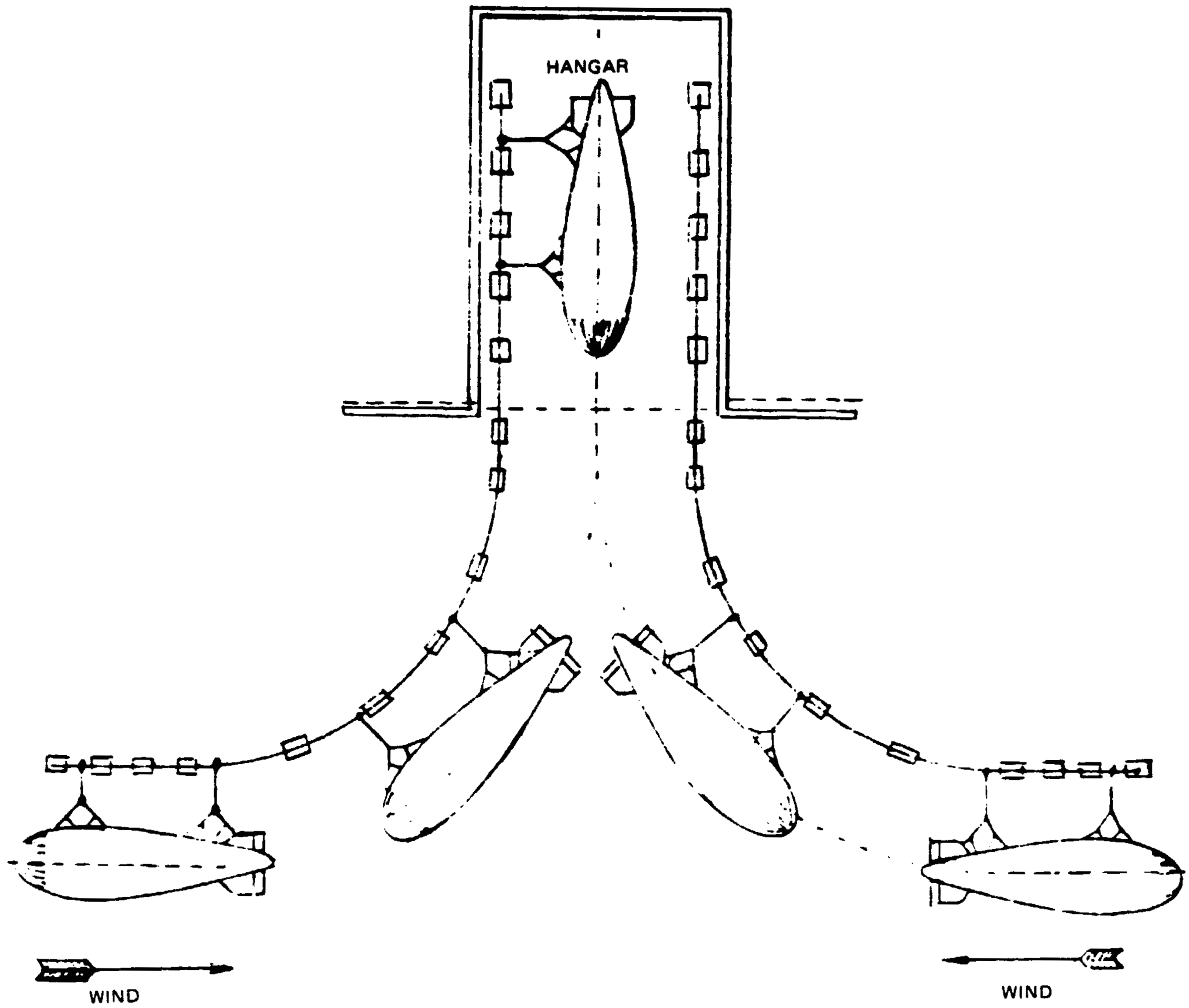

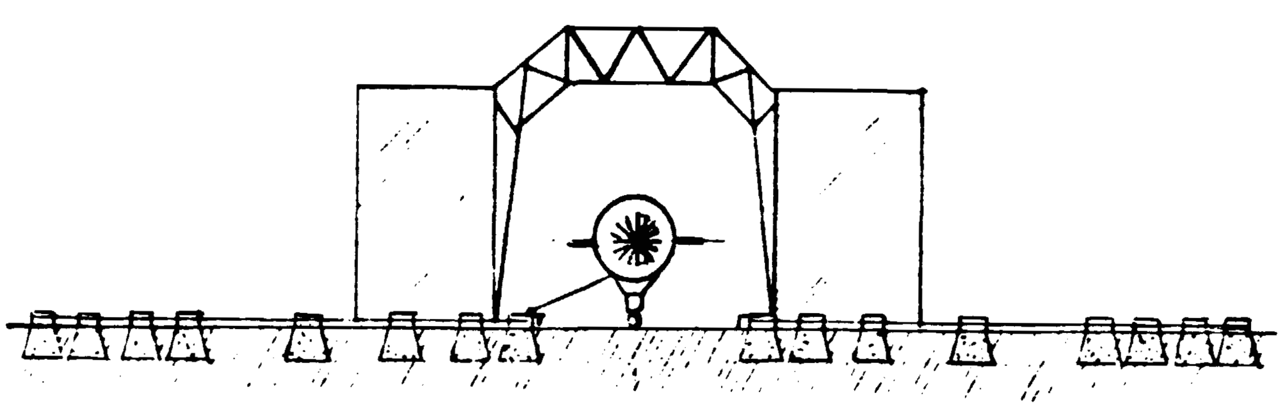

Figure 1-4 - Italian Single Rail and Trolley (1923)

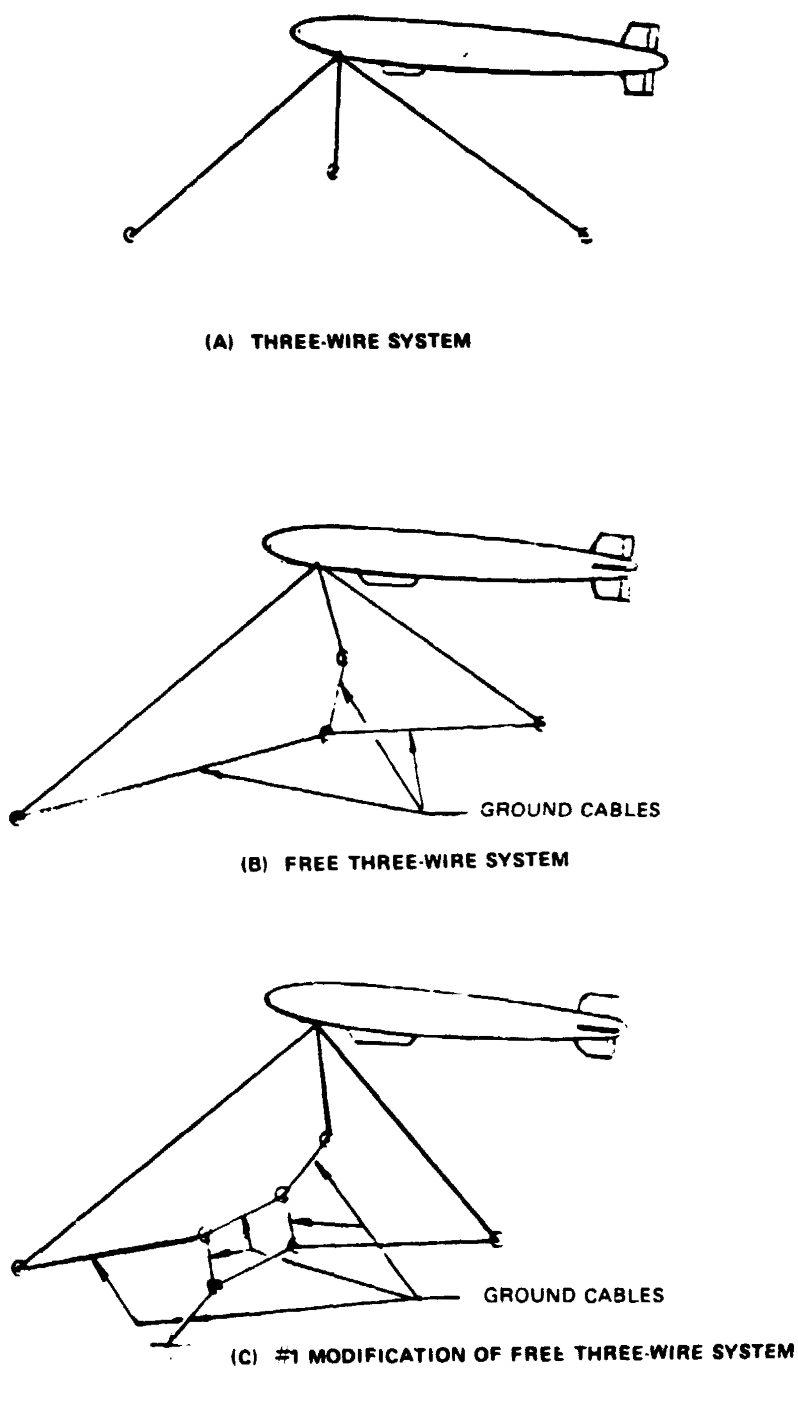

Figure 1-5 - Three-Wire Mooring System

Four variations were attempted:

1. The Usborne system consisted of two vertical wires attached to the car. This proved to be unstable in high winds.
2. The basic three-wire system utilized wires attached at one point on the airship to form an equilateral pyramid. This configuration was used to bring the rigid airships to their mooring masts even through the system itself proved to be too unstable for mooring out.
3. The free-three-wire system enables the three cables to feed from the apex of the equilateral pyramid through sheave blocks anchored to the ground and attached to a free-moving central ring. This concept eliminated the rigidity of the fixed cable system. As a result, the free-three-wire system provided the airship with more stable riding out characteristics.
4. A four-wire system had one additional wire from the ring (described above) to a ground anchor point. This, in effect, formed the ring into a parallelogram. Although this system was tested, it was not successful.

Conclusions resulting from experiences with mooring-by-wire systems were:

1. For maximum stability, an airship would have to be trimmed four to five degrees down by the tail and held a similar amount off wind.
2. Since heating and cooling causes rapid change in the airship static condition, a rapid ballasting system would have had to be developed.
3. To keep tension on the wires, the airship would have to be maintained in a light static condition.
4. Ballasting and fueling an airship moored in this manner would be very difficult.
5. A crew would have to remain on board at all times. Crew changes would be very difficult.
6. The mooring area would be large.

The mooring by wire system was proven to be too unstable and cumbersome to be practical, except possibly as an alternative emergency mooring system.

g. Vickers Masterman Mast

The Vickers mast was an early development by the English for non-rigid airships. Its unique design enabled the airship to be cradled in a yoke rather than be constrained at a single attachment point (see Figure 1-6). Two pads were fastened to the envelope several feet behind the nose to reinforce the contact areas between the airship and the end points of the yoke.

To initiate the mooring procedure, the ground crew, with handling guys, would walk the airship upwind toward the mast. At the yoke, a man would be stationed at a winch in each yoke. Once the airship was properly positioned in the yoke, cables would be attached to the envelope and reeled in such a manner that the airship was securely attached to the mast.

While the Vickers mast saw limited use for several years, deficiencies in the following areas accounted for its final demise:

1. The mooring patches were cumbersome and had sufficient weight to cause the airship to become nose heavy
2. The patches were difficult to attach
3. The mooring operation was extremely sensitive to high, gusty winds and therefore required an excessive number of ground personnel
4. There was insufficient positive maneuvering action during mooring
5. The positioning of two men on the yoke of the mast was hazardous

h. Nose Mooring Systems

(a) General

The expansion of military airship programs stimulated the search for acceptable mooring systems. Hangars were operationally effective but prohibitive in cost. Thus, development of an outside mooring technique was mandatory. The nose mooring system appeared to be the most suitable.

Consistent with this approach was the development of nose battens in non-rigid airships. While early airships were slow enough to obviate this need, newer and faster craft required nose stiffening to prevent in-flight fabric deformation. Similarly, a nose mooring approach necessitated the development of a system to distribute the mooring loads. A fabric-covered metal nose cone structure satisfied both these needs.

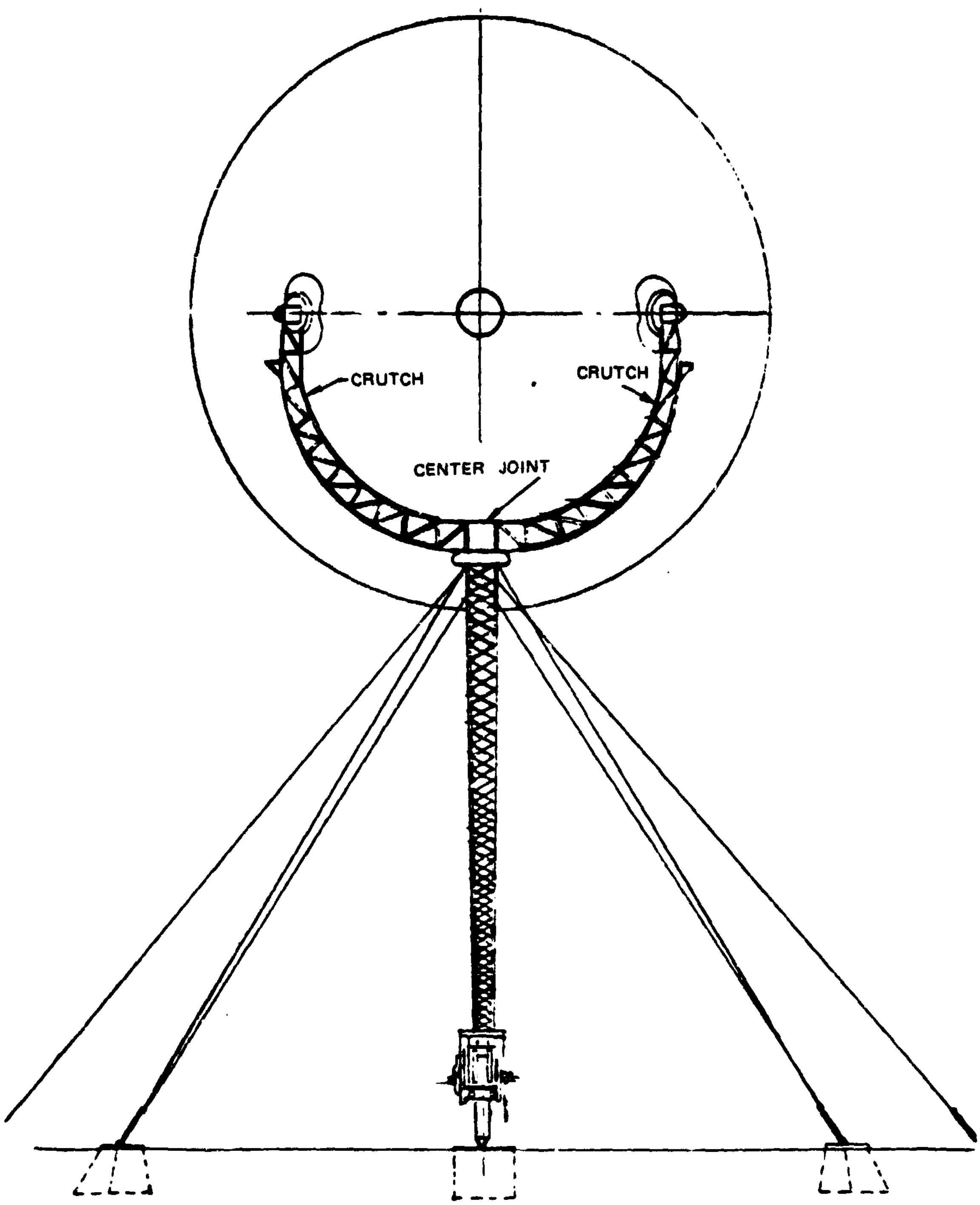

Figure 1-6 - Vickers Mooring Mast (1923)

This led to new airships with a grooved, bearing-mounted spindle installed in the nose cone and a flexible steel pull-in cable secured to the spindle. Battens were attached to the base of the nose cone to distribute the mooring loads evenly over the envelope surface. Initially, these battens were made of wood but were eventually replaced by stronger and lighter aluminum battens. The spindle in the nose cone was mated to a device atop a mooring mast. These early masts were simply variations of guyed built-up steel structures with a hand winch at the bottom and a buffer at the top against which the airship would be drawn. As airships increased in size, more efficient and stronger masts were produced.

(b) Terry Mast (for Non-Rigid Airships)

One type of mast developed early by the military was known as the terry mast (see Figure 1-7). This mast consisted of a structural steel center pole supported by eight guys anchored in the ground. On top of the mast a 13-foot-diameter cone-shaped buffer was mounted. The buffer ring had felt pads secured around the lip to reduce envelope wear at the contact points. The buffer was attached to an arm of a circular casting that rotated on bearings on top of the mast. Counterweights were attached to another casting arm opposite to the buffer.

A pull-in line was attached to two nose patches and run through a sheave on the mast head, down through the mast, and out through another sheave at the bottom, finally to a winch. Once the hookup was made, the winch reeled in the airship until the envelope nose was snug inside the buffer cone. Tension was kept on the pull-in line, and the winch was locked.

While this configuration had merit in terms of minimizing ground crew requirements, it had several drawbacks:

1. The cone and counterweight were heavy and exhibited a flywheel characteristic in shifting winds.
2. Load distribution was unsatisfactory. The buffer cone should have been extended by four to six feet and contoured to the envelope's shape.
3. The nose patches were unable to sustain the pull-in cable load.
4. Considerable stresses built up in the envelope immediately aft of the buffer ring. In actual recorded cases, battens were broken and envelope fabric torn due to these stresses.

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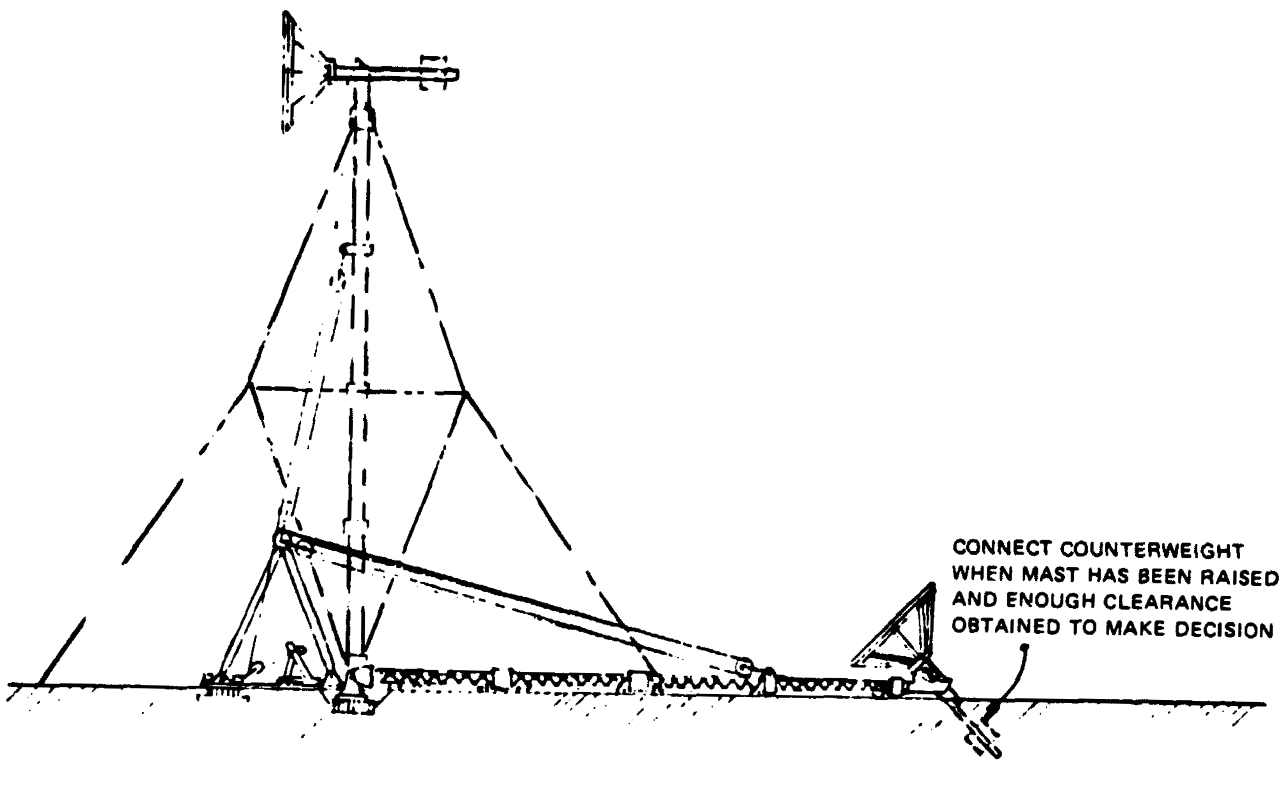

Figure 1-7 - Terry-Type Mooring Mast (1923)

5. Forward and aft shocks around the buffer ring were experienced during mooring operations in gusty winds.

(c) High Mast

Coincident with the rapid development of rigid airships for intercontinental travel in the 1920's was the design of a high mast. This system resulted in the elimination of a hangar as a necessity for airship operations, thereby providing a solution for more efficient (both operationally and economically) mooring hardware that could be made available at several terminal locations (see Figure 1-8). This approach, however, was not devoid of drawbacks. A moored airship was, in fact, always being flown at the mast. Consequently, an on-board flight crew was a continuous requirement. In addition, undesirable air currents were occasionally encountered at the mooring height, thus causing extreme airship attitudes.

In the same decade, the U. S. Navy entered the rigid airship world with the delivery of the ZR-1 Shenandoah in the fall of 1923 and the ZR-3 Los Angeles one year later. Accommodation in the form of a 100-foot high mast was provided at Lakehurst, New Jersey (see Figure 1-9). A sequential description of the airship's operations at this site is as follows:

1. The mast and airship are prepared for the mooring operation.
2. When all is ready, the airship approaches the mast into the wind.
3. When near the 500-foot circle, the main mooring wire is dropped.
4. The ground crew connects the airship and mast wires.
5. The airship then rises until the mooring lines are taut, discharging ballast if necessary to accomplish this.
6. The main winch starts to haul in the airship.
7. After the main hauling line is taut, the left yaw line is let down on a messenger block carrying the end of the line to the mast cup.
8. The same operation is repeated for the right yaw line.
9. When the airship's yaw lines are coupled to the mast yaw lines, they are cast adrift from the mast platform and hauling is begun.

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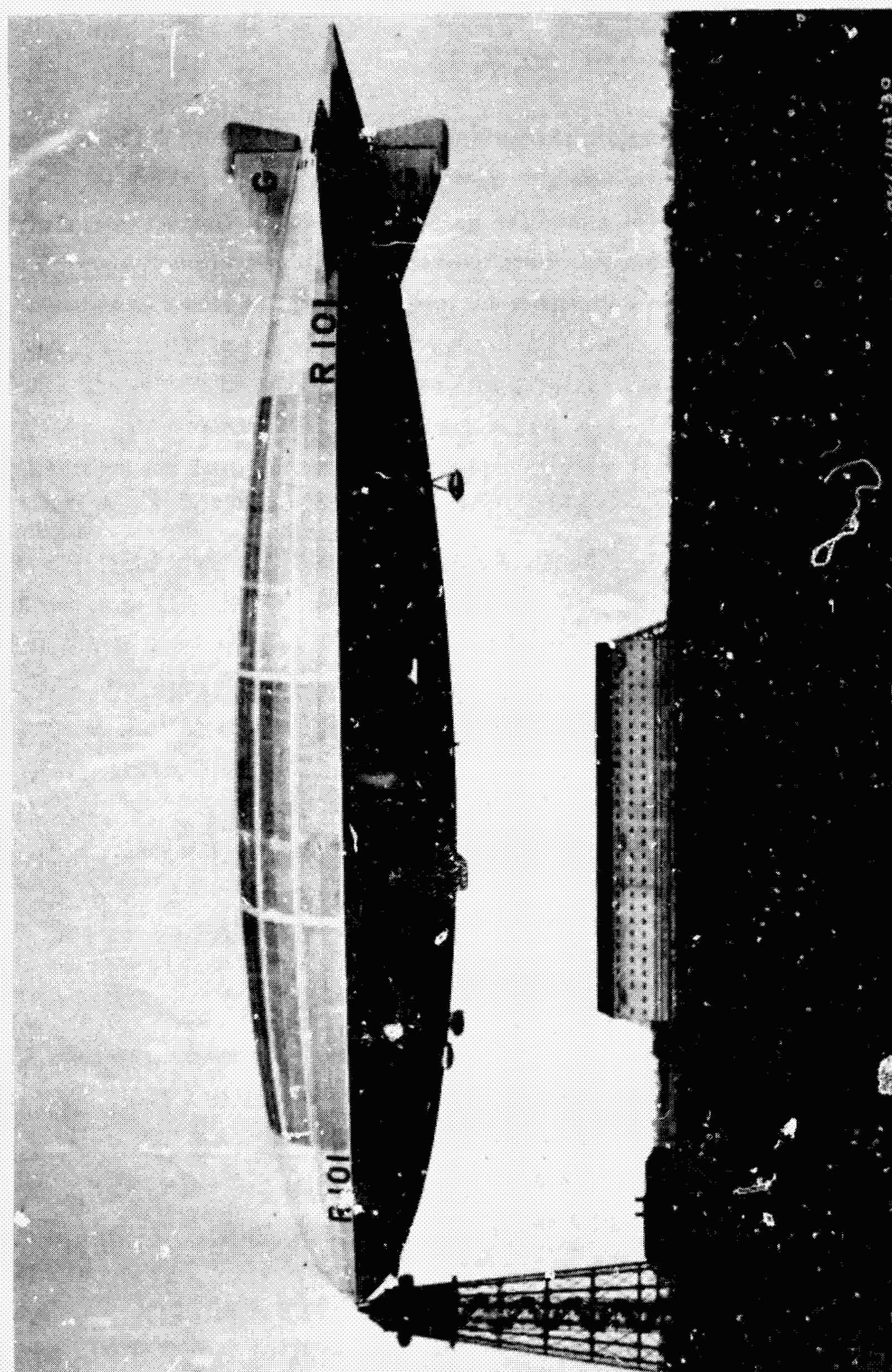

Figure 1-8 - English High Mast (Cardington, England), 1930

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Figure 1-9 - Navy High Mast (Lakehurst, New Jersey), 1925

10. Each mast yaw winch is operated until a predetermined mark on its guy appears at the snatch block anchorage, which indicates that there is just enough line between the snatch blocks and the bow of the airship to allow the airship's cone to be brought down into the mast cup. The mast yaw winches are then stopped and the lines held.
11. When the airship's cone is about 25 feet from the mast cup, the speed is reduced and maintained "dead" slow.
12. The main hauling line continues to draw the airship forward and down until the airship's cone enters the revolving cup on the mast and locks itself into place with the three spring locks.
13. When the airship is secured to the mast, all airship lines are returned to the airship.
14. The airship is immediately readied for flight so that an emergency unmasting could be accomplished if a situation required it.
15. Ballast lines and the tail-drag are hooked up.

The egress operation is as follows:

1. The airship is trimmed and weighed off light so that it will rise immediately after release.
2. The release pendant is slacked off a few inches to allow movement of the cone in the mast cup.
3. The releasing hook is tripped, and the airship rises carrying the releasing pendant out through the ram and cup.
4. The releasing pendant is retrieved and secured in the airship and the tail-drag is dropped.

Fifteen ground personnel were required for high mast rigid airship mooring operations.

(d) USN "Stub" or Expeditionary Mast (for Rigid Airships)

In the late 1920's, the U. S. Navy became interested in the stub or expeditionary mast. It had several advantages over the high mast. Since the stub mast was designed for quick assembly and disassembly, it could be made transportable. This made it usable for temporary mooring-out sites (see Figure 1-10). The stub mast's low height meant that the airship would be moored horizontally a few feet above the ground. A detachable castering, pneumatic wheel was designed for attachment to the aft power car. This allowed the airship to swing around the mast without damage. However, some conditions would cause the airship to kite. Various systems were tried to counter this phenomenon such as drag chains, drag wheels, and rail-mounted mooring-out cars. All of these concepts met with limited success.

(e) Self-Propelled Mobile Mooring Mast (for Rigid Airships)

To facilitate ground handling of the large rigid airships, the U. S. Navy experimented with a 100-ton, self-propelled, mobile mooring mast (see Figure 1-11). This pyramid mast was 60 feet on a side and was mounted on crawlers. The wide base and mass of this mast overcame the overturning moment imposed by moderate wind loads on the rigid airships. By mounting each corner of the triangular base on crawlers, and through the use of a self-contained power source, the mast unit was able to traverse the Lakehurst terrain successfully. A similar self-propelled mobile mast was used on the Akron and Macon airships in Akron, Ohio.

(f) Rail-Type Hauling-Up and Mooring-Out Circles

The U. S. Navy rigid airship program expanded dramatically in the early 1930's with the addition of the ZR-4 Akron and the ZR-5 Macon to the fleet. Ground handling equipment and techniques had improved, but further development was required such as:

1. A method of eliminating the hazardous transfer of an airship from a fixed mooring mast to a mobile mast for docking operations

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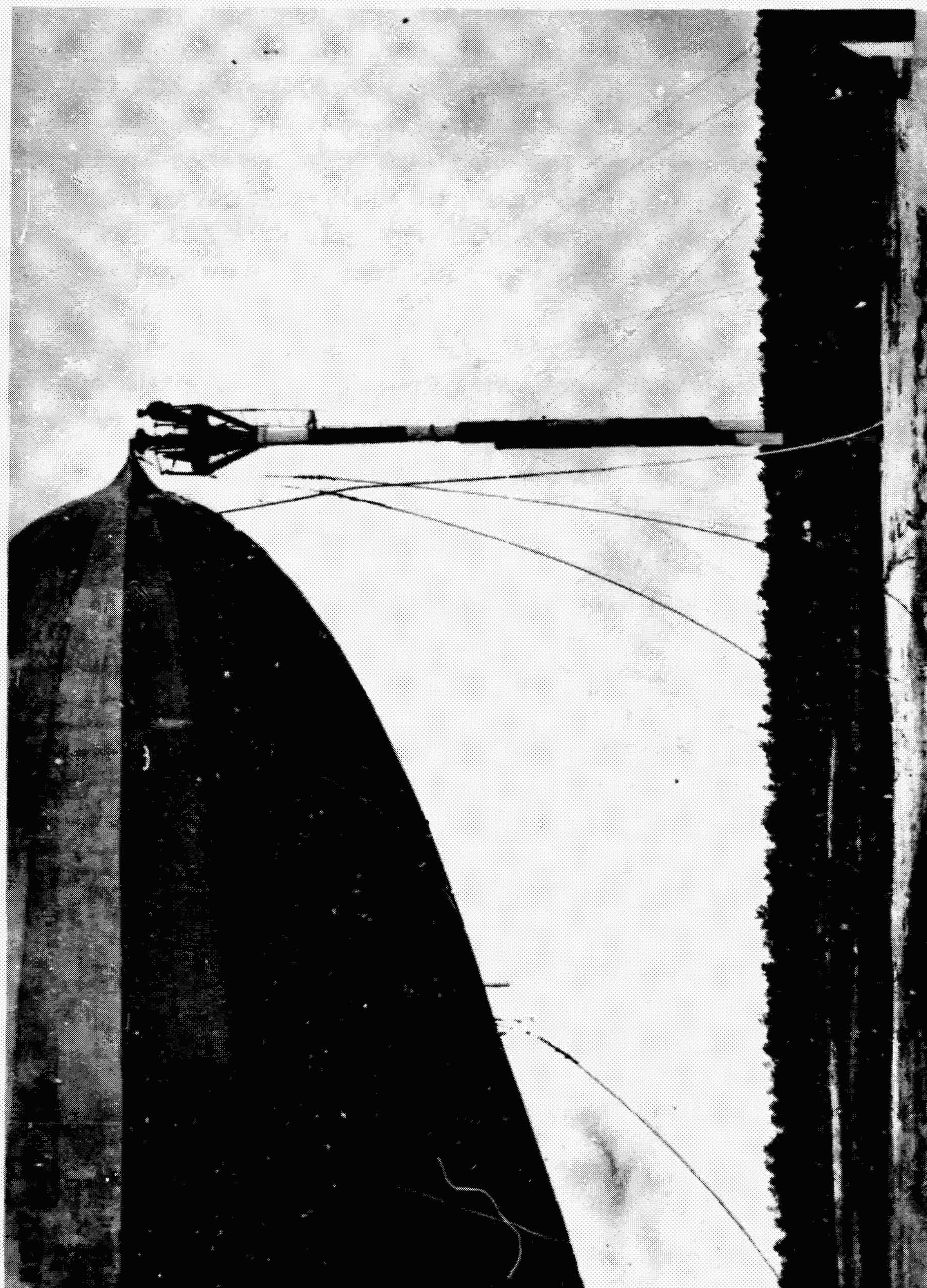

Figure 1-10 - Stub or Expeditionary Mast (1927)

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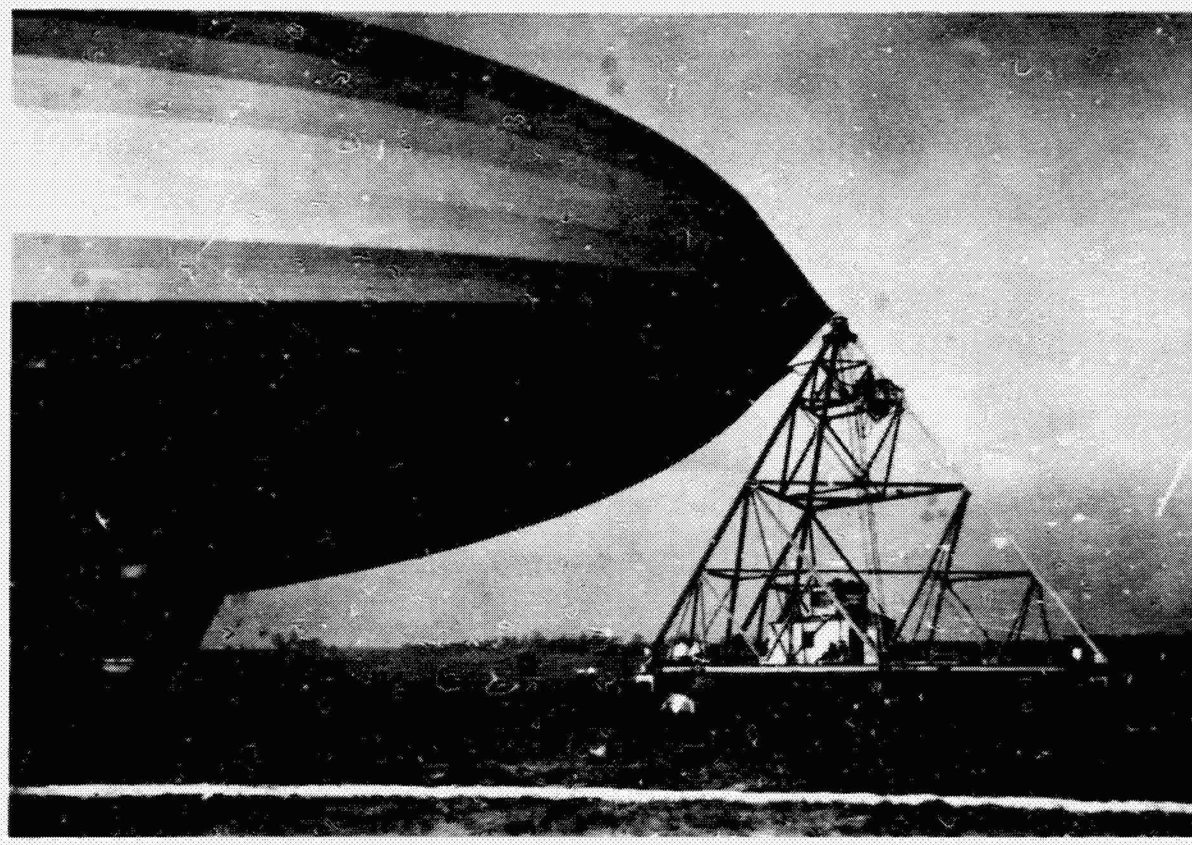


Figure 1-11 - Self-Propelled Mobile Mast (1932)

2. A system that would hold the airship securely during docking operations regardless of the winds
3. Equipment that would reduce the need for large numbers of personnel in the ground handling crews

The final outcome was a docking/undocking, ground handling, and mooring system totally mounted on rails (see Figure 1-12). This system consisted of:

1. Two railroad tracks, 64½ feet apart, running through the hangar and 1200 feet out onto the field.
2. An intersecting 650-foot-radius circular track used for hauling-up operations.
3. Additional track extending out to another circle used for mooring out.

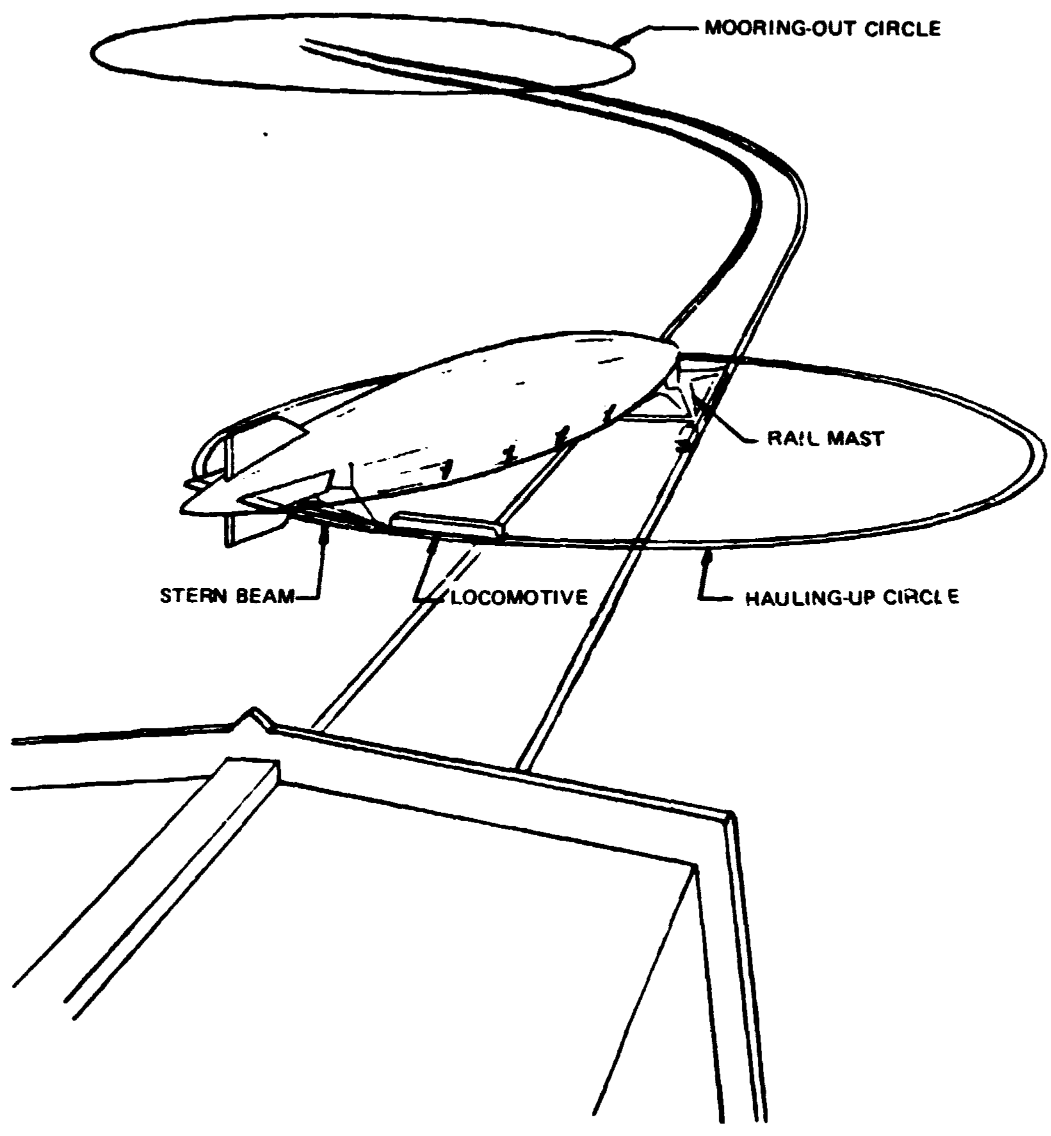


Figure 1-12 - Rail-Type Hauling-Up and Mooring-Out Circles (1930)

4. A rail-mounted, locomotive-powered, mobile mooring mast.
5. A rail-mounted stern handling beam coupled to
6. A second locomotive mounted on the hauling-up circle to swing the stern beam.

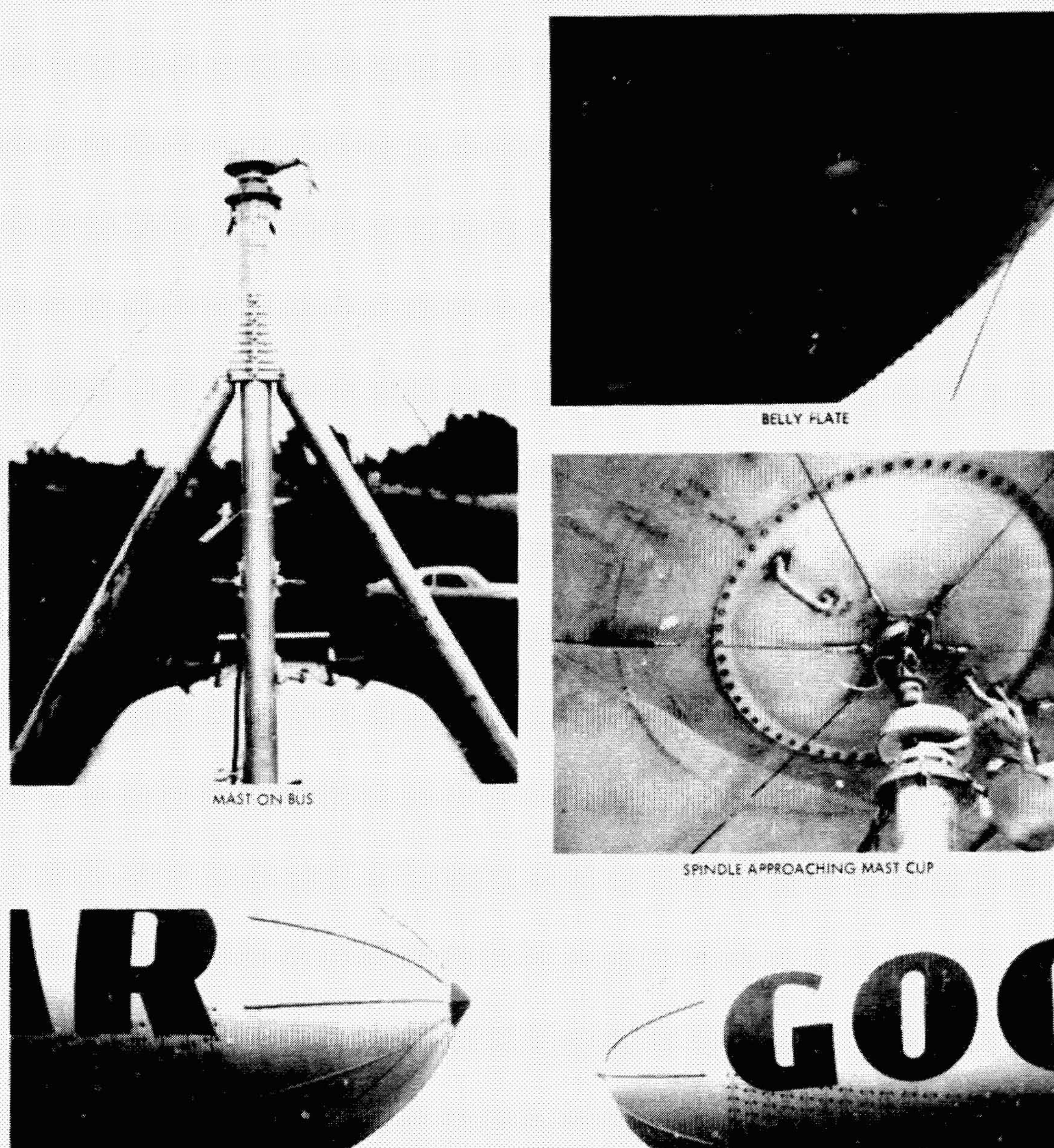
The airship was towed in or out of the hangar secured between the mobile mooring mast at the nose and the 178,000-pound stern handling beam. The mobile mast would be stopped at the center of the hauling-up circle. The stern beam was transferred from the hauling-up circular track to the straight track by means of jacking trucks. The stern locomotive would position the stern beam as required for the docking or undocking operations. If the airship were to be moored out, it would be positioned into the wind and disconnected from the stern beam. A taxi wheel supporting the aft part of the airship was attached, and then the mobile mast would pull the airship out to the mooring circle.

i. Belly Mooring Mast System (Non-Rigid Airships)

In the late 1920's, The Goodyear Tire & Rubber Company developed a belly mooring system that was unique to its commercial airship fleet. Because of its limited load sustaining ability, it was eventually replaced by an expeditionary mast as the main mooring system. The belly mooring system (see Figure 1-13) consists of a metal disc mounted in the underside of the airship envelope approximately half way between the nose and the front of the car. Several cables attached radiate from the periphery of the disc and have their ends attached to envelope finger patches. A gimbaled spindle is mounted in the center of the disc, with a short pull-in cable attached to it.

A modified bus (see Figure 1-14) was the original mobile ground support vehicle. It contained compartments to carry auxiliary blowers, power supplies, and tools. Facilities to accommodate the crewmen and their luggage were also provided inside the bus. Atop the bus was mounted a short collapsible mast. When erected, it was anchored to the roof of the bus; outrigger wheels on each side of the bus were engaged for lateral stability. A cup and locking device were attached to the top of the mast.

The airship would land to the ground crew and be held in place. One man would pull on the tail lines to raise the belly mooring disc a few feet higher than the top of the bus-mounted mast. Linemen would man two nose lines to keep the nose of the airship steady and into the wind. A mast man was positioned on the mast to direct the spindle into the cup. He would thread



BELLY PLATE

MAST ON BUS

SPINDLE APPROACHING MAST CUP

BUS MANEUVERING AIRSHIP

Figure 1-13 - Belly Mooring Mast (1964)

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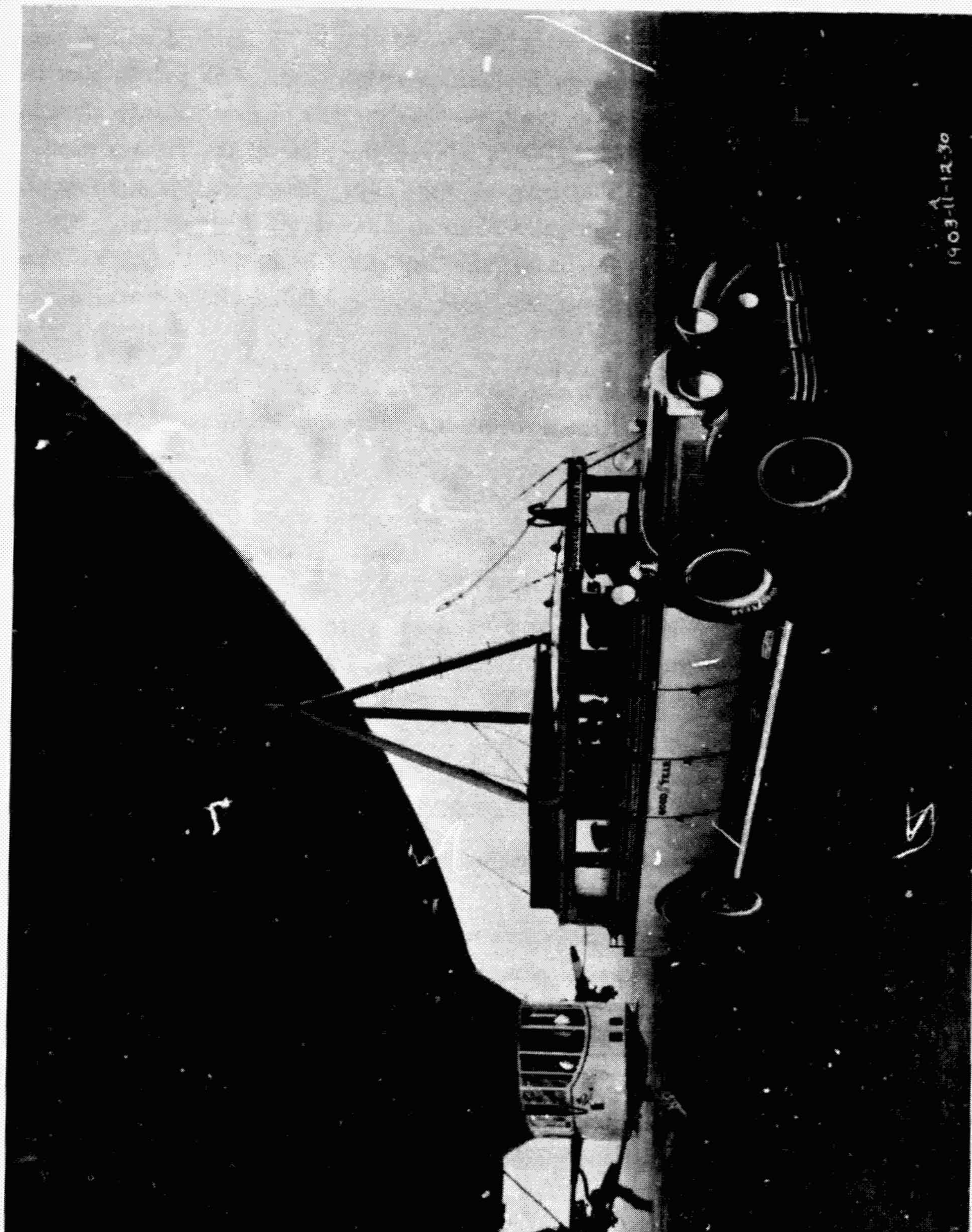

Figure 1-14 - Early Belly Mooring System (1930) a pull-in rope down through the cup to a pull-in man standing alongside the bus on the ground. The bus would be driven under the nose of the airship, at which time the mast man would couple the ground pull-in rope to the short pull-in cable on the belly mooring disc. The pull-in man then pulled down on the rope at the same time the tail line man slowly slacked off his pull on the tail line. This allowed the nose of the airship to slowly lower until the spindle slid into the mast cup. The mast man then locked the spindle in the cup, thereby securing the airship to the mast. With the airship secured to the bus mast, the bus could be driven to any location on the field or into a hangar if men were put on tail lines to maintain directional stability.

Though the buses used in the early operations have gradually evolved into a modern configuration, the mooring operation described above has remained the same (see Figure 1-15).

2. DEVELOPMENTS AFTER WORLD WAR II

a. Expeditionary Mast

An air-transportable mast was developed for the Navy by Meckum Engineering, Inc. (see Figure 1-16). The mast was an aluminum structure supported by steel cables and anchors. By removing or adding sections, the mast could accommodate models SG, M, or ZPG airships. Figure 1-17 shows the anchor layout of the system. A similar mast was developed for Goodyear's commercial airship operation (see Figure 1-18).

A description of the mooring technique used with expeditionary masts follows:

1. Right and left nose lines and a pull-in line attached to the nose of the airship hang free during the landing approach.
2. The airship is flown upwind to the ground crew. Linemen grab the nose lines and spread them out approximately 45 degrees to the airship. The ground crewman assists in stopping the airship. Once the airship is stopped, the nose lines are further spread 90 degrees to the airship. Sufficient tension is then maintained on the lines to keep the nose of the airship into the wind.
3. Another group of ground crewmen called the car party moves in around the airship car. Their responsibilities include ballasting and maneuvering the airship as required.

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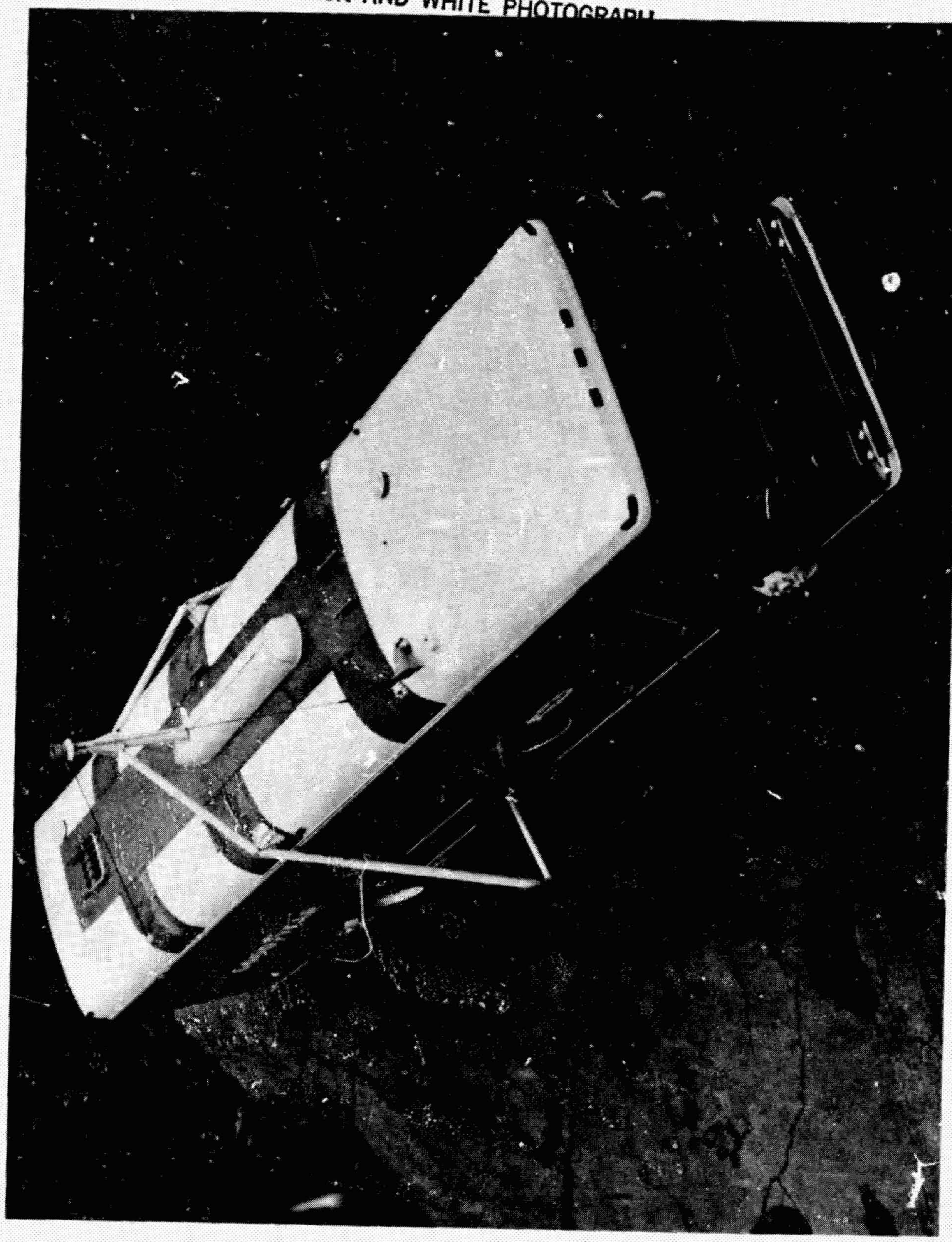

Figure 1-15 - Modern Goodyear Bus with Belly Mooring Mast (1979)

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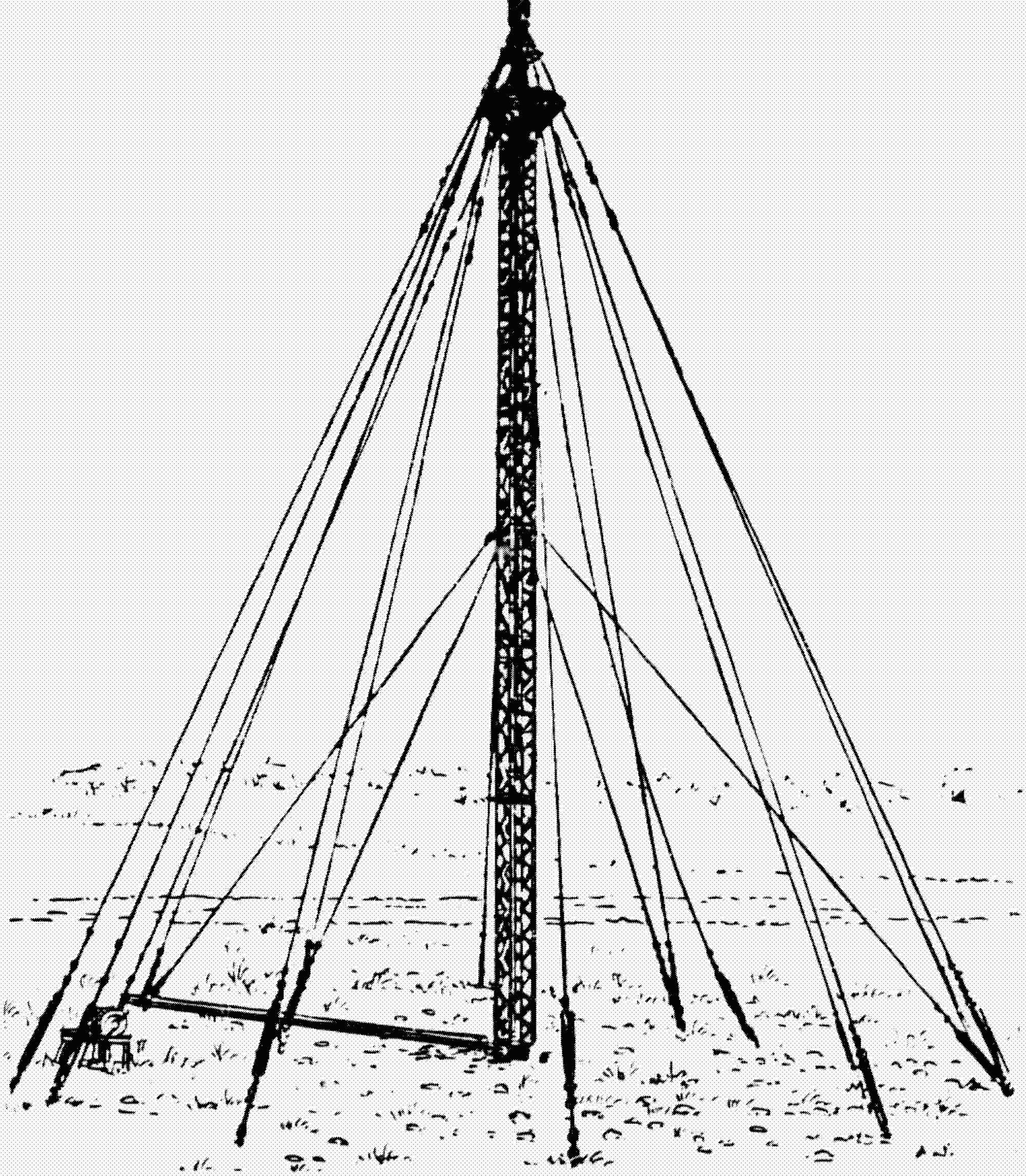

Figure 1-16 - Mooring Mast after Raising

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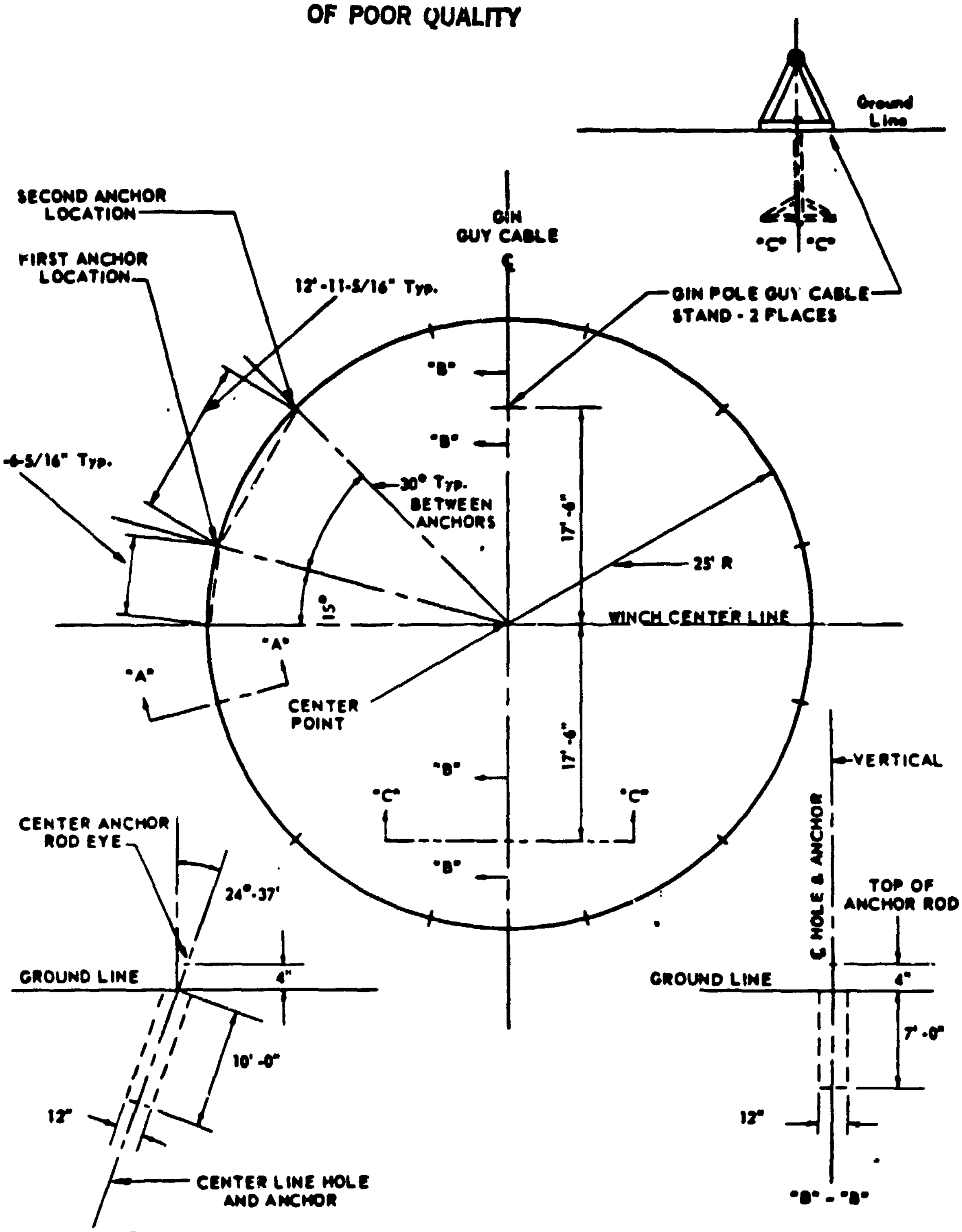
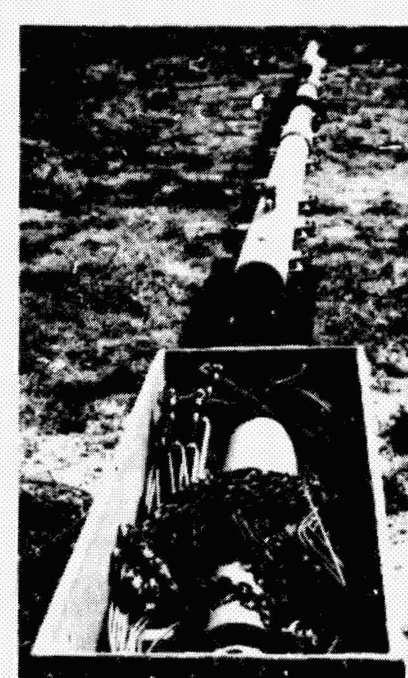


Figure 1-17 - Anchor Layout (Reference ii)



MAST LAID OUT FOR ASSEMBLY

DRIVING STAKE

INSTALLING MAST ON CENTER PLATE

RAISING MAST

MAST FULLY ERECTED

Figure 1-18 - Goodyear Expeditionary Mast (1964)

4. **Directing the ground handling operation from a position under the nose of the airship stands the crew chief.**
5. **The airship is maneuvered to a position 50 feet downwind from the mast.**
6. **At this point, the mast and airship pull-in lines are connected.**
7. **The mast pull-in line is extended until tension is experienced in the line.**
8. **A four-point mooring control is now effected.**
   a. **Nose linemen pull right and left on the nose lines for cup alignment.**
   b. Pull-in men pull the airship forward toward the mast cup.
   c. The pilot uses reverse thrust to keep the airship from overriding the mast cup.
9. The airship is eased forward until the airship nose spindle mates with the mast cup, at which time a top man on the mast throws a locking lever engaging four dogs into a groove on the spindle securing the airship to the mast.

A total of 16 ground personnel was required.

b. Mobile Mast

Since the rigid airship self-propelled masts were too large for the non-rigid airships, a smaller towed mast was developed prior to World War II. As airships became larger, modifications and improvements were made to accommodate the new airships. Various types of mobile masts are described below:

1. Type III mast - weight of 39,000 pounds, used with ZS2G-1 and ZSG-2/3/4 airships
2. Type IV mast - weight of 44,020 pounds, used with ZPG-2/2W, ZS2G-1, and ZSG-2/3/4 airships
3. Type IVB mast - weight of 47,900 pounds
4. Type IVB mod mast - weight of 55,900 pounds
5. Type V mast (see Figure 1-19) - weight of 128,670 pounds, used with ZPG-2/aW and ZPG-3W airships

Ground handling maneuvers are affected by many variables such as shifting of wind velocities, ground effects, hangar effects, variable mule line tension tractor speed and direction, and mule speed and direction.

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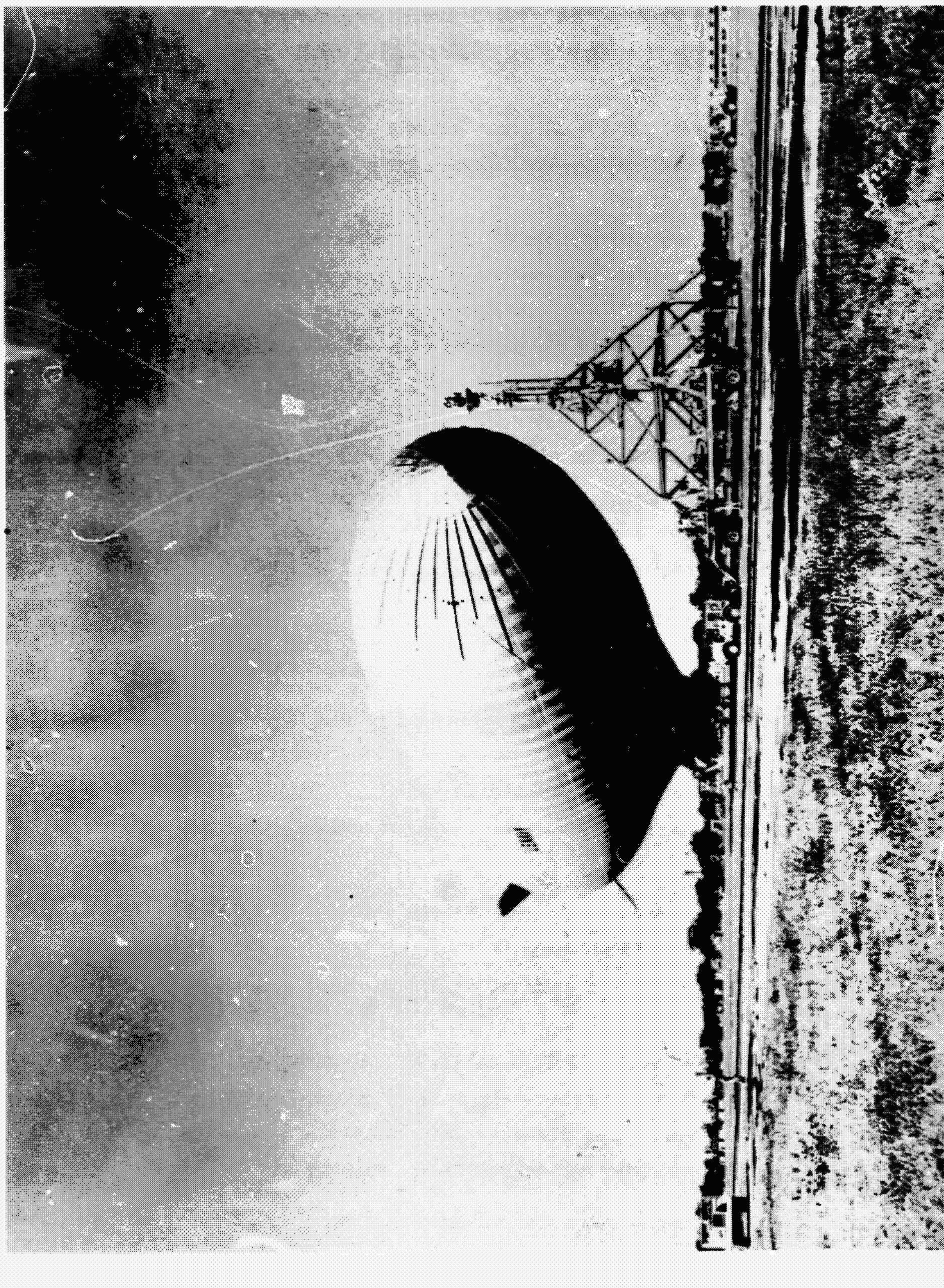

Figure 1-19 - ZPG-3W Airship Mooring to Type V Mast with MC-3 Mules on Nose Lines (1958)

Table 1-1 (Reference 10) reflects the mast and airship mooring wind limitations imposed by the Navy while utilizing the various mobile masts. The wind direction is assumed to be colinear with the major axis of the airship. The table assumes no accounting for side loading.

TABLE 1-1 - MAST AND AIRSHIP WIND SPEED MOORING LIMITATIONS (MPH)

Mast	Airship condition*																
	ZPG-3W					ZPG-2/2W				ZS2G-1				ZSG-2/3/4			
	1A	1B	2	3	4	1A	1B	2	3	1A	1B	2	3	1A	1B	2	3
V	78	71	58	14	58	66	66	66	12	-	-	-	-	-	-	-	-
IVB mod	-	-	-	-	-	63	58	42	12	56	66	60	14	66	66	66	14
IVB	-	-	-	-	-	63	54	36	12	66	66	55	14	66	66	65	14
IV	-	-	-	-	-	61	52	32	12	66	61	52	14	66	66	61	14
III	-	-	-	-	-	-	-	-	-	49	46	28	11	58	58	38	13

*Conditions:

1A: Mast dogged - airship free to weather vane.
1B: Mast undogged (tied to tractor) - airship free to weather vane.
2: Mast towed and maneuvered at 5 mph with airship free to weather vane.
3: Mast undogged (tied to tractor) - standard docking and undocking .
4. Mast undogged (tied to tractor) - upper tube extending or retracting.

c. Mobile Winches (Mules)

The K-type airship required from 50 to 100 men, depending on wind velocity and direction, for ground handling. The Navy became interested in developing a technique that could reduce this manpower requirement, which led to the development of mobile winches, commonly called mules (see Figures 1-19 and 1-20). These units are basically four-wheel drive, fore and aft steering tractors with a winch mounted on the back. The Navy referred to a 30,000-pound type as an MC-3 (see Figures 1-19 and 1-21) and a lighter 17,500-pound type as an MC-4 (see (see Figure 1-20).

Heavy takeoffs and landings on non-rigid airship main landing gears were standard practice by the beginning of World War II. The installation of reverse pitch propellers provided the pilot with the capability of braking the airship. Integrating these innovations with the mobile mast and mules resulted in landing and mooring procedures as follows:

1. The slightly heavy airship lands into the wind.
2. At touchdown, the pilot applies reverse thrust to slow the airship.

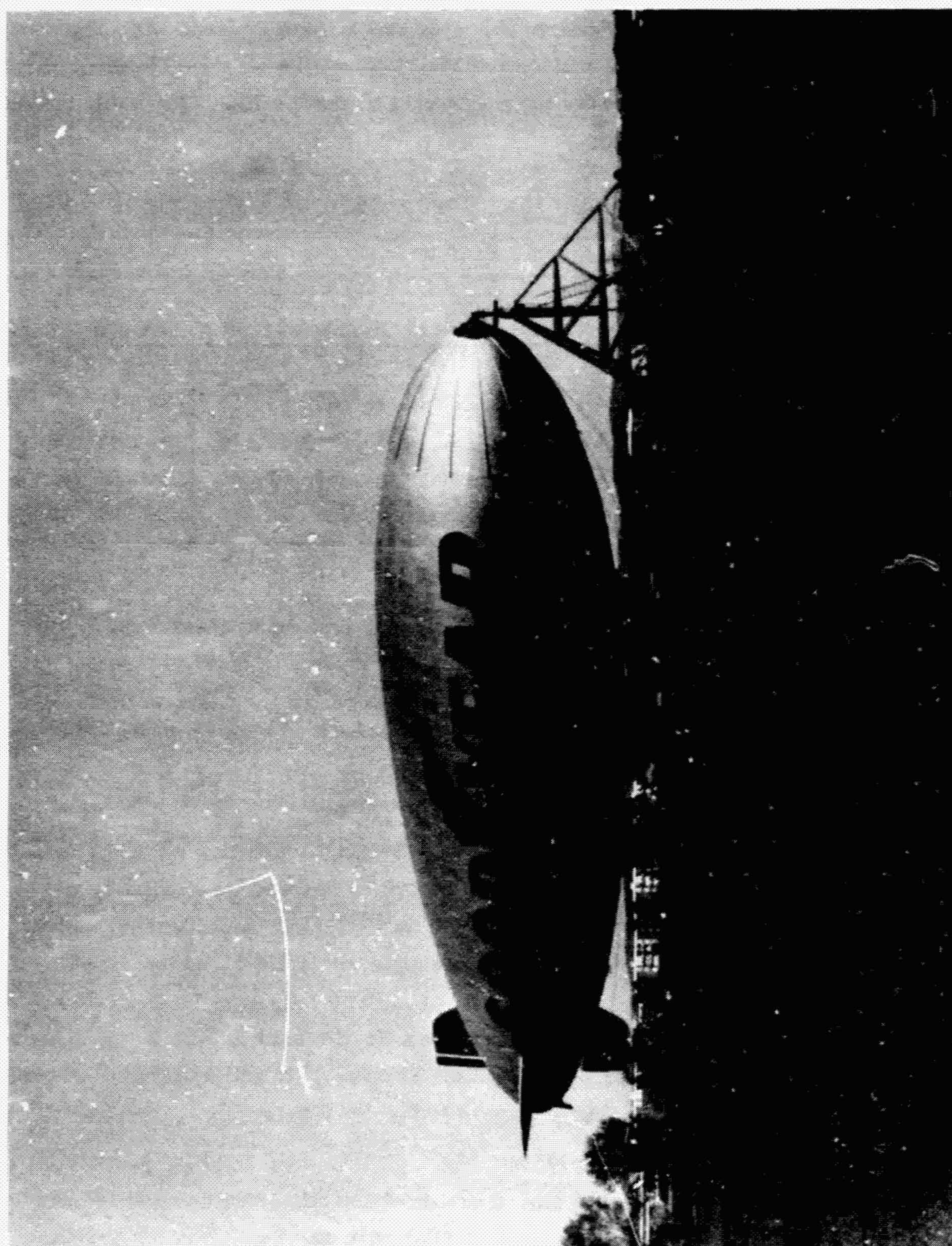

Figure 1-20 - Goodyear Commercial Airship Ground Handling Equipment (Rome, Italy), 1973

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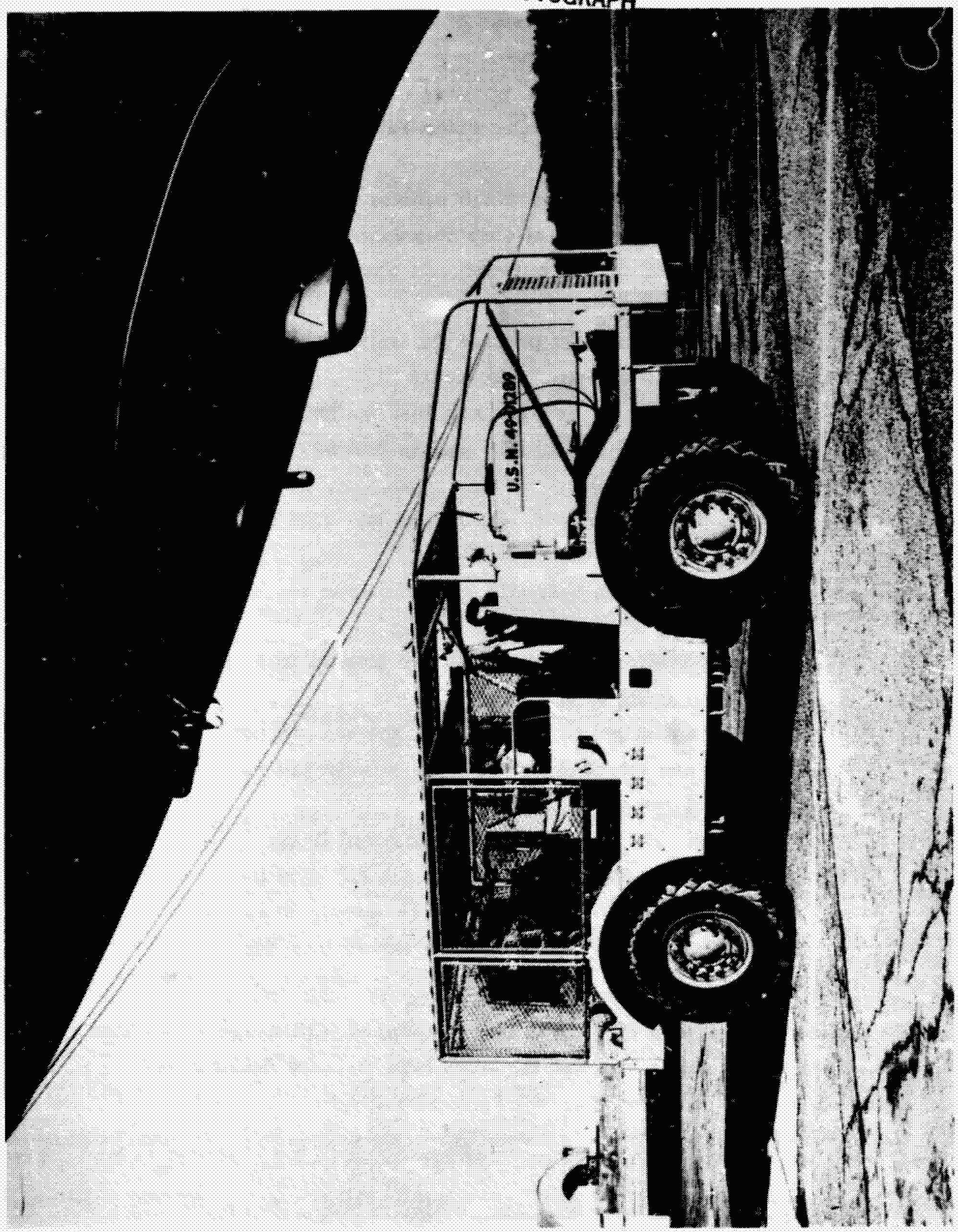

Figure 1-21 - MC-3 Mobile Winch (1958)

3. Mules stationed on each side of the approach end of the landing area swing in and run parallel to the airship.
4. Linemen run in and pick up nose lines and spread them out.
5. The mules move in and the winch cables are connected to the nose lines.
6. Tension is taken on the winch cables, and the mules assist in bringing the airship to a stop, as required.
7. The mules are driven outward and abreast of the airship nose.
8. The airship is held in position by mule winch cable tension, pilot engine, and empennage control.
9. The mobile mast is brought into and stationed in front of the airship until the airship pull-in line is coupled to the mast pull-in line.
10. Slowly, the airship is winched in to the mast until the nose spindle locks into the mast cup.
11. The nose lines are then disconnected from the mules and stored out of the way of the airship.
12. The mast tractor tows the mast and airship to a safe position in front of the airdock.
13. The mules proceed to each side of the airship tail, where tail lines are attached between the airship tail handling points and the winch cables.
14. Tension is taken on the winch cable tail lines.
15. When all is ready, the mules pull the tail into the wind as the mast is maneuvered until the airship lines up with the airdock. The airship is then moved into the airdock and secured.

Those Goodyear airship operations bases equipped with hangars (Houston, Texas and Rome, Italy) still use the MC-4 type mule for docking and undocking.

3. MARITIME EXPERIENCE

a. General

In order to completely integrate airship services into Naval operations, several attempts have been made to develop hardware and operational procedures that would accomplish this goal. This objective has been manifested in several areas: ship-mounted masts, aircraft-carrier operations, and water takeoffs and landings.

b. Ship-Mounted Masts

The only mast ever to be erected on a ship was a reproduction of the Lakehurst high mooring mast on the U.S.S. Patoka (see Figures 1-22 and 1-23). A sister ship, the Ramapo, had been scheduled for a mast but this was never accomplished. Originally classed as an oiler, the Patoka was delivered in 1919. Its overall dimensions were 463.25 x 60 x 26.25 feet (mean draught) with a displacement of 5375 tons.

The Patoka was equipped with two 80-foot steel lattice-work booms. The horizontal angle between each boom and the ship's centerline was 60 degrees from aft. A small boat carried the haul-in line end astern of the Patoka. With the Patoka steaming 45 degrees into the wind, an airship would fly across the haul-in line. A grappling hook suspended from the airship would snatch the haul-in line, and slack would be taken up. The Patoka would then turn into the wind. The rest of the mooring would proceed in the manner as previously described for land-based high masts. The only airships to use this mast were the Los Angeles, Shenandoah, and Akron, with the Los Angeles' 44 moorings being the most numerous.

Though it enjoyed only limited success, the Patoka experience precipitated other designs such as the one shown in Figure 1-24. This concept was never developed.

c. Aircraft Carrier Operations (References 12, 13)

Though the Los Angeles landed aboard the aircraft carrier Saratoga on January 27, 1928 and despite the occasional airship landing on a carrier deck during World War II, a serious investigation into the feasibility of airship fleet operations from a carrier was not initiated until early 1950. By the close of the following year, however, all Navy airship pilots were required to qualify for carrier operations.

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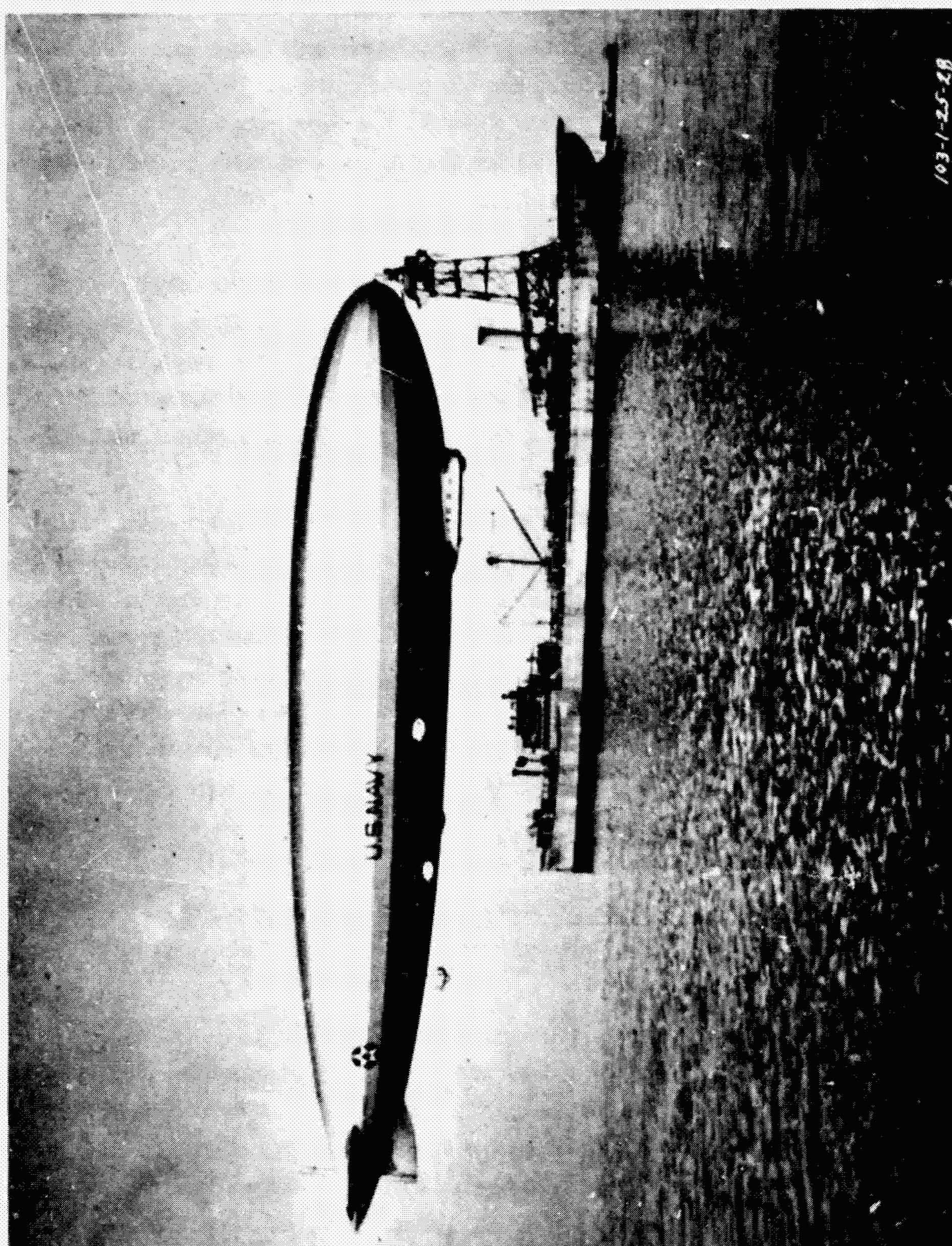

Figure 1-22 - U.S.S. Patoka High Mast (1928)

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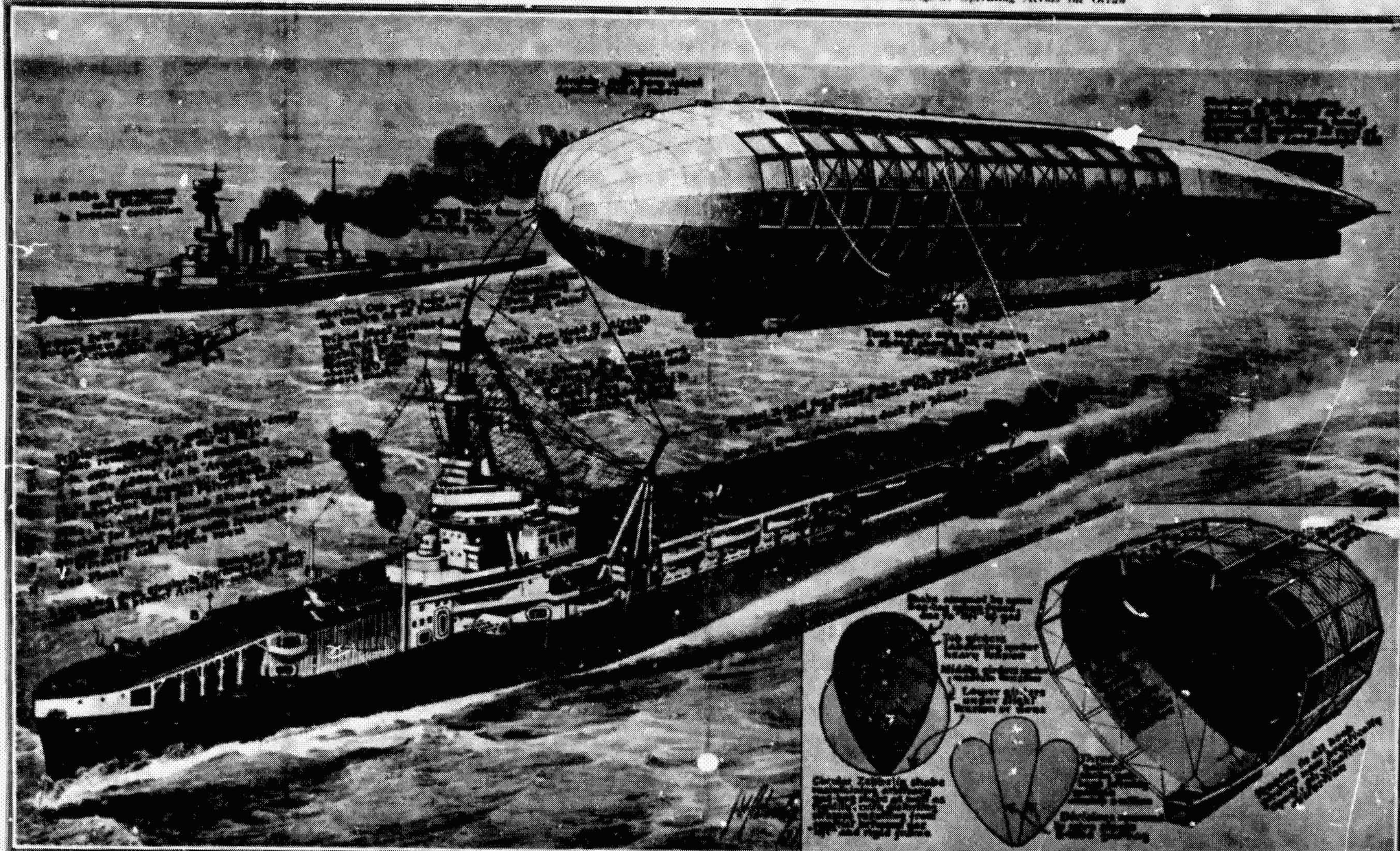
Figure 1-23 - The Shenandoah Leaving Mast on the U.S.S. Patoka

THE RENEWED INTERNATIONAL INTEREST IN BIG DIRIGIBLES—The Problem of Mooring Airships to Vessels at Sea.

How "Courageous" and "Glorious" Could be Adapted to Serve as Bases for Specially-constructed Dirigibles Operating Across the Ocean



DRAWN BY S. W. CLATWORTHY

A SUGGESTION FOR A MODIFIED WARSHIP TO SERVE AS AN AIRSHIP BASE AT SEA, EMBODYING FEATURES REQUISITE FOR SUCH AIRCRAFT, AND SHOWING THE MOORING MAST AND IMPROVED TREFOIL CONSTRUCTION OF THE AIRSHIP

Within the past few months there has been a very marked recrudescence of activity in connection with the big dirigible, especially in America and in Germany. The British Navy, too, has decided to retain airships, and the picture reproduced here is an attempt to visualise a possibility of the near future. An American rigid has just been successfully moored to an experimental mast placed in an apparently makeshift position on a ship: the operation could certainly be performed as shown on a ship travelling at full speed steering directly with the wind, with a portion of the airship's motors maintaining, at first—when making fast—a speed rather in excess of the ship, and then when hauling in less. The ship depicted is an imaginary version of H.M. Ships "Courageous" and "Glorious" as they might be converted when such an event occurs. The head of the mast is the same as that once successfully used at Pulham, and the existing warship tripod is retained, but raised to a more suitable height. The airship itself is a pioneer of aviation of the type advocated by Mr. H. O. Short of Messrs. Short Bros., who built the successful wooden rigids, "R.31" and "R.32" in the war, which may eventually oust the Zeppelin type, which at present reigns supreme. The Zeppelin was the product of persistent military zeal rather than an evolution of true aeronautical engineering. Its inherent weakness, it is claimed, lies in its circular section, since the gas-bags, if freed, would rise to a shape resembling that of an inverted drop of water, as explained in the inset, and, being prevented from doing so by the frame, there are perpetual distorting strains in the ship even when at rest. The Short design proposes "natural shape" bags, placing three "inverted drop" sections together in a trefoil to obtain a fixed shape suitable for navigation. Their dividing walls are removed and the excellently placed "lift" water seen substituted, directly supporting the chief weights ranged along the keel. The ultimate hull resembles that of a submarine, which, of course, is buoyant in water just as the airship is in the air. Much internal complication in the Zeppelin necessitated by its struggle to maintain its shape would be swept away. This design is a proposed London-New York passenger liner, 4,450,000 cubic feet, to carry fifty passengers at sixty knots for 6,000 nautical miles.

Figure 1-24 - Suggested Warship Modifications (1924)

The deployment of a carrier deck landing party is shown in Figure 1-25. During landing and takeoffs, the carrier would maintain a heading into the wind (±10 deg) and vary its speed to provide a relative wind velocity of 24 to 28 knots over the deck. The following procedures would then prevail:

Landings:

1. As the airship approaches the carrier from astern, the pilot attempts to have the short lines reach the carrier deck so that the two men at station (A) can each grab one line and rush it to the short line crew (D) as the airship moves in.
2. When the rear end of the airship car is over the carrier deck, the drag rope is dropped and taken by the drag rope crew (B) to hold back.
3. When the forward hand rail of the car comes within reach, the car crew (C) takes hold and tries to keep the landing wheel down on the deck.
4. During this time, the short line crews (D) help to hold the airship back and also try to keep it near the center of the deck.
5. With the airship now in the hands of crews (B), (C), and (D), the bow is brought down so that the two catwalk ropes (R_1) can be connected to the short cable pendants by the men (E), after which the catwalk crews (F) take over (two short cable pendants are added at the short line patch assembly for carrier operations).
6. This relieves crews (D), and the short lines are brought in toward the car.
7. If the airship is to be held on deck for an extended period of time, a center rope or cable (R_2) is hooked into a strong point at the forward end of the car.

Takeoffs:

1. The LSO signals the pilot to rev up the engines and then the crews (B) and (C) to clear the area.
2. The LSO then signals the men (E) to pull the quick releases of the catwalk ropes, leaving the airship free to take off.
3. The airship takeoff is with a turn to the port, away from the carrier island structure.

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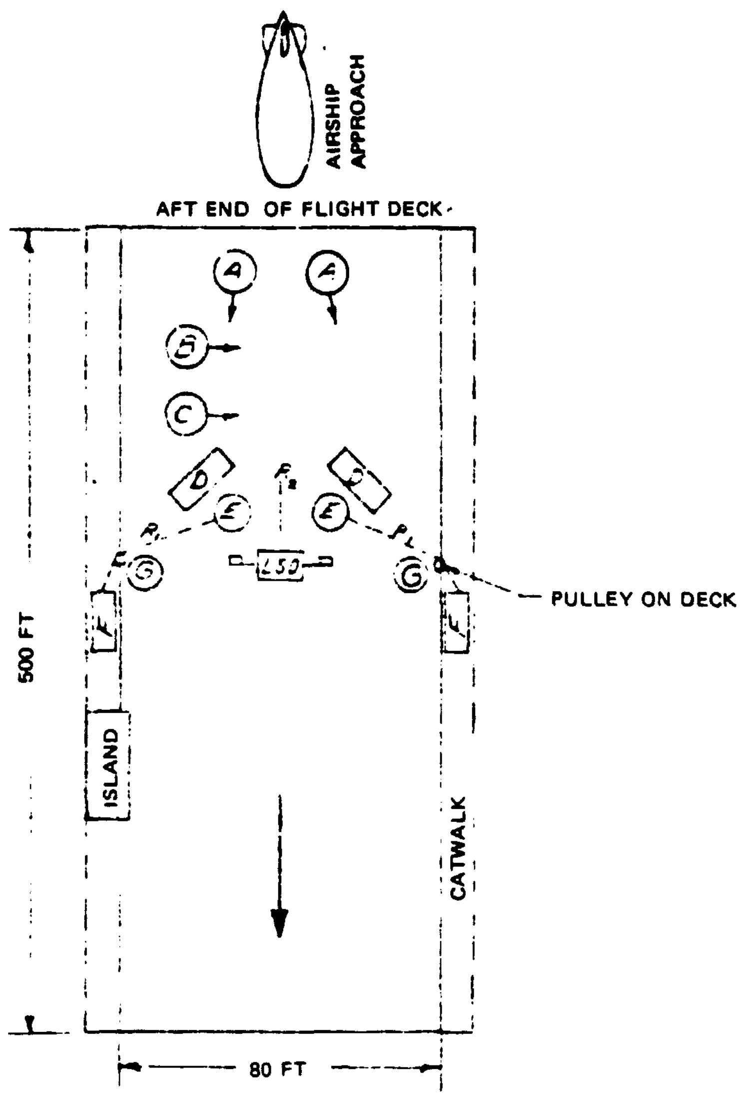

Figure 1-25 - Disposition of Landing Crew on Carrier Deck

(A) - Men near aft end of carrier deck to catch short lines and rush them to crews (D)
(B) - Drag rope crew, three or four men
(C) - Car crew (forward hand rail), three or four men
(D) - Short line crews (six to eight men each)
(E) - Two men each to connect catwalk ropes (R_1) on landing, one of them to operate quick release at takeoff
(F) - Catwalk crew, below deck level (10 to 12 men each)
(G) - Safety man with hatchet to cut catwalk rope in case quick release fails at takeoff
(LSO) - Landing officer
(R_1) - Catwalk ropes
(R_2) - Center rope or cable

4. The two safety men (G) are there to cut the catwalk ropes in case of a quick-release failure

The total ground party crew numbered 47 to 57 men.

Carrier suitability tests of the XZS2G-1 airship were conducted aboard the CVS class aircraft carrier U.S.S. Antietam during May and June, 1956. These tests were to determine the ability of the ZS2G-1 airship to operate beyond the useful range of the airship from land bases. Results of the test were favorable. It was concluded, however, that operations in conjunction with smaller carrier types would require the utilization of inflight replenishment features for fuel, armament, personnel, and provisions.

The K-type airships were the only models qualified for aircraft carrier operations (see Figure 1-26). The larger airships that followed were capable of extended operations through airborne replenishment systems, thereby obviating the need for carrier deck landings. Although the requirement of pilot qualification was maintained, no extensive operational use of aircraft carriers as mobile airship bases was undertaken.

d. Water Takeoffs and Landings (Reference 14)

The U. S. Navy, recognizing that the possibilities of water operations had not been fully explored, experimented in 1939 with the J-4 airship. Two inflated strips mounted along the bottom of the car were used for flotation when the airship landed on the water. No formal results of these experiments were documented.

Goodyear experimented in 1930 and 1931 with water landings and takeoffs using both single and double floats. It is reported by personnel who flew both flotation devices that the twin float system provided more stability, especially when side gusts were encountered. The twin floats, however, were set only three to five feet apart.

In 1946, Goodyear was awarded a Navy contract to conduct an airship improvement test program. One item of the contract was to investigate water takeoffs and landings utilizing the Navy's L-type airship, L-1. Tests on single and twin fixed floats were conducted. A single swivel float concept was investigated but never tested.

The stated objectives of these tests were to determine the limiting wind and water conditions for water takeoffs and landings;

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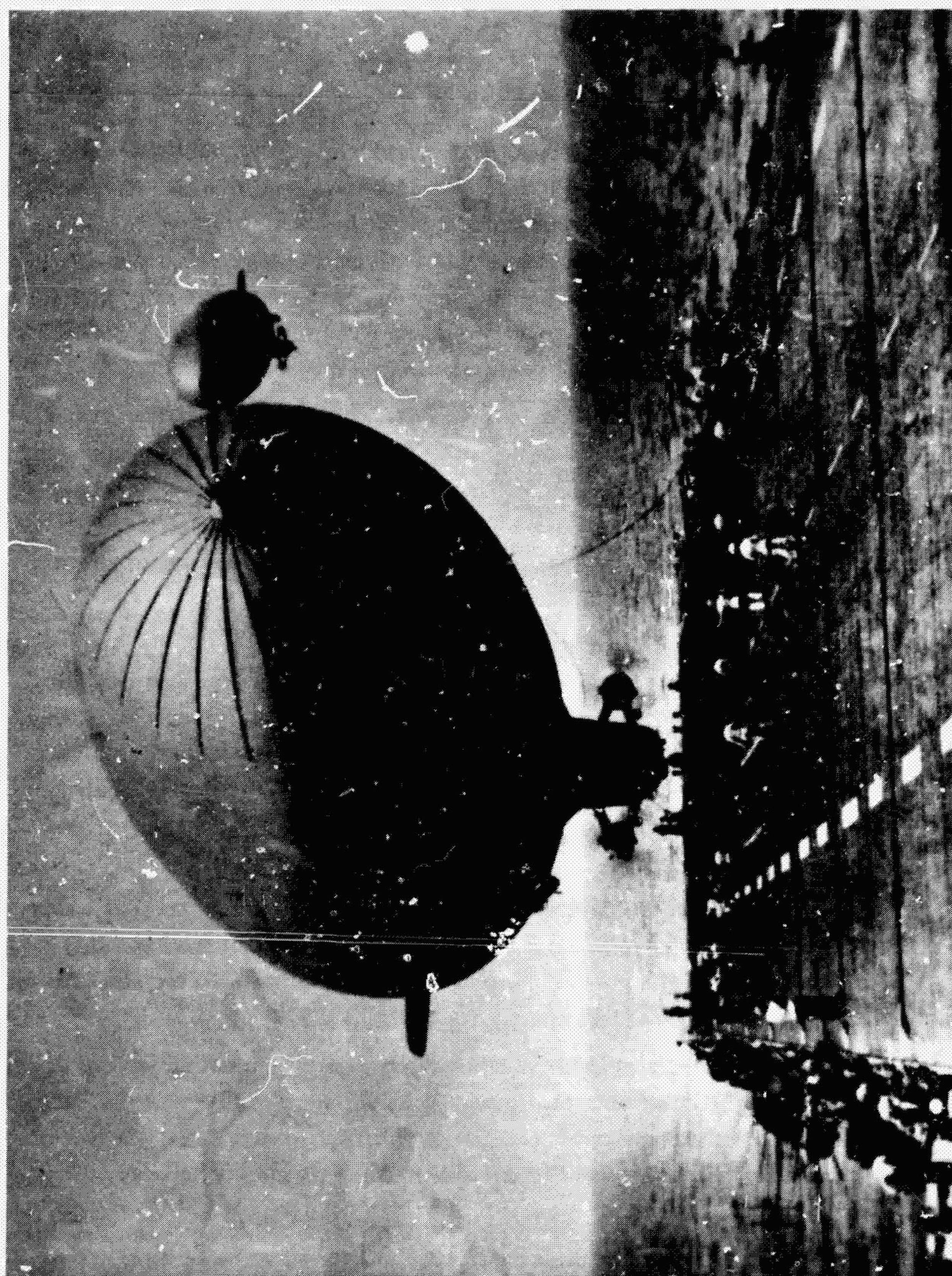

Figure 1-26 - K Ship Landing Aboard Aircraft Carrier to develop a flying technique to land on the water without the aid of ground personnel; and to determine the effect of the arrangement on speed and fuel consumption.

In general, the single fixed float was found to be unsatisfactory because of its poor stability in lateral rolls. Twin float operations, however, with the floats 10 feet apart, demonstrated greatly improved stability against roll (see Figure 1-27). On at least one occasion, however, the airship rolled far over on the starboard side and partially submerged the starboard engine. Although the report concluded that the results obtained exceeded expectations, no further development of floatation systems for airships was pursued by the Navy or Goodyear.

4. SUMMARY

The historical development of ground handling systems has been adversely impacted by two items: (1) the lack of low-speed controlability of an airship; and (2) the large surface area of the airship.

In order to compensate for the first item above, airships have traditionally been designed to accommodate external loads applied through ground handling lines to some point on the ship. The availability of large numbers of ground personnel was a prerequisite for airship operations. The large rigid airships built in Akron typically required 300 men for ground handling. As the airship industry evolved and large non-rigids became dominant, the desire to develop a ground handling approach that was less dependent on manpower grew. This resulted in the mobile mast/mule system, which still remains as the state-of-the-art for ground handling.

Once the airship was on the ground, its susceptibility to weather conditions became obvious. Early airships were placed in hangars to avoid environmental effects, but the limitation this placed on the airship as a viable transportation mode was intolerable. Hence, a variety of experiments was undertaken in order to develop a mooring system that would permit the airship to sustain most weather conditions. The eventual outcome, when the various cable systems and mast types had proven unsuccessful, was the bow mooring concept. While this approach still has limitations, it has proven to be the best solution to date.

Figure 1-27 - L-1 Airship Taking Off from Lake Erie

SECTION II - THE MPA VEHICLE CONCEPT

1. GENERAL

The baseline MPA design used in this study is the 875,000-cu ft ZP3G model as defined in References 15 and 16 prepared for the Naval Air Development Center by Goodyear Aerospace. Pertinent extracts are provided below.

2. ZP3G CONFIGURATION

The conceptual design of the ZP3G is shown in Figures 2-1 and 2-2. Its overall length is 324 ft, the maximum diameter of the envelope is 73.4 ft. In this configuration, the propulsion systems are shown in the cruise or conventional takeoff position. The forward propellers, however, do rotate plus or minus 90 deg and the stern propulsion system rotates a plus 90 deg for VTOL operation.

The conceptional design uses four ballonets. The forward and aft ballonets serve to trim the airship in addition to compensating for large altitude changes. The center ballonets permit nominal changes in altitude, which are repeatedly required in some missions, without affecting the airship trim condition. Ballonet configuration is governed by geometric restrictions and size. To maintain trim fore and aft, ballonets are nearly equal in volume and location relative to the center of buoyancy. The catenary system on the ZP3G restricts the size of the forward ballonet; therefore, the geometry of the aft ballonet is controlled. The remaining ballonet air volume is made up in the center section of the envelope, outboard of the car suspension system. Although the ballonets are less efficient weightwise, the huge surging air mass plus the flapping and flexing of the ballonet fabric, during partial inflation, is minimized when the ballonet consists of several compartments.

Bow stiffening and the X-type tail for the ZP3G concept are of conventional design, as flight dynamics and performance characteristics of a similar sized N airship with this volume and configuration have been substantiated. Furthermore, the X-type empennage provides the necessary ground clearance for short takeoffs with a reasonable angle of attack. A base structure for the fin suspension cables is an added feature since it eliminates the fin catenary and reduces the number of brace cables. In the concept, the car is supported at the floor level by the internal and external catenaries. A separate catenary system for the forward propulsion system divorces the powerplant from the

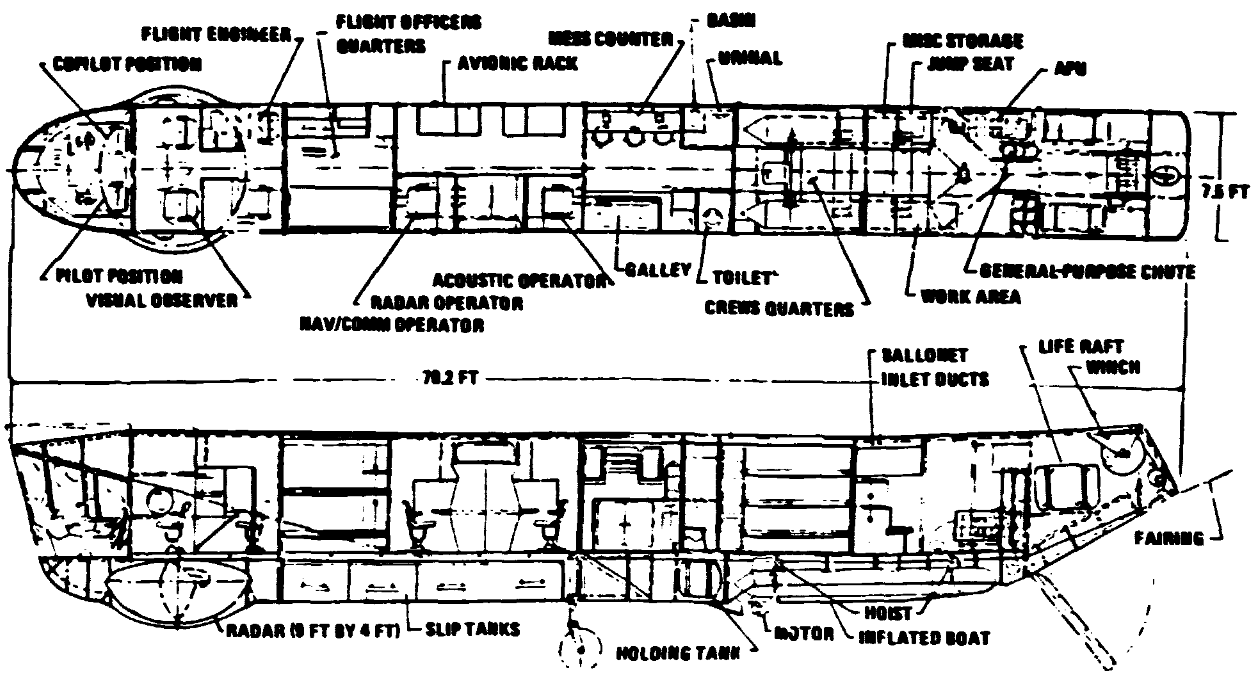

Figure 2-1 - Inboard Profile

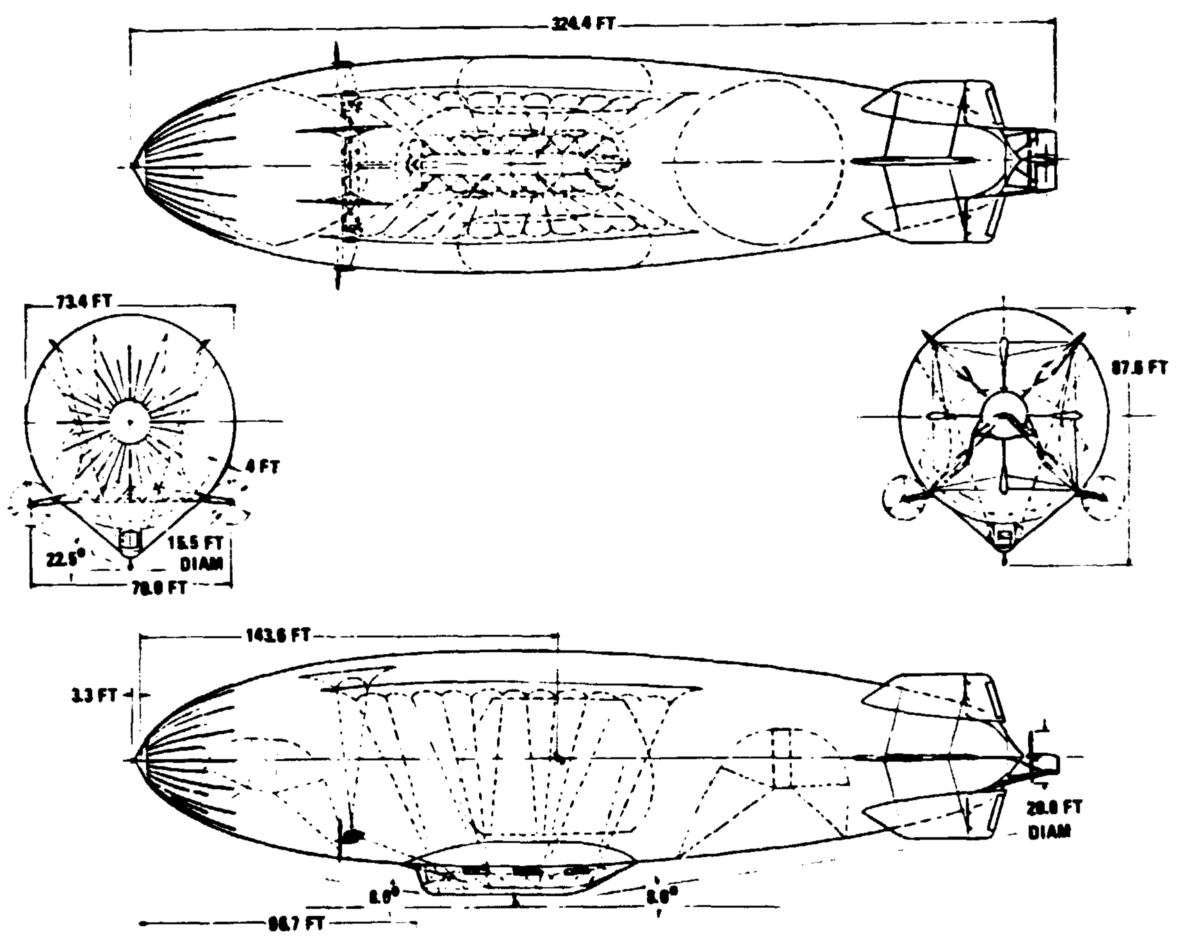

Figure 2-2 - ZP3G Airship

car to permit a more stable platform and reduce the noise level for the crew. Location of the forward propellers in this position is also necessary to balance the thrust forces during the hover mode of operation. The stern propulsion system is mounted on an inverted V tail, which provides the tilt capability for the propeller. The V tail also supports the deflectable ruddervator, which greatly improves control effectiveness in both hover and low-speed cruise via ruddervator deflection in the propeller slip stream.

3. MAJOR CHARACTERISTICS

Principal characteristics of the ZP3G conceptual design are listed in Table 2-1. The envelope volume of 875,000 cu ft is the design volume. With Dacron fabric, the increase in volume due to stretch is assumed to be two percent. A ballonet volume of 216,250 cu ft permits the airship to fly missions at 5000-ft altitude. Under standard atmospheric conditions, it limits the ballonet ceiling to 9700 ft. The dynamic lift of 8500 lb in hover is established as follows. The total propeller thrust at maximum power setting is 12,500 lb. On the stern propeller, 1500 lb of thrust is reserved for low-speed attitude control; 2500 lb of excess thrust is required for acceleration from hover to climb, leaving a total of 8500 lb for dynamic lift. A 3900-lb negative lift is also available with the propulsion system to counteract excess static lift during landing. This capability is provided by rotating the forward propellers down 90 deg. The 3900 lb is limited by an assumed maximum acceptable negative pitch attitude of 10 deg for the vehicle and not by the available propeller thrust. The pitching moment resulting from this force is counteracted only by the metecentric center of the airship since the negative thrust of the stern engine is minimal in this mode of operation. Again, this negative lift feature should be used only when necessary because the loss of thrust on the stern propeller greatly reduces the attitude control capability. The gross weight of 60,664 lb could be increased 3200 lb when a vectored thrust STOL operation is incorporated. This, in turn, would increase the useful payload to 25,704 lb.

The performance summary is listed in Table 2-2. Maximum speeds are taken at sea level using the takeoff thrust of all engines. Range is listed at 40 and 50 knots minimum speed. Although the 40-knot velocity obtains an additional 100 naut mi. the 50-knot speed reduces flight time by 25 percent. The maximum available horsepower for climb occurs at 55 knots. However, catenary limitations restrict the pitch angle of the airship to 30 deg; with this limitation, the velocity for maximum climb is 71 knots. The air system, proposed in the

TABLE 2-1 - MAJOR CHARACTERISTICS

Design item	Characteristic
Envelope volume	875,000 cu ft
Ballonet volume	216,250 cu ft
Fineness ratio	4.40
Beta factor	0.86
Static lift at 2000-ft altitude	52,164 lb
Dynamic lift	8,500 lb
Maximum gross weight	60,664 lb
Weight empty including fixed mission payload	38,160 lb
Useful load	22,504 lb
Powerplant	
Allison GMA-500 (3)	800 SHP each

concept, limits the maximum rate of climb to 2400 ft per minute; therefore, climb at the normal rated power is restricted unless the air valve system discharge rate is increased.

For conventional takeoff, the vehicle attitude assumes a maximum pitch angle of 6 deg to ensure a margin of safety for tail clearance. The performance for acceleration and deceleration uses maximum power at sea level. To accelerate from zero velocity, the airship is considered to be neutrally buoyant. For the time to decelerate, from the 97-knot maximum speed, a six-second transition phase is assumed to change the propeller from zero to full reverse thrust. In Table 2-2, range and endurance assume that the vehicle is operating at the 2000-ft altitude with a useful payload of 6370 lb. Liftoff is STOL with vectored thrust, and the performance is based on 90 percent of the maximum fuel load of 23,750 lb.

TABLE 2-2 - ZP3G PERFORMANCE SUMMARY

Design item	Performance
Maximum speed (8500 lb heavy)	94 knots
Maximum speed (8500 lb heavy, rear engine only) (maximum continuous power)	52 knots
Maximum speed (neutrally buoyant)	97 knots
Range at 40 knots	3407 naut mi
Range at 50 knots	3290 naut mi
Best climb velocity	71 knots
Rate of climb at maximum power	3375 ft/min
Rate of climb limited by air system	2400 ft/min
Conventional takeoff distance (8500 lb heavy)	1025 ft
Velocity at liftoff	50 knots
Distance to clear 50-ft object	2400 ft
Velocity at clearance height	65 knots
Time to accelerate to 40 knots (neutrally buoyant)	15 sec
Time to accelerate to 92 knots (95% maximum speed, neutrally buoyant)	64 sec
Time to decelerate from 97 knots to 0 knots (neutrally buoyant)	55 sec
Altitude limit	5000 ft
Ballonet ceiling	9700 ft
Endurance: less than or equal to 25 knots	101 hr

SECTION III - MOORING SYSTEM ALTERNATIVES

1. GENERAL

Several potential mooring systems could be utilized with the maritime patrol airship with varying degrees of effectiveness. To assess those systems that have the highest probability of success, it is first necessary to identify all candidate solutions and perform a preliminary distinction for the airship mooring systems that warrant additional investigation.

The approaches to securing the MPA while on the ground can be divided into the following categories: those that secure the airship at a single point and permit the vehicle to rotate about that point as required due to wind loads; those that completely restrain the MPA from motion while on the ground; those that protect the airship from being subjected to the weather elements. In addition, those that have maritime applications are assessed.

A rudimentary description of each of these systems is provided. Details of structural and operational analyses are given in later sections of this report.

2. SYSTEMS PERMITTING ROTATION

a. Bow Mooring

Bow mooring the MPA requires the securing of the airship by the bow to a mast with the airship weight near equilibrium but slightly heavy. The two standard mast types are the stick mast and the mobile mast. The stick mast is transportable and requires a system of cables and ground anchors in order to achieve structural acceptability. The mobile mast is normally employed at a hangar site. It is a pyramidic shaped structure with a triangular base that is on wheels. It is used primarily to move airships to and from the hangar and is normally towed by a tractor or ground handling mule.

A significant attribute of the bow mooring system is that it does not necessitate any structural changes to the airship. Nose battens that are developed for aerodynamic loads are equally effective at transferring bow mooring loads over a sufficiently large envelope area. Since no rolling moments are introduced by bow mooring, no changes are required in the envelope and suspension systems.

A more detailed oeprational description of previous and existing bow mooring approaches is given in Section I.

b. Belly Mooring

Placing a mast on the underside of the envelope at a point between the bow and the control car constitutes belly mooring. The advantages to this sytem over bow mooring are that it requires a shorter mast and requires a smaller area for rotation. The operational approach is similar to bow mooring.

The primary drawbacks are that it precipitates a number of changes to the airship. At the very least, some type of attachment capability must be built into the envelope. Since this point is below the centerline of the airship, rolling moments are introduced into the airship that must be dissipated through the envelope and suspension system to the mast. Therefore, stronger envelope fabric and increased structural capability in the catenaries is mandated.

For the MPA considered in this report, a design change incorporating a tricycle landing gear was provided in order to counteract the effects of the rolling moment. The single gear was placed on the car at a point 104 feet from the nose, while the aft gear are 148 feet from the nose and are laterally displaced from the centerline a distance of 30 feet. Though the use of anything other than a single landing gear is uncommon, it is not without prededent. The ZPG-3W, the largest non-rigid airship ever built, had a tricycle gear.

c. Center Point Mooring

The concept of center point mooring is simply the extension of belly mooring to its extreme. This approach was an integral part of the original Goodyear heavy lift airship design that incorporated a tail-less symmetrical envelope and four rotor systems attached to an interconnecting structure (Reference 36).

When an airship is moored about its center point and is struck by the wind, it will reach an equilibrium angle that does not coincide with the original wind angle. For example, the heavy lift model mentioned previously had an equilibrium position whereby the main axis was normal to the wind direction. This was due to its symmetric shape. For the MPA, which has a traditional airship profile and is equipped with tail surfaces, the equilibrium position is 40 degrees to the wind direction. This, in effect, becomes a total restraint system in which the direction of the wind is a constant. Therefore, this approach is not further addressed in this report.

3. COMPLETE RESTRAINT SYSTEMS

a. Car Secured

The firm attachment of the MPA's control car to the ground can be effected by providing four landing gears placed on outriggers at some variable distance from the airship centerline - which, in turn, are secured to the ground - or by providing direct attachment of the car to the ground through the use of cables and the replacement of the landing gear with a skid arrangement.

As with any mooring system other than bow mooring, the loads that the airship is subjected to while on the ground must be transferred through the envelope and suspension system to the ground. The additional disadvantage with total restraint is that no energy can be dissipated through motion. This will result in significant structural penalties should the airship design be driven by this approach to mooring.

b. Envelope Secured

A second possible total restraint system would be to directly secure the envelope to the ground. This would be accomplished by attaching external catenary curtains on each side of the envelope and providing cable attachments to anchor points on the ground. Though this concept would relieve the envelope and internal catenary system of exposure to mooring loads, it creates several other problems. There would be considerable additional drag; there would be the potential interference with the operation of the forward propulsion units; there would be logistic difficulties in actually providing cable attachments to the curtain and in maintaining ground location while the cables were being attached to previously set anchors.

4. PROTECTIVE SYSTEMS

a. Wind Screens

To provide adequate protection from wind loads, a wind screen must be sufficiently tall to direct the wind above the airship. A preliminary pragmatic investigation based on pressure distributions of an airdock-style building (Reference 39) suggests that a 76-foot vertical wall would be required (see Figure 3-1). Based on the overall length of the MPA, the total wall area per side would be approximately 25,000 square feet. The structural requirements for the walls alone would appear to outweigh any advantage that this approach might have. It is

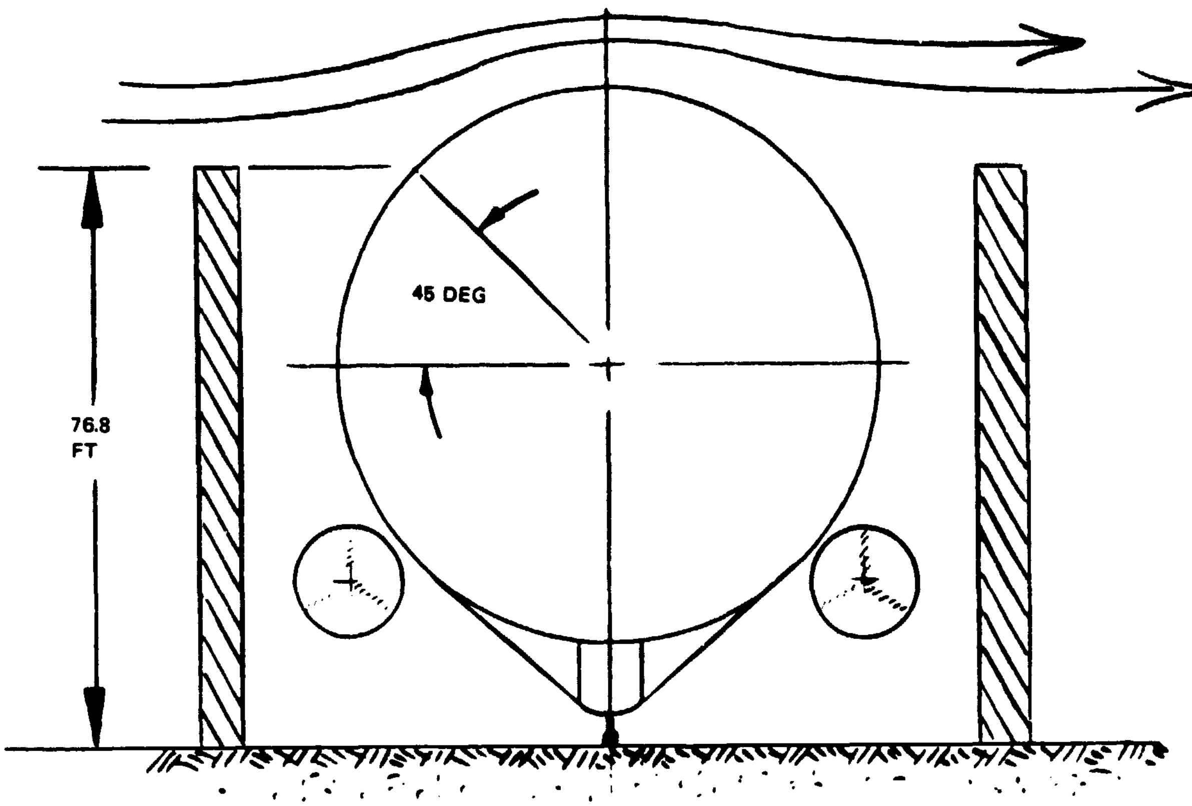

Figure 3-1 - Barrier Height Requirement

further compounded, however, by the following: the airship must still be secured within the confines of the two walls to account for wind angles that are colinear to the airship and to resist upward motion caused by the negative pressure as a result of the air flow above the wall; the need for a mobile mast to place the airship between the walls; and the permanency dictated by the size of the structures.

b. Hangars

The ultimate approach to airship mooring is to provide all-weather protection with a hangar. Though undoubtedly the most expensive approach to mooring, there are several benefits that accrue to the operator with a hangar. These include the virtual elimination of mooring-related airship damage; the convenience of maintaining a single facility for erection and maintenance needs; and the utility of a large protected area to service other aircraft.

An appropriate hangar for the MPA would have the following attributes:

Dimensions: Length - 425 feet
Width - 150 feet
Height - 128 feet

Structural:	Designed for location anywhere in continental U.S.A. Definition of major structural elements include a concrete floor (6-inch minimum) with anchor points (6000 lb) laid out on a 20-foot by 20-foot grid.
Architectural:	Includes insulated roof and siding, some truck doors and man doors, access to the roof, louvres, smoke curtains, and so forth.
Mechanical:	The mechanical services include conventional heating for localized areas; adequate lighting; 60 cycle power at 120 v/ 240 v/460 v - 480 v; water and sewer; air - 100 psi and 30 psi (dry); overhead monorails (4000 pound) the full length of the building with service platform and appropriate access ladders.
Main doors:	Sliding or rolling type; entire front of hangar must be clear when the doors are open.

A section view of a possible hangar is shown in Figure 3-2. Additional cost items required with airship hangar operations are a mobile mast and a pair of ground handling mules.

The use of air-supported structures as airship hangars is also being touted by Environmental Structures, Inc. (ESI) of Cleveland, Ohio. There has been a precedent in this area, however, as Westdeutsche Luftwerbung (WDL) has had experience with an air-supported airship hangar (see Figure 3-3). Unfortunately, the hangar has twice been damaged by high winds and has collapsed with an airship inside. The airship suffered considerable damage.

The advent of new materials has apparently marked the beginning of a new era for air-supported structures, and experiences such as WDL's will not be repeated. This is the claim of ESI and a description of their approach follows.

The advanced air-supported structures concept was developed by Goodyear to enclose large areas economically. It utilizes steel cables about five feet apart as the main load-carrying elements. The film between the cables acts as the gas barrier and can be anything from window clear to opaque. It is dielectrically sealed to the cables and usually comes in a double layer with dead air insulating space in between. This insulating layer can be created or eliminated at will through the use of a special sill channel at the perimeter of the structure.

To date, no size limitation has been encountered, and spans up to 1000 feet have been investigated. The recommended width-to-height ratio for high stability is 4-5 to 1. For the height required for the MPA, this translates to a span width of about 600 feet, making the total coverage area 255,000 square feet.

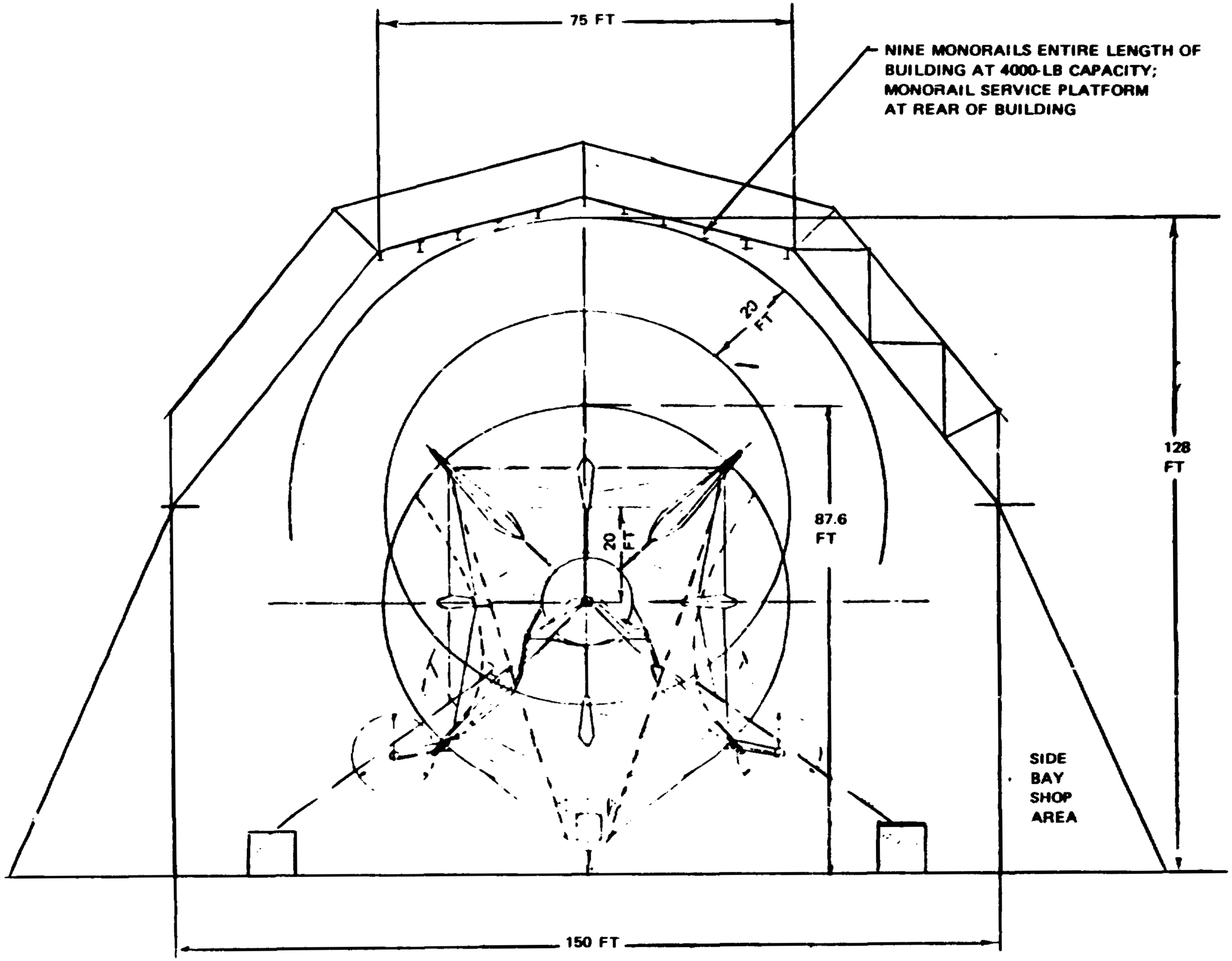

Figure 3-2 - Section View of Candidate Conventional Airship Hangar

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Figure 3-3 - WDL's Air-Supported Hangar

A control system regulates the pressure inside in response to the wind outside. At high wind speeds, the internal pressure increases to stiffen the structure. This would, in turn, affect the pressure setting for the airship envelope which would require adjustment.

Entry by an airship would require some special provision given the size of door that is necessary. This area has not been adequately investigated by the manufacturer, and some considerable doubt remains as to its feasibility.

The entire structure is premanufactured, and the cover could arrive at the site in a single piece. Once the foundation has been prepared and the mechanical equipment installed, the cover can be blown into position within a few hours.

5. MARITIME SYSTEMS

a. General

Two types of maritime operations are discussed in Section I: aircraft carrier operations and water landings and takeoffs. Since these capabilities have been demonstrated in the past, it is unlikely that any worthwhile innovation could be made. Furthermore, remanning and refueling operations at sea have been demonstrated by Navy airships.

b. Sea Anchors

The feasibility of using sea anchors to moor airships was the basis of a study undertaken by Goodyear for the U.S. Navy in 1956 (Reference 17). The motivation was to develop a system whereby the airship would remain airborne at a low altitude above the water while suspending ASW detection devices in the water. The design goal was to limit the airship to a four-knot drift in a 35-knot wind. The airship considered in the study was the ZPG1, which was the base vehicle in the design of the MPA (see Figure 3-4).

The results of the study were generally positive. It was anticipated that the most risk involved would be during "blow-downs" resulting from sudden and strong wind shifts. Some type of flotation gear installation on the airship was recommended in the event the water surface was contacted.

This study was initiated as an attempt to overcome the control inefficiencies of the airship at low speeds. The predicted inherent capabilities of the MPA should overcome these deficiencies.

6. SUMMARY

The purpose of identifying alternate mooring systems was to define those systems that warrant additional investigation as to their suitability for the maritime patrol airship. The following systems are subjected to a more in-depth review; bow mooring, belly mooring, total restraint, and hangar systems.

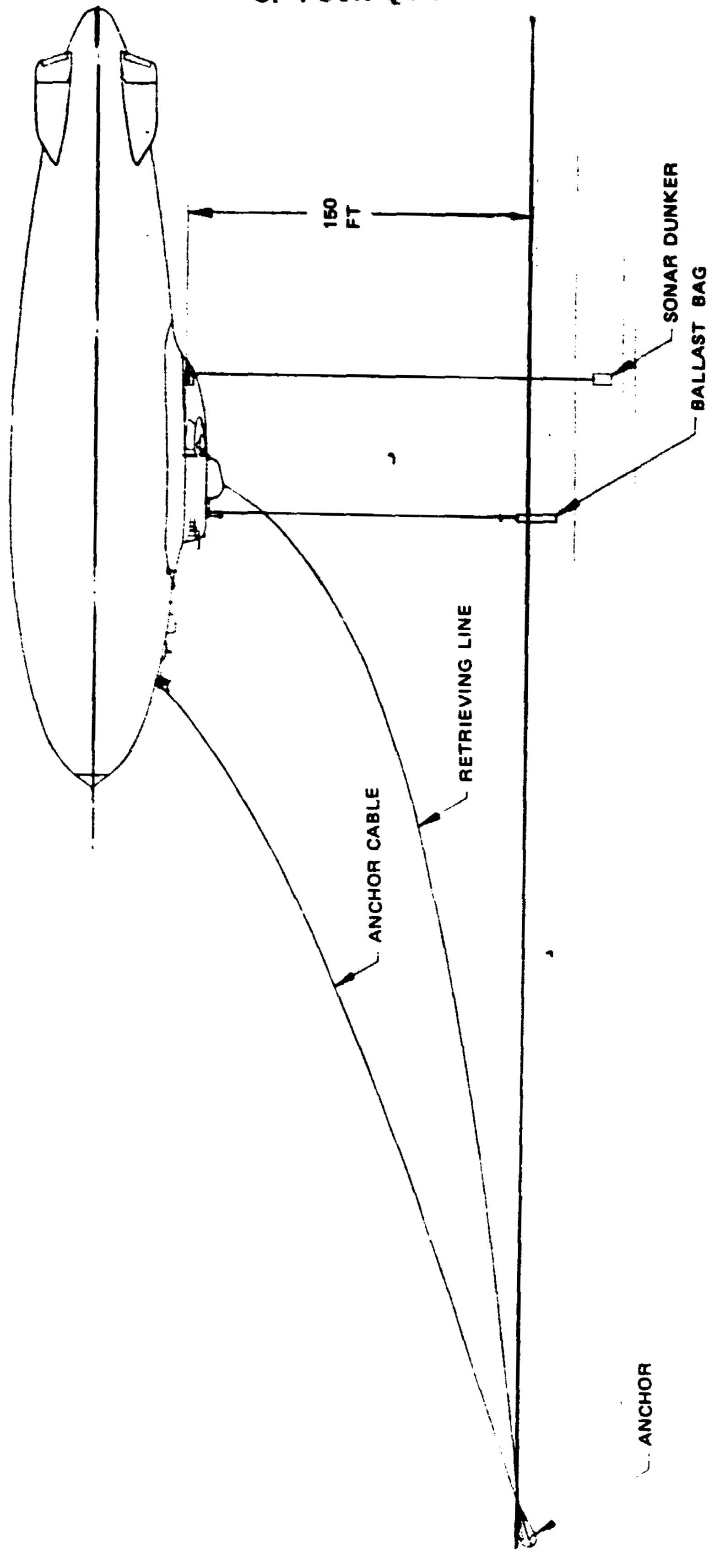

Figure 3-4 - Proposed Sea Anchor System on ZPG1 (Reference 17)

SECTION IV - STRUCTURAL ANALYSIS OF A FULLY RESTRAINED AIRSHIP

1. GENERAL

A first-order study of airship empty weights versus wind velocity for different mooring concepts and structural concepts (different internal suspension systems, envelope pressures, or other attachment approaches) was initiated to establish practical steady-state wind velocity operating limits. The following analysis is limited to a static condition, and envelope deformation is not considered. The static analysis is appropriate for fully restrained airship.

2. STATIC AERODYNAMIC FORCES AND MOMENTS

The first task was to estimate the static aerodynamic forces and moments acting on the different configurations for the different mooring concepts. The static data for these curves was selected from References 18 through 26. The type and scope of data presented in each reference are listed in Table 4-1. The model description, test Reynolds number, range of data collected, and any simulation of the ground effect as indicated by the vertical velocity gradient are presented in Table 4-1.

In Reference 18, the authors considered that direct extrapolation by continuation of the curves for model results to the Reynolds number of the full-size airships is not justified or satisfactory, inasmuch as an extension of a curve too many times its original length can lead to erroneous conclusions. They suggest instead that a more satisfactory method is to consider the flows about the bodies for the two cases of model and full size to see if any critical change in the flow is expected in passing from model scale to full scale. For 90 degree yaw angles, a section of the hull becomes circular, and two types of flow occur. For Reynolds numbers less than 4 to 5 x 10^5, based on diameter, the flow is characterized by early separation. For Reynolds numbers greater than this value, the flow becomes turbulent, and separation occurs further back on the cylinder. Once the Reynolds number for this critical range has been exceeded, the flow in cylinder tests has shown no marked changes with increasing Reynolds number. Thus, it is believed that the flow over the full-size airships will be generally similar to the flow over models tested above the critical Reynolds number range. It was further pointed out that the effects due to the ground gradient should scale almost directly with the larger Reynolds number. The system of coordinates

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TABLE 4-1 - TYPE AND SCOPE OF DATA USED IN REFERENCES

Ref No.	Model Size Where Tested	ℓ/D	R_N & Velocity	Static Coefficients for Range of Model Angles Deg. Pitch	Yaw	Roll	Reference Dimensions R_N	Force	Moment	Model Location Relative to Ground Plane Height/Diam.	Vertical Velocity Gradient
18	1/40 Akron ℓ=235.5 in. full-scale wt	5.9 $(\frac{235.5}{39.8})$	(5 to 19) 10^6 20-100 mph 4.04 (R_N on $\mathcal{V}^{1/3}$)	-2-2 at ψ=0,30, 180 0→20	0,30,60 90,180	0-10 at ψ=0,30, 180	ℓ Ref vel measured at 5 ft or 200 ft full-scale height	$\mathcal{V}^{2/3}$	$\mathcal{V}$	H/D=$\frac{5.6}{39.8}$ to $\frac{11.6}{39.8}$	$V = h^{1/7}$ $q = h^{2/7}$
19	8 Models - ZRS-4 Bare Hull, with Fins, finishes, VDT	3.6→ 7.2 5.3→ 6.8	$(1\text{-}40)10^6$	0→20	0	0	ℓ	$\mathcal{V}^{2/3}$	$\ell\mathcal{V}^{2/3}$	Centerline	None
20	Cylindrical Models 1, 1.75, & 2.5 D inches 7 x 10 wt	-	$(0.6\text{-}1.6)10^5$	0-Two cylinder relative to each other - cross flow	90		Diam.	Frontal Area D x ℓ	None	H/D=0 to 4	None
21	1/79th Heavy Lifter No Tail & Tail 76-069 7x10 wt; q=3.1 psf	2.9 (equiv. ellipsoid)	0.75×10^6 Hull Roughed; sand grains	0-90 at ψ=0	0-90 at α=0	0	ℓ	$\mathcal{V}^{2/3}$		H/D=0.5 to 2	None
22	1/75th ZPN Docking Unlocking-Hanger X Tail - Nose First, Water	4.37 $(\frac{51.88}{11.75})$	5×10^5 V=1.18 fps water	0	0,30,60, 90,120, 150 180	0	ℓ	$\mathcal{V}^{2/3}$	$\mathcal{V}$	Scaled ZPN to Ground Plane	$V \approx h^{1/33}$ $q \approx h^{2/33}$ $V \approx h^{1/7}$ $q \approx h^{2/7}$
23	1/75th ZPN Docking Unlocking with Hanger (1) ZPN Only (2) Tail First, Water Basin	4.37 $(\frac{51.88}{11.75})$	5×10^5 V=1.18 fps water	0	0,60,90, 120(1) 0,30,60, 90,120, 150, 180(2)	0	ℓ	$\mathcal{V}^{2/3}$	$\mathcal{V}$	Scaled ZPN to Ground Plane	$V \approx h^{1/33}$ $q \approx h^{2/33}$
24	1/120 Navy C Balloon - 3 ft. wt. University of Washington	3 (12/4)	6×10^5 V=92 fps	0-90 at ψ=0	0	0	ℓ	$\mathcal{V}^{2/3}$	$\ell\mathcal{V}^{2/3}$	Tunnel Centerline	None
25	Aerocap Model without Tails 7x10 U of D	2.64 $(\frac{67.95}{25.77})$	4.9×10^6 V=148 fps	0-30 at ψ=0 5,10	0,5,10	0	ℓ	$\mathcal{V}^{2/3}$	$\mathcal{V}$	Tunnel Centerline	None
26	Single Hull Model Thin & Thick Tails 4x4 GAC Tunnel	2.99 $(\frac{16.88}{5.64})$	1.7×10^6 V=212 fps	(-) 15-45 at ψ=0	(-) 15-45 at α=0	0	ℓ	$\mathcal{V}^{2/3}$	$\mathcal{V}$	Tunnel Centerline	None

selected is based on that used in Reference 18 and is repeated in Figure 4-1. The data used from the references to establish aerodynamic loads for the analysis are presented in Figure 4-2.

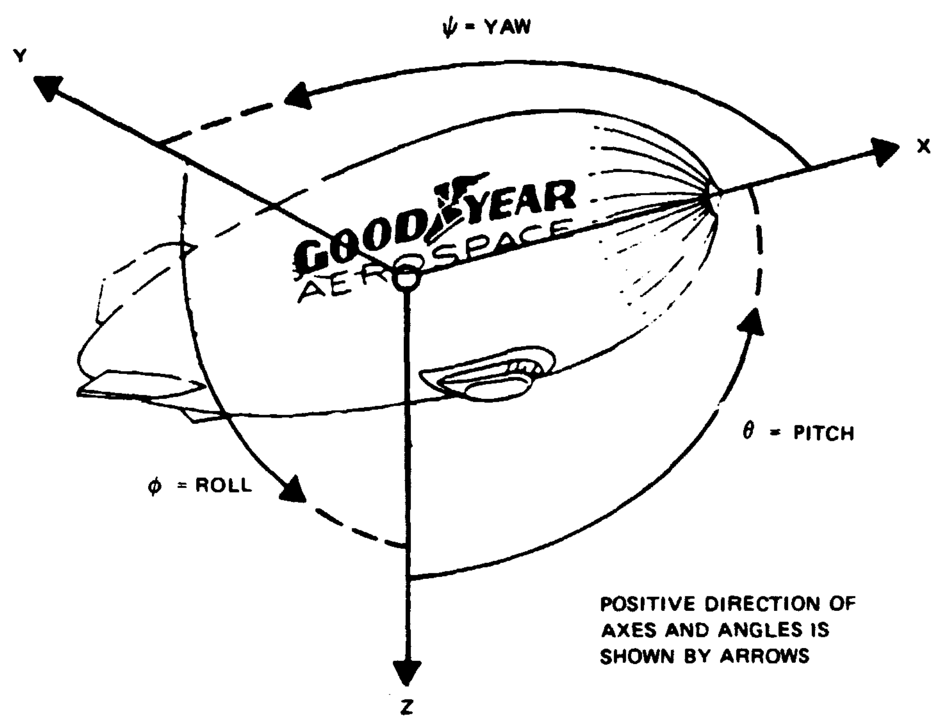


Figure 4-1 - Coordinate System

Figure 4-2 includes data presented as a curve from the extensive testing of a large airship model of the Akron in a large wind tunnel at yaw angles from 0 to 180 degrees (Reference 18), testing of a model of the heavy lifter in the 7 x 10 wind tunnel at yaw angles presented as a curve from 0 to 90 degrees (Reference 21), testing of a model of the ZPN in a water basin at yaw angles from 0 to 180 degrees (References 22 and 23), and wind tunnel tests of tethered balloon shapes (References 24 and 26). The coefficient values for the forces based on $V^{2/3}$ are similar despite the different model fineness ratios and testing facilities and techniques. The coefficient values from References 18, 21, 22, 23, 24, and 26 are most similar for C_y, which corresponds to the largest force acting on an airship at yaw angles from 60 to 120 degrees. The second largest force acting at yaw angles from 60 to 120 degrees is lift corresponding to minus values of C_z.

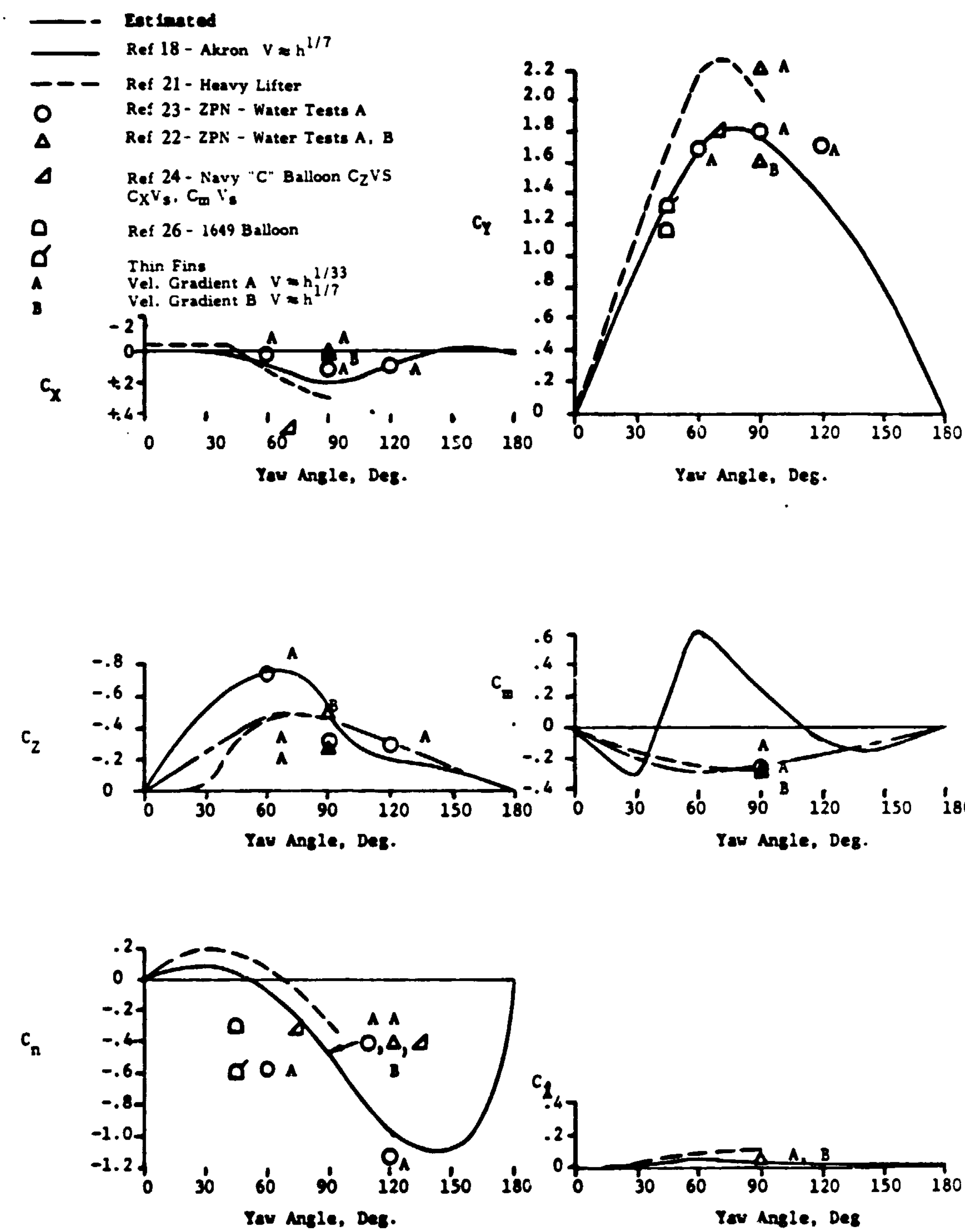


Figure 4-2 - Force and Moment Coefficient Values About Center of Buoyancy of Airships with Tails versus Angle of Yaw (Pitch and Roll Angles of Zero)

Agreement of the C_z values at 90 degrees of yaw is very good between Reference 18, 21, and 22 with the velocity gradient B ($V\alpha h^{1/7}$). The difference in coefficient values at 60 degree of yaw may be due to the differences in the values of fineness ratio of the different models, the selected test velocity gradients over the models, and the test H/D ratios (distance from ground/model diameter). The least similar values are associated with the longitudinal forces that have the smallest coefficient values, and the values appear to be very sensitive to the selected test velocity gradients and the test H/D ratios.

The similarity of values for the moment coefficients based on V from the different references is not always as good as for the force values. The yawing moment coefficient, C_n, which corresponds to the largest moment, has fair correlation between References 18, 21, 22, and 24 at 90 degrees of yaw. The pitching moment coefficient, C_m, is very sensitive to model fineness ratio and relative tail sizes as can be observed from the data of Reference 18 as compared to the data from References 21, 22, and 23 at a yaw angle of 90 degrees. From these data, specific coefficient values were selected at 60, 90, and 120 degrees of yaw for use in the structural weights analysis. The selected values are listed in Table 4-2.

TABLE 4-2 - BODY AXIS STATIC AERODYNAMIC FORCES AND MOMENTS

	Yaw Angle					
	60 Deg		90 Deg		120 Deg	
Force/moment	Coefficients	Forces (lb) and Moments (ft-lb)	Coefficients	Forces (lb) and Moments (ft-lb)	Coefficients	Forces (lb) and Moments (ft-lb)
Axial force	0.10	915 q	0.20	1,830 q	0.10	915 q
Side force	1.60	15,553 q	1.80	14,638 q	1.50	13,723 q
Vertical force	-0.76	-6,953 q	-0.60	-5,489 q	-0.20	-1,830 q
Rolling moment	0.03	26,250 q	0.02	17,500 q	0.03	26,250 q
Pitching moment	0.60	525,000 q	-0.20	-175,000 q	-0.10	-87,500 q
Yawing moment	0.05	43,750 q	-0.50	-437,500 q	-1.00	-875,000 q

Forces = $C_{x,y,z}\, qV^{2/3}$, Moments = $C_{l,m,n}\, qV$

V = volume = 875,000 cu ft, $V^{2/3}$ = 9148.3 sq ft

Empty weight = 38,160 lb

Buoyancy = 52,164 lb at 2000 ft

q = dynamic pressure (psf)

3. LOADS ON A FULLY RESTRAINED AIRSHIP

a. General

A preliminary analysis was conducted to determine the loads imposed on the landing gear due to winds acting on the airship when the landing gear totally constrains the airship's motion. For this first-order analysis, the airship is considered to be a rigid body with a rigid four-point landing gear. The assumed distribution of the landing gear forces in the different directions due to the different aerodynamic forces and moments acting on the airship is listed in Table 4-3. Sketches defining the aerodynamic sign conventions follow this table. The coordinates used are further defined in Table 4-4 and Figures 4-3 through 4-6. The analysis determines the landing gear forces due to the different aerodynamic forces and moments, proportions the forces between each of the four landing gear points, and superimposes the values at each point of the corresponding components and adds them to determine the total force values in the vertical, longitudinal, and lateral directions at each landing gear point. The signs in the resulting equations were made so that tensions between the landing gear and the constraint are positive (+).

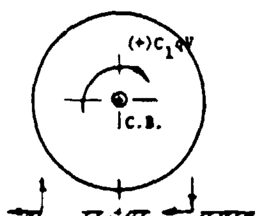
This investigation is a pragmatic approach to the generation of a solution. Implicit with this are the assumptions that (1) the landing gear positions are at the corners of a rectangle with the location of the CB at the center of that rectangle and (2) the stiffness of the the landing gear support structures are symmetric with respect to both the X-Z plane and Y-Z plane.

b. Vertical Landing Gear Forces

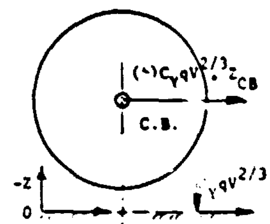
Transferring the rolling moments to the plane of the landing gear, the components of the vertical forces can be determined by the sum of the moments due to the values of $C_y qV^{2/3}$ about y = 0, and Z = 0; that is, the intersection of vertical centerline and the ground and $C_l qV$ (see Figure 4-3).

TABLE 4-3 - ASSUMED DISTRIBUTION OF LANDING GEAR FORCES IN THREE DIFFERENT AXIAL DIRECTIONS

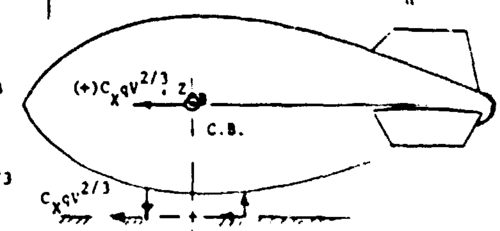
Axial Direction of Resulting Landing Gear Forces	Aerodynamic Forces Through CB			Aerodynamic Moments About CB		
	Longitudinal C_X	Lateral C_Y	Vertical C_Z	Rolling C_l	Pitching C_m	Yawing C_n
Vertical	$C_X q\ V^{2/3}$	$C_Y q\ V^{2/3}$	$C_Z qV^{2/3}$	$C_l qV$	$C_m qV$	-0-
Horizontal Longitudinal	$C_X qV^{2/3}$	-0-	-0-	-0-	-0-	$.5C_n qV$
Horizontal Lateral	-0-	$C_Y qV^{2/3}$	-0-	-0-	-0-	$.5C_n qV$



Loads due to Rolling Moment $C_l qV$
(End View)



Loads due to Lateral Force $C_Y qV^{2/3}$
(End View)



Loads due to Longitudinal Force $C_X qV^{2/3}$
(Side View)

TABLE 4-4 - COORDINATE SYSTEM

A. The aerodynamic forces pass through the coordinates of the CB located at:

x	y	z
l_{CB}	0	$-Z_{CB}$

where: l = 0 at nose; (+) toward tail

y = 0 at centerline; (+) centerline to starboard

Z = 0 at ground level; (+) downward

B. Landing gear coordinates are:

Landing gear	X	Y	Z
A_1	l_{LG_F}	$-Y_{LG_F}$	0
B_1	l_{LG_R}	$-Y_{LG_R}$	0
A_2	l_{LG_F}	Y_{LG_F}	0
B_2	l_{LG_R}	Y_{LG_R}	0

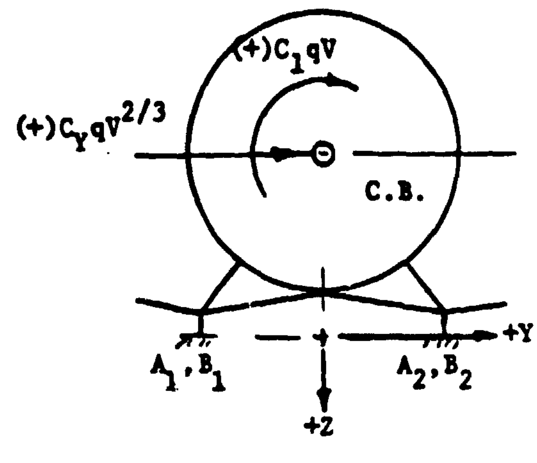


Figure 4-3 - Moments About Y=0, Z=0; View Looking Forward Along Centerline

Assuming all four landing gear points share the vertical forces equally (symmetrical stiffness), then these components are:

$$\text{Vertical force at } A_1,\ B_1,\ A_2,\ B_2 = \left[\frac{C_l qV + C_Y qV^{2/3}(Z_{LG} - Z_{CB})}{4\ (Y_{CB} - Y_{LG})}\right] \quad (1)$$

where: $Z_{LG} = 0$

$Y_{CB} = 0$

Z_{CB} = height of airship center of buoyancy above ground (ft)

Y_{LG} = lateral locations of A_1, B_1, A_2, B_2 (ft)

Tension = (+)

Again, transferring the pitching moment to the plane of the landing gear, the components of the vertical forces can be determined by the sum of the moments due to the values of $C_x qV^{2/3}$ about l_{CB} and Z = 0, and $C_m qV$ (see Figure 4-4).

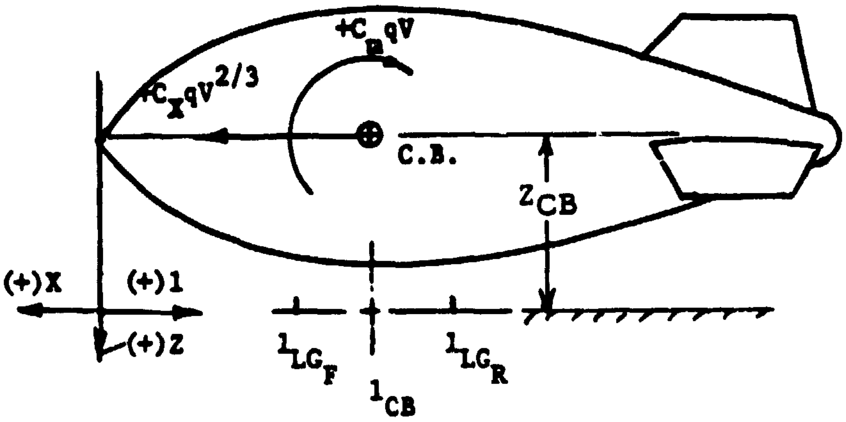


Figure 4-4 - Moments About l_{CB}, Z=0, View Looking Port to Starboard

Assuming all four landing gear points share the vertical forces equally, then the values of these vertical force components are:

$$\text{Vertical force at } A_1,\ B_1,\ A_2,\ B_2 = \frac{C_m qV - C_x qV^{2/3}\ (Z_{LG} - Z_{CB})}{4\ (l_{CB} - l_{LG})} \qquad (2)$$

Where: l_{CB} = distance of airship center of buoyancy from nose (ft)

l_{LG} = longitudinal location of A_1, B_1, A_2, B_2 (ft)

The vertical forces due to the vertical loads, $C_z qV^{2/3}$, buoyancy and weight, can be determined by summing only the vertical forces assuming the forces are in alignment (see Figure 4-5).

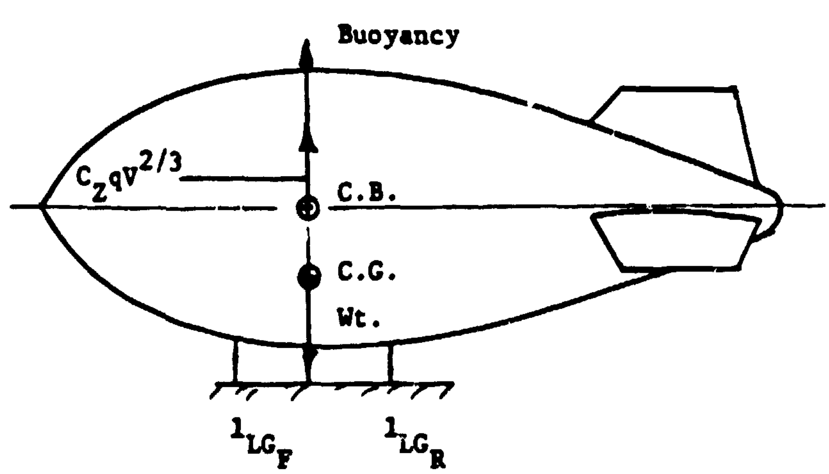


Figure 4-5 - Vertical Loads, View Looking Port to Starboard

Assuming all four landing gear points are equally spaced forward and aftward of the CB, they will share the vertical forces equally. The values of these vertical force components are:

$$\text{Vertical force at } A_1, B_1, A_2, B_2 = \frac{\Delta\rho V - C_Z qV^{2/3} - \text{weight}}{4} \tag{3}$$

Where: $\Delta\rho$ = difference in the densities of air and helium (lb/cu ft)
wt = Weight of airship (lb)

Superpositioning and adding the vertical components from (1), (2), and (3) results in the total vertical landing gear forces at A_1, B_1, A_2, B_2 or

$$\text{Total vertical force at } A_1, B_1, A_2, B_2 = \frac{C_1 qV + C_Y qV^{2/3}(Z_{LG} - Z_{CB})}{4(Y_{CB} - Y_{LG})} +$$

$$\frac{C_m QV - C_X qV^{2/3}(Z_{LG} - Z_{CB})}{4(l_{CB} - l_{LG})} + \frac{\Delta\rho V - C_Z qV^{2/3} - Wt}{4} \tag{4}$$

Where tension at restraint = (+)

c. Horizontal Landing Gear Forces

The horizontal forces in the longitudinal and lateral directions were established in a similar manner. Longitudinal landing gear forces were determined assuming one-half of the yawing moment results in longitudinal landing gear forces and the other half results in lateral forces; the longitudinal forces can be determined from the value of $C_X qV^{2/3}$ acting through and about l_{CB} and Z=0 (see Figure 4-4) and a 0.5 $C_n qV$ acting about a vertical centerline through the CB (see Figure 4-6).

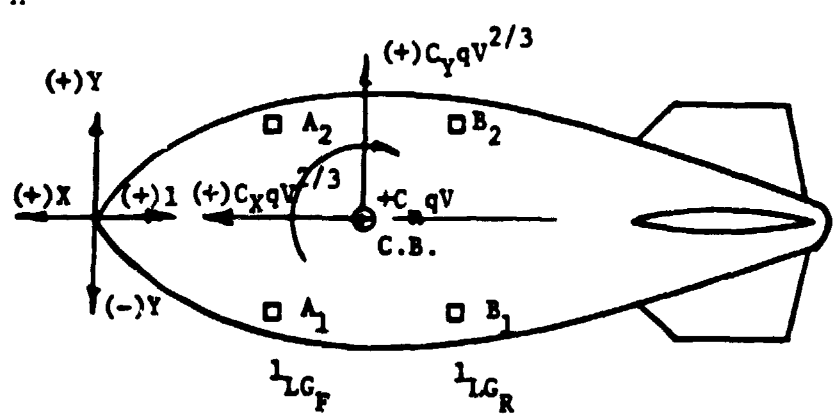


Figure 4-6 - Moments About Vertical Axis through CB, View Looking Down at Airship

Assuming all four landing gear points share each of the longitudinal forces equally, then the total longitudinal forces imposed by each landing point are:

Total longitudinal landing gear forces at A_1, B_1, A_2, B_2 =

$$\frac{C_X q V^{2/3}}{4} + \frac{.5 C_n q V}{4(Y_{CB} - Y_{LG})} \qquad (5)$$

Where a force forward = (+)

The lateral landing gear forces were determined assuming the values of $C_Y q V^{2/3}$ and $0.5C_n qV$ acting through and about a vertical centerline through the CB (see Figure 4-3) and $0.5C_m qV$ acting about l_{CB} and Z=0 (see Figure 4-4).

Assuming all four landing gear points share each of the lateral forces equally, then the total lateral forces imposed by each landing gear point are:

Total lateral landing gear forces at A_1, B_1, A_2, and B_2 =

$$\frac{C_Y q V^{2/3}}{4} + \frac{.5 C_n q V}{4(l_{CB} - l_{LG})} \qquad (6)$$

Where a force from port to starboard = (+)

The aerodynamic coefficients to be used with the prior equations were presented as curves in Figure 4-2.

4. COMPUTER MODEL FOR FULLY RESTRAINED AIRSHIP

A computer model to evaluate the static loads developed at the gear points in a fully restrained airship mooring system was developed in accordance with the equations presented in the preceding section. Forces in the vertical, lateral, and longitudinal directions are computed for various landing gear spans. Figure 4-7 shows the effect of wind speed on these forces. Note that the maxima do not occur at the same wind angle. The highest vertical load is a result of a 90-degree cross wind, while both the lateral and longitudinal peaks occur at 120 degrees. The effect of landing gear placement with respect to the main axis of the airship is shown in Figure 4-8. Naturally, as the moment arm is increased, the peak vertical load diminishes.

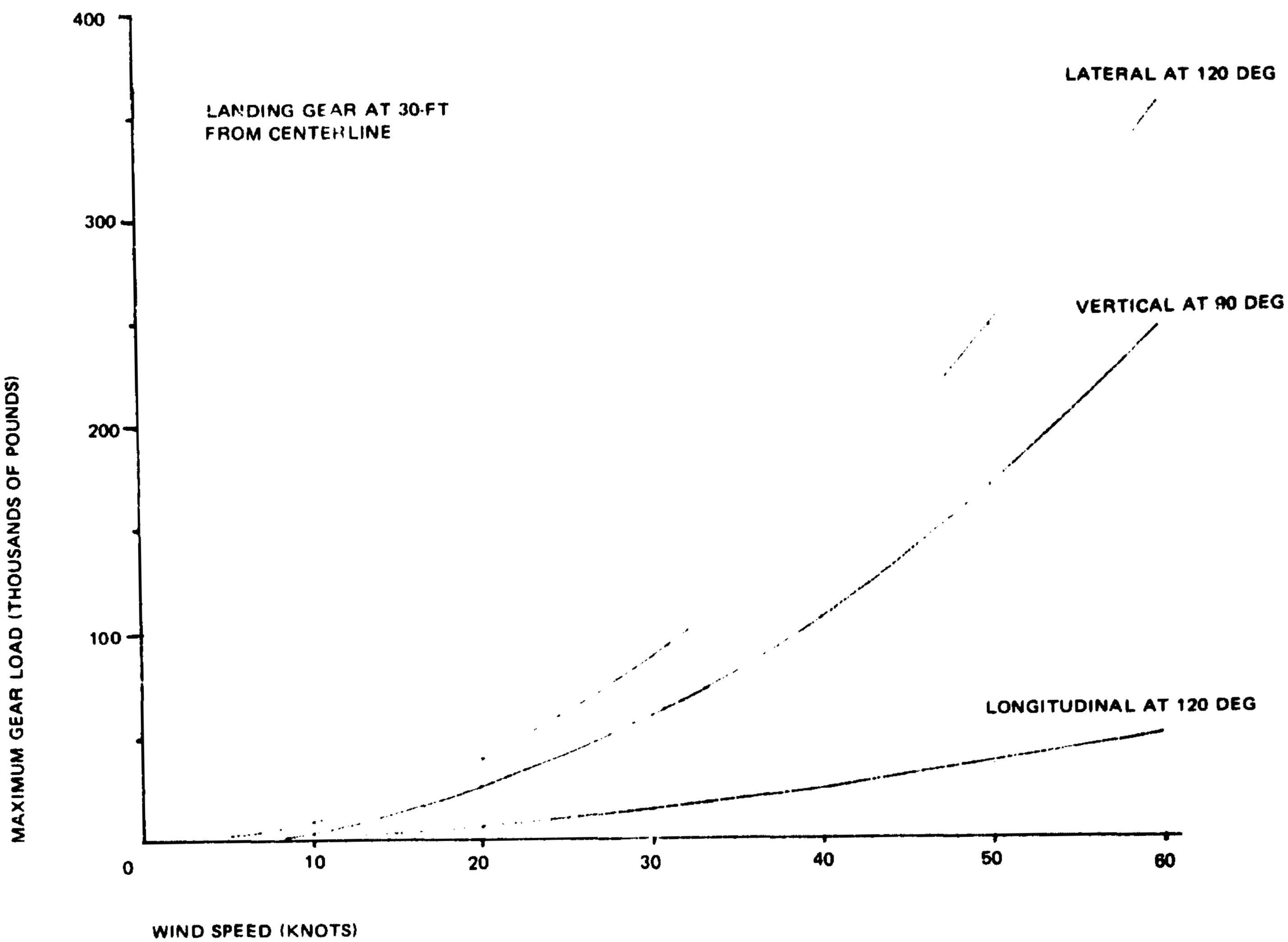


Figure 4-7 - Maximum Gear Forces versus Wind Speed

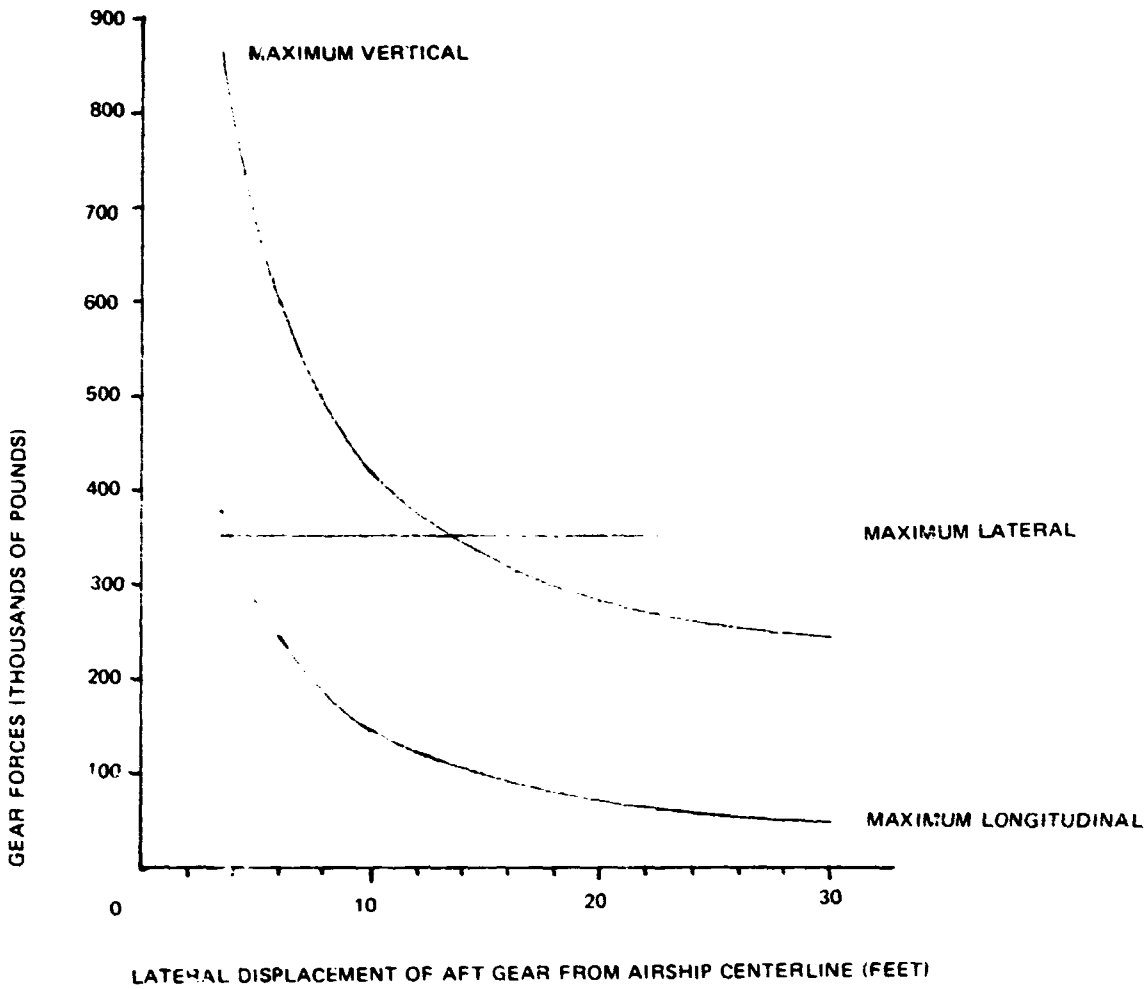


Figure 4-8 - Maximum Gear Forces versus Landing Gear Placement

SECTION V - DYNAMIC ANALYSIS OF A MASTED AIRSHIP

1. GENERAL

Dynamic loads analysis and associated computer programs were developed to determine mooring loads for each mooring application for systems with rotational capability. A description of the logic and results of the calculations are presented.

2. DYNAMIC FORCES AND MOMENTS ACTING ON THE AIRSHIP

For those mooring styles in which the airship is free to rotate (bow moored, belly moored, and center point moored), consideration must be given to dynamic forces and moments. The static analysis is therefore extended to encompass this realm.

The airship was divided into ten equal-length segments. The total aerodynamic forces acting on the airship were considered for the analysis to be the sum of the aerodynamic forces acting on each segment. The segmented approach was chosen because the relative wind speed and relative wind direction change drastically over the length of the airship as its angular velocity increases. For instance, with bow mooring the relative wind velocity acting on the tail becomes negative long before the airship reaches its maximum rotational velocity caused by a wind direction shift.

The segmented method was selected as a first-order engineering approach since it did not require the generation of damping term coefficients associated with more conventional analyses. Simulations using the segmented approach predict that the airship will respond to the wind as expected with little overshoot as it aligns with the wind.

The following assumptions are integral with this approach:

1. A steady-state wind condition is assumed. A more rigorous investigation would involve a review of gust response and accelerative effects that are beyond the scope of this study. Appendix A summarizes approaches that may be appropriate.
2. The aerodynamic forces and moments acting on the entire airship are a summation of the individual forces and moments for each segment. The forces on each segment are simply a function of the localized airspeed and yaw angle, while the individual moments consist of the product of segmental forces and their moment arms.

3. The airship rotates in the horizontal plane only. It is recognized that kiting of a moored airship will undoubtedly occur, but the magnitude of the kiting forces is insignificant compared to the lateral forces at large yaw angles. The vertical forces were uncoupled from the horizontal forces.
4. The rotational accelerations of the airships are limited only by the effects of rotational inertia. No attempt was made to quantify forces such as those to initiate rolling in the landing gear to overcome rolling resistance.
5. The rotational velocity is limited when the sum of the moments about the mast due to the aerodynamic forces acting on the segments becomes zero.

The values of C_x or C_y over the length of the airship for yaw angles from 0 to 20 degrees were developed from force distribution data for airships versus angle of yaw (Reference 33). The values of C_x or C_y over the length of the airship for yaw angles greater than 20 degrees were calculated using pressure distribution data (References 33 and 34) and the relative projected area of the segments. The resulting force distribution values for C_y versus the airship length for different angles of yaw are presented in Figure 5-1. The C_y values for each yaw angle were integrated over the airship length for comparison with the corresponding C_y values for the total airship, and the curve values were adjusted until the values were equal. The curve was then divided into ten equal-length segments of the airship. The average C_y value for each segment was then calculated from the curve values within each segment.

The values of the yawing moment coefficients were calculated next from the values of the force coefficients for each of the ten segments and their positions from the center of pressure of the airship. These calculated values were compared with the yawing moment coefficient (C_n) values measured for the total airship. If the values did not correspond, the shape of the force coefficient curve was slightly adjusted while preserving the area under the curve that corresponds to the value of C_y for the total airship. This process was repeated until the calculated values of C_y and C_n based on the segments equaled the values of C_y and C_n measured for the total airship.

This calculation process can lead to more than just one solution for the force distribution curves. However, the force distribution curves belong to a family with the values corresponding to the forward portion of the airship being well

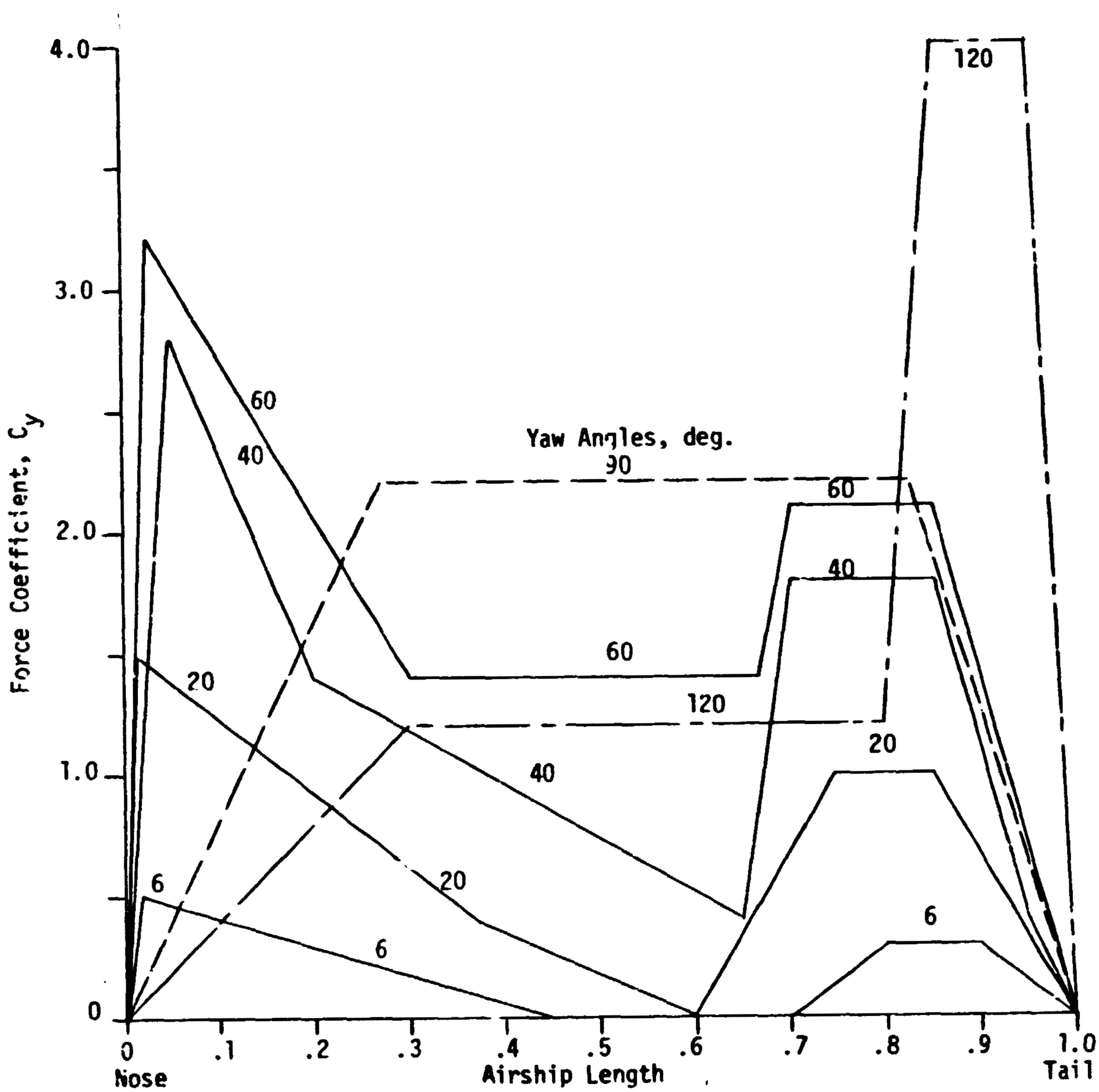


Figure 5-1 - Force Coefficient versus Airship Length for Various Yaw Angles defined at yaw angles of less than 20 degrees and reasonably defined from pressure distributions at angles of yaw greater than 20 degrees. The portion of the curves requiring judgment for the iterative solution is related to the tail region. With these constraints, the shapes and values for the force distribution curves are limited to within a reasonably narrow range that is compatible with an engineering analysis of the forces acting on the airship during its rotation about a mast.

The resulting average values of C_x and C_y for each of the ten segments versus angle of yaw are presented in Figures 5-2 and 5-3, respectively. The sign conventions used in the analysis are indicated in Figure 5-4.

The aerodynamic forces and moments acting on the airship segments were calculated using a computer program that allowed the airship to rotate in a horizontal plane about a vertical mooring mast. The program allowed positioning the mast at any position along the airship. The relative wind velocity (vector) at each airship segment due to the selected wind velocity and the velocity of the airship segment determined the value of the coefficient and dynamic pressure acting on each segment. Initially, the resistance to rotation is due to inertia of the airship and its virtual mass. As time passes, the airship's rotational velocity increases and the aerodynamic forces acting on the tail of the airship become less, and then they resist the actions of the aerodynamic forces on the more forward sections. Finally, it was calculated that the aerodynamic forces resist rotation of the airship and slow the rotational velocity of the airship to small values as the airship heads into the wind. The airship rotates only a few degrees beyond heading into the wind because of the small rotational momentum remaining.

The following equations were developed for this analysis:

$$F_{latr} = \sum_{i=1}^{10} F_{y_i} - \sqrt{\frac{M}{Iy}} \sum_{i=1}^{10} (L_i - L_m) F_{y_i} \tag{16}$$

$$F_{long} = \sum_{i=1}^{10} F_{x_i} + \sqrt{MI_y} \quad \dot{\theta}^2 \tag{17}$$

$$F_{mast} = \sqrt{F_{latr}^{2} + F_{long}^{2}} \tag{18}$$

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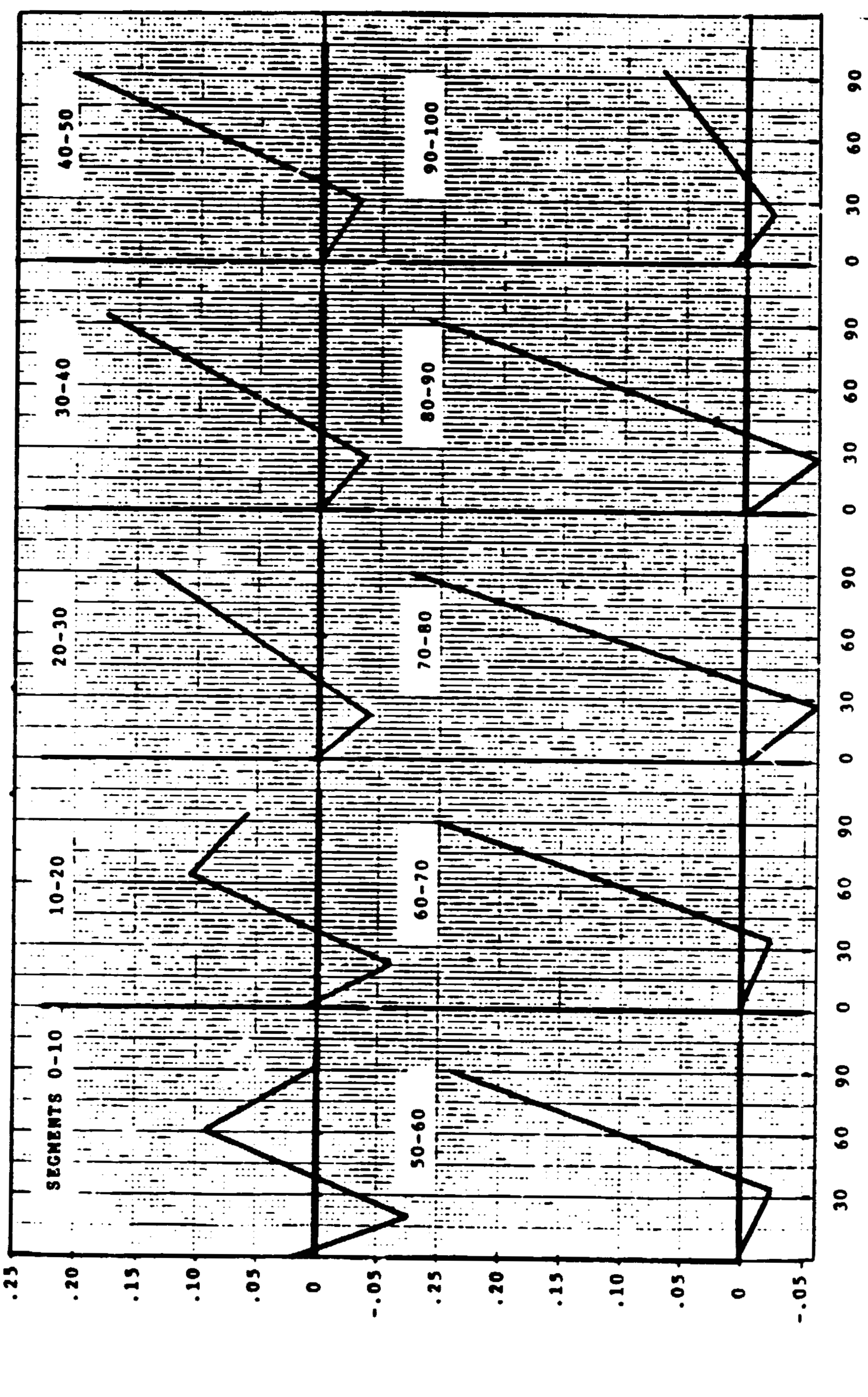

Figure 5-2 - C_x by Segments, Nose to Tail (-)

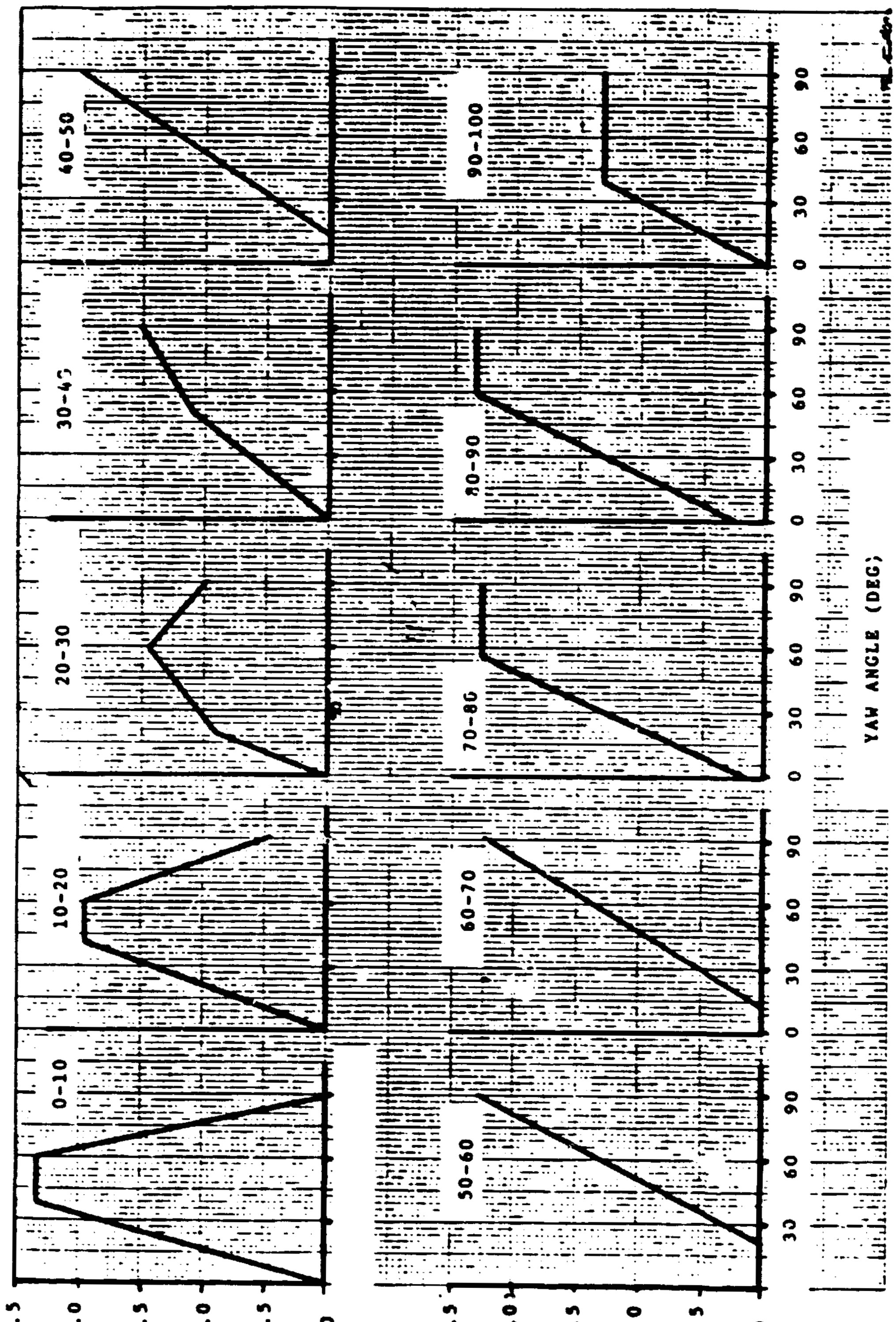

Figure 5-3 - C_y by Segments, Centerline to Starboard (+)

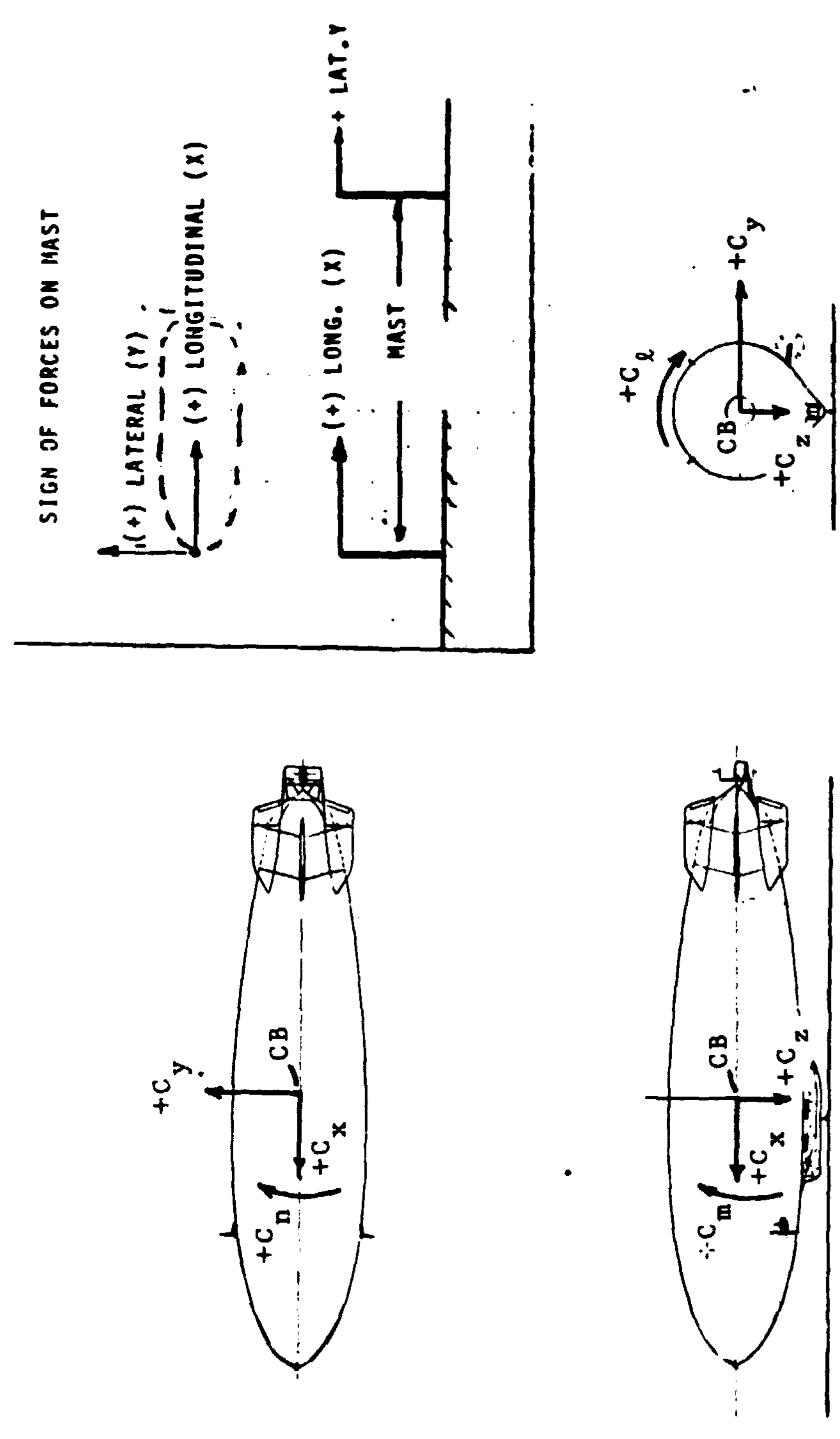

Figure 5-4 - Sign of Forces and Moments

$$\ddot{\theta} = \left[\sum_{i=1}^{10} (L_i - L_m) F_{y_i} \right] / I_y \qquad (19)$$

where

$$F_{y_i} = 927 \ \rho \frac{V_T^2}{2} C_{y_i} \qquad (20)$$

$$F_{x_i} = 927 \ \rho \frac{V_T^2}{2} C_{x_i} \qquad (21)$$

$$V_T^2 = V_w^2 \sin^2 (\psi - \theta) + \left[V_w - \cos (\psi - \theta) - \dot{\theta} (L_i - L_m) \right]^2 \qquad (22)$$

and

$$I_y = I_{cg} + (L_{cg} - L_m) \ m \qquad (23)$$

3. COMPUTER MODEL FOR SYSTEMS WITH ROTATIONAL CAPABILITY

The computer program deals with the dynamic loads analysis for bow, belly, and center point mooring situations. An annotated logic sequence for the program is shown in Figure 5-5.

a. Data Inputs

A description of the data input requirements is as follows:

1. Airship profile table of distance from the nose versus envelope radius
2. Segment location identifying the location of each analyzed segment with respect to the nose
3. C_x and C_y tables providing tabular data of the information that is graphically illustrated in Figures 4-1 and 4-2
4. Moment of inertia about the center of gravity, including the effect of virtual mass
5. Airship mass, including virtual mass
6. Location of the mast with respect to the nose of the airship
7. Location of the airship's center of buoyancy with respect to its nose
8. Time and iteration intervals
9. Height of the airship's center line
10. Initial values for angular displacement, angular velocity, wind speed, and wind direction

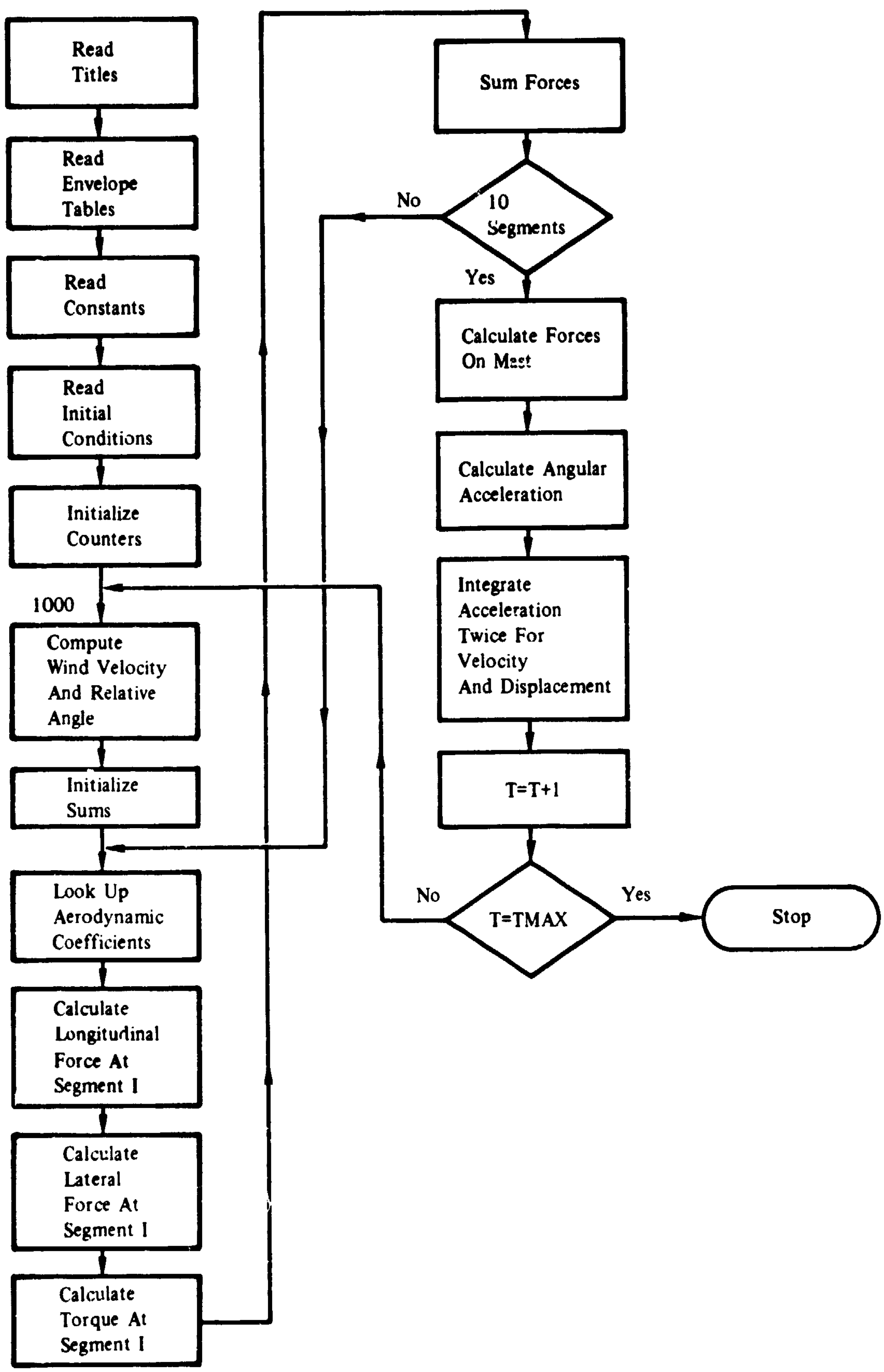

Figure 5-5 - Moored Airship Dynamic Simulation Logic Sequence

b. Computed Inputs

Two computed inputs for the simulation model are: (1) mast height, which is a function of mast location and the airship profile; and (2) moment of inertia about the mast.

c. Outputs

A tabular listing of the airship configuration data, mooring style data, and initial conditions is provided at the beginning of a computation. Computed values of angular acceleration (THEDD), angular velocity (THED), angular displacement with respect to the original airship location (THE), the transverse load on the mast (FLATR), the longitudinal force on the mast (FLONG), and the total force on the mast (FMAST). Since there is no rolling moment associated with bow mooring, there are no landing gear forces to compute. However, belly mooring introduces significant landing gear loads which are tabulated (FLGA 1, FLGB 1, FLGB 2) for the forward, port, and starboard gears, respectively. The magnitude of these loads is determined by their geometric locations in apportioning the overall lateral and longitudinal forces on the airship.

4. COMPUTER MODEL RESULTS AND ANALYSIS

a. General

A series of graphs was generated to identify predicted performance attributes of the dynamic mooring systems for varying input conditions. Initial wind characteristics (speed and direction) are indicated on the graphs. Peak forces are defined as the highest ocurring force over the integration time.

b. Mast Forces Versus Mast Location

Three graphs plotting the peak mast forces against the mast location are shown in Figures 5-6, 5-7, and 5-8 for total mast force, lateral mast force, and longitudinal mast force, respectively. Distance "0" represents bow mooring, 143.6 indicates center point mooring, and all intermediate values are belly mooring.

As the mast is moved from the bow toward the center of the airship, FLATR increases while FLONG decreases. The net effect on FMAST is to increase as the mast distance from the bow increases.

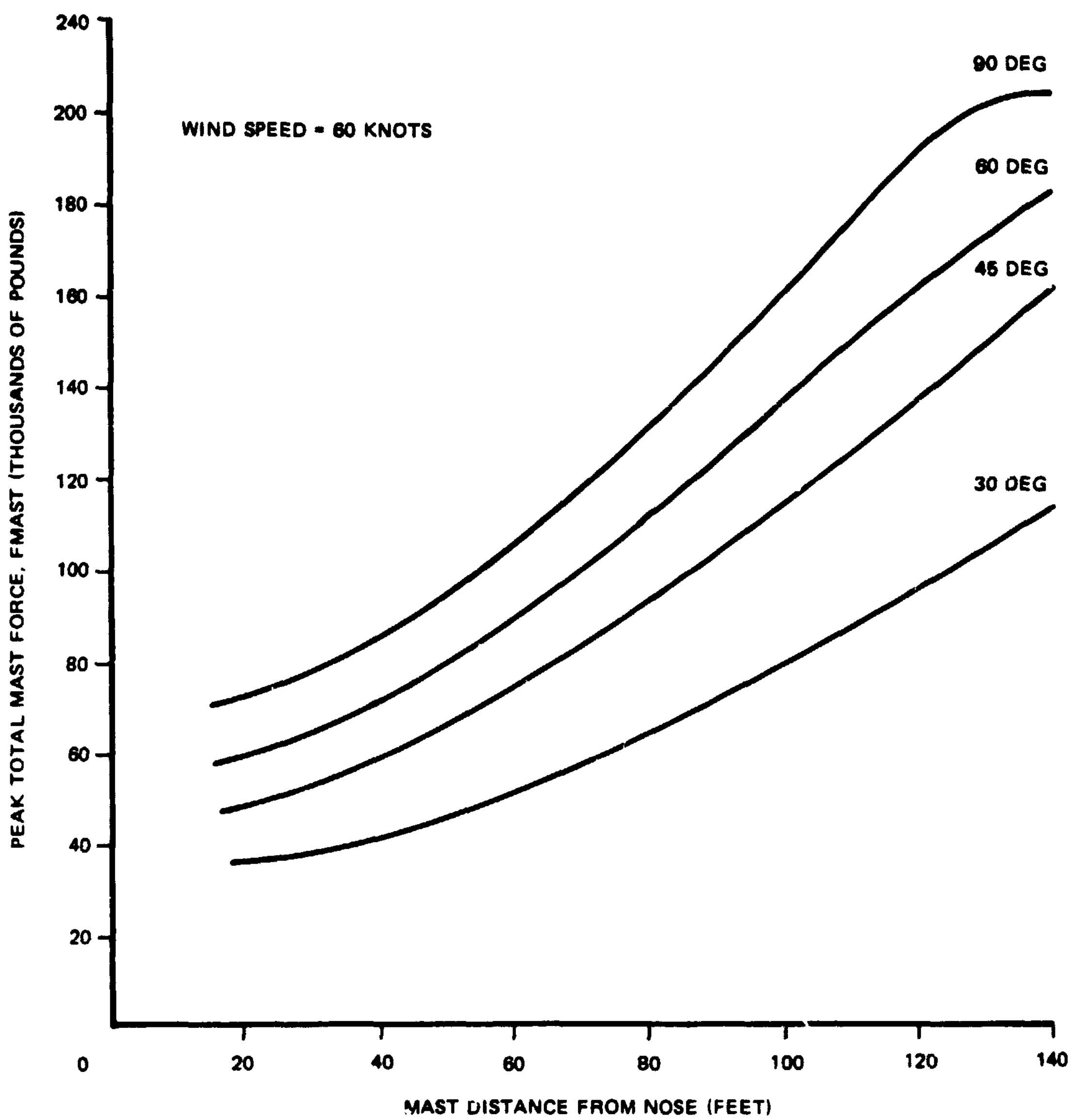

Figure 5-6 - Peak FMAST versus Mast Location

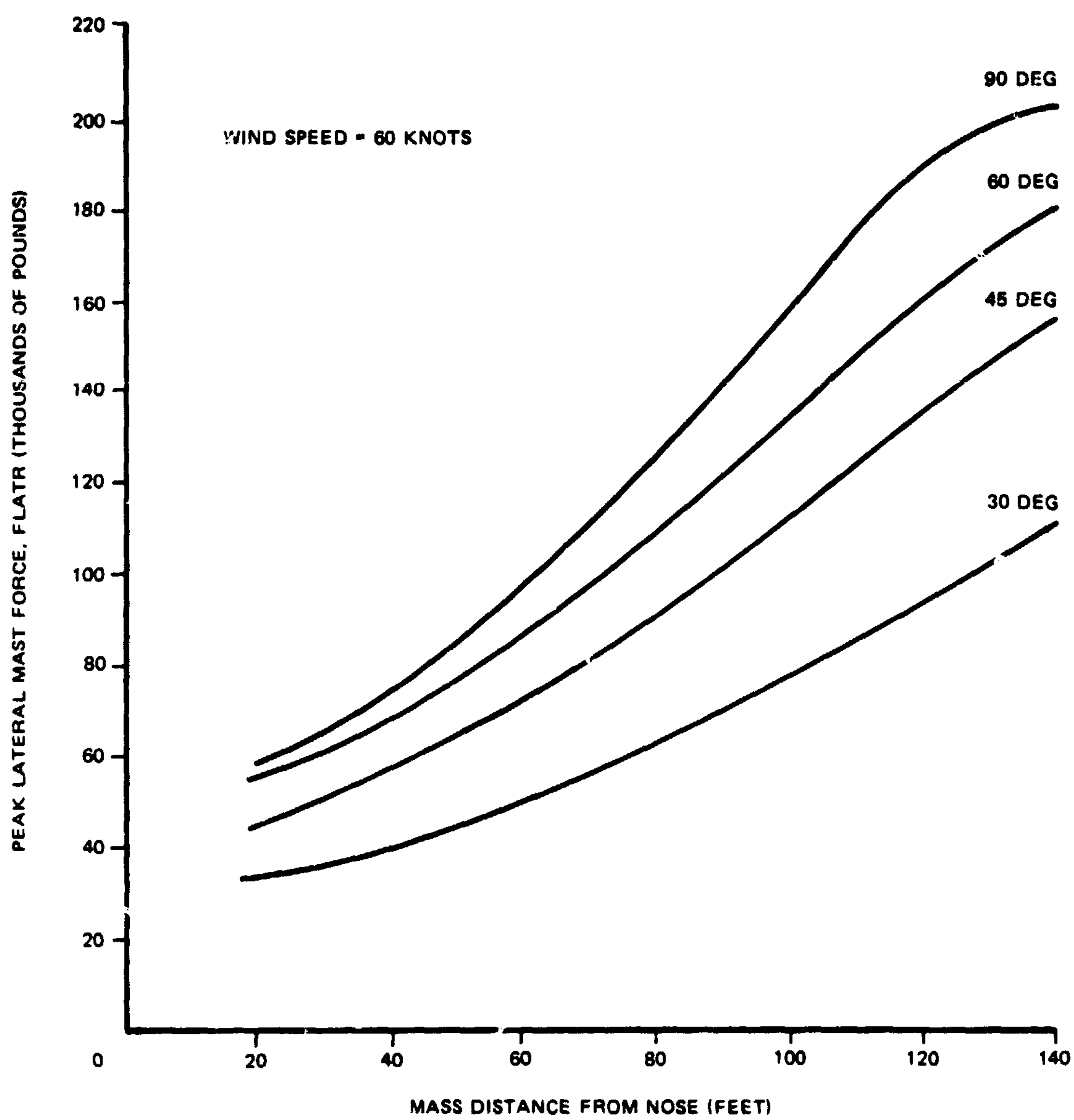

Figure 5-7 - Peak FLATR versus Mast Location

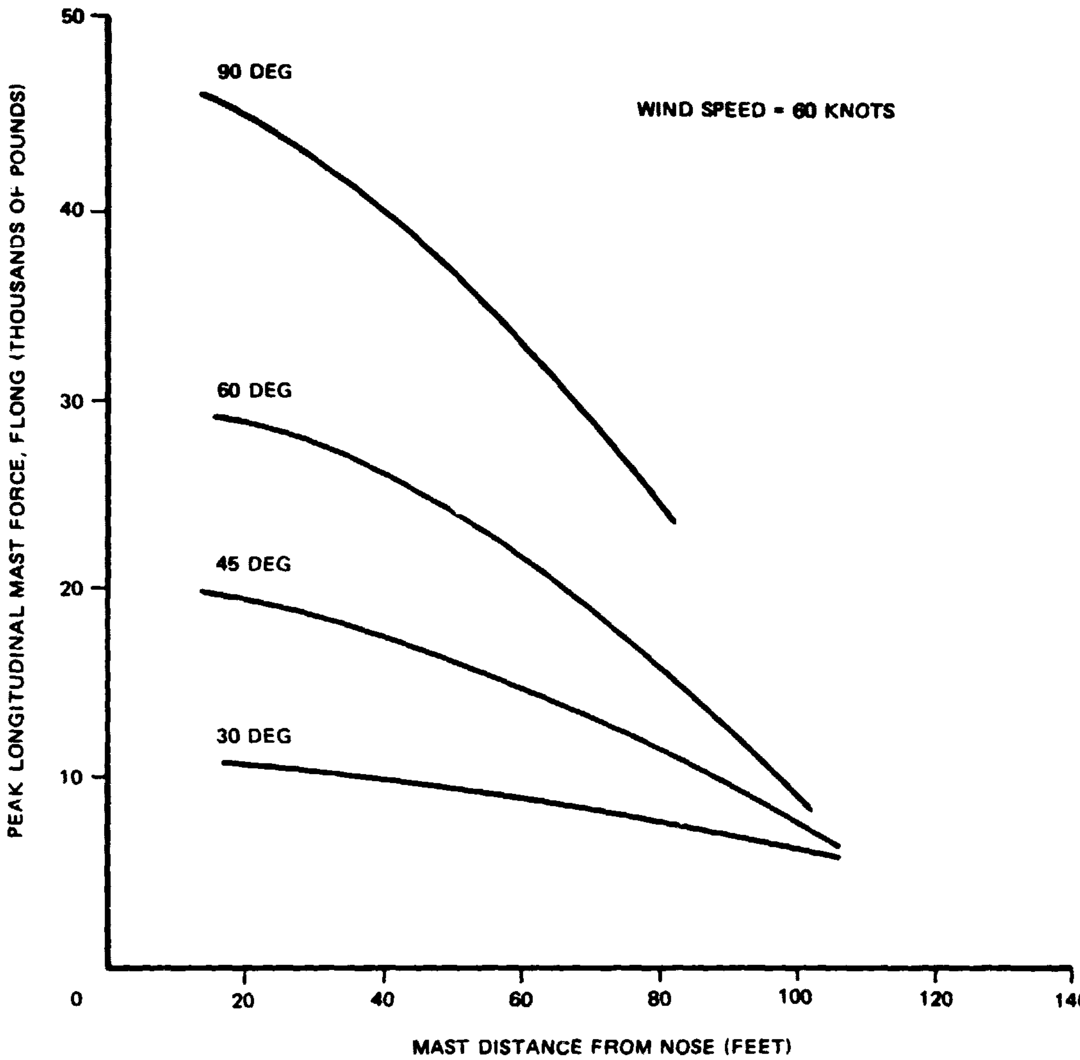

Figure 5-8 - Peak FLONG versus Mast Location

c. Bow Mooring

The peak forces generated on the mast are sensitive to both the wind's originating direction with respect to the airship and its speed. Figures 5-9 and 5-10 illustrate these relationships.

d. Belly Moored

For this analysis, the mast location for a belly moored airship was arbitrarily assigned at 75 feet from the nose. This value coincides with the longitudinal placement of the envelope-mounted powerplant and represents a point that does not fall within the forward ballonet. In this case, as shown in Figures 5-11 and 5-12, the lateral force is predominant for all angles.

e. Equilibrium Angle

In these dynamic mooring concepts, the wind causes the airship to rotate about the mast. As indicated in Figure 5-13, however, once the mast distance from the nose exceeds 90 feet, the airship no longer lines up with the prevailing wind. For example, at an initial wind direction of 30°, with the mast at 120 feet from the nose, the airship would be at equilibrium at approximately (30 - 7°) or 23°.

Appendix B contains listings and graphs for both bow and belly mooring conditions at 60-knot wind speeds for angles between 15 degrees and 90 degrees in 15-degree increments.

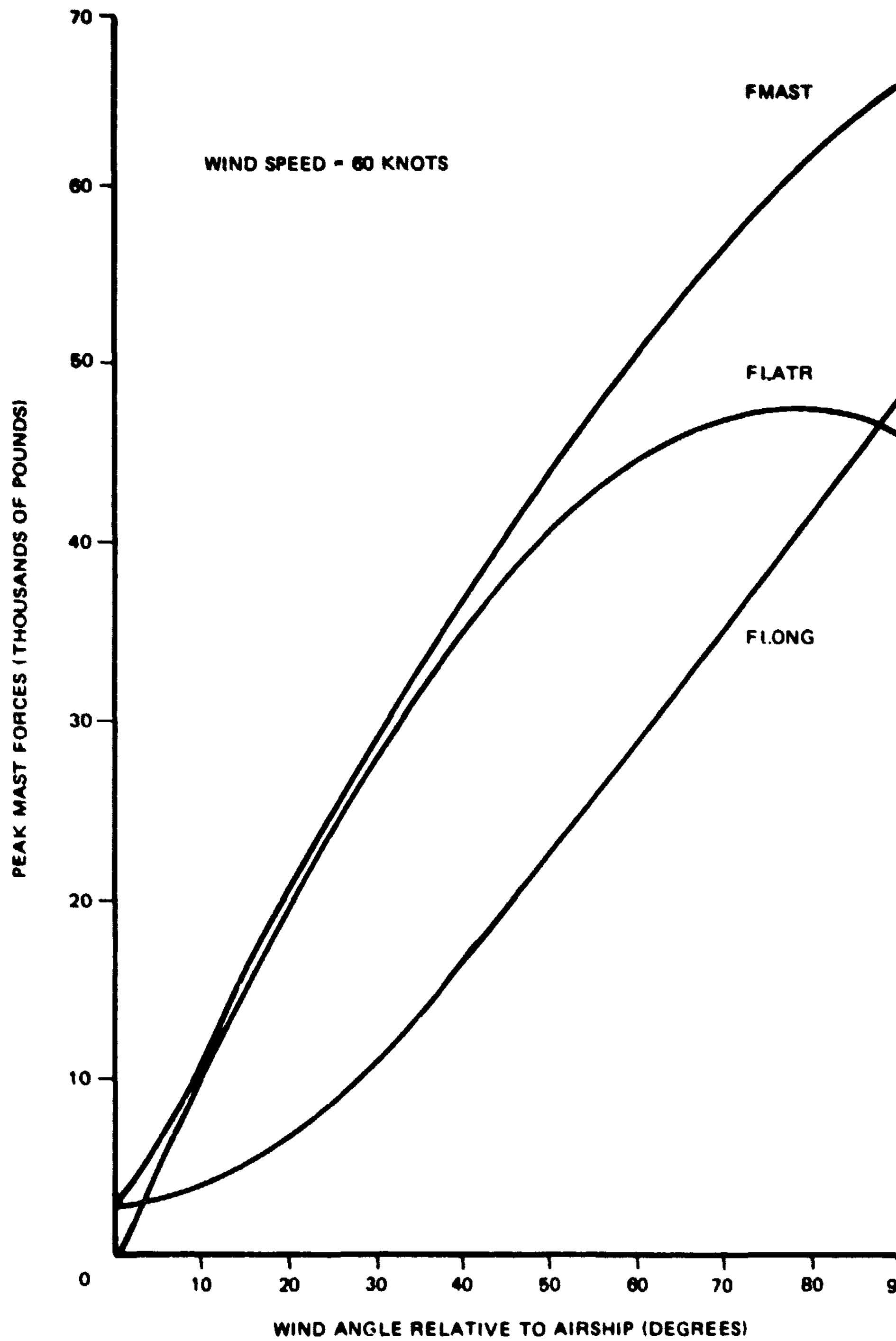

Figure 5-9 - Peak Mast Forces versus Wind Angle
for Bow Moored MPA

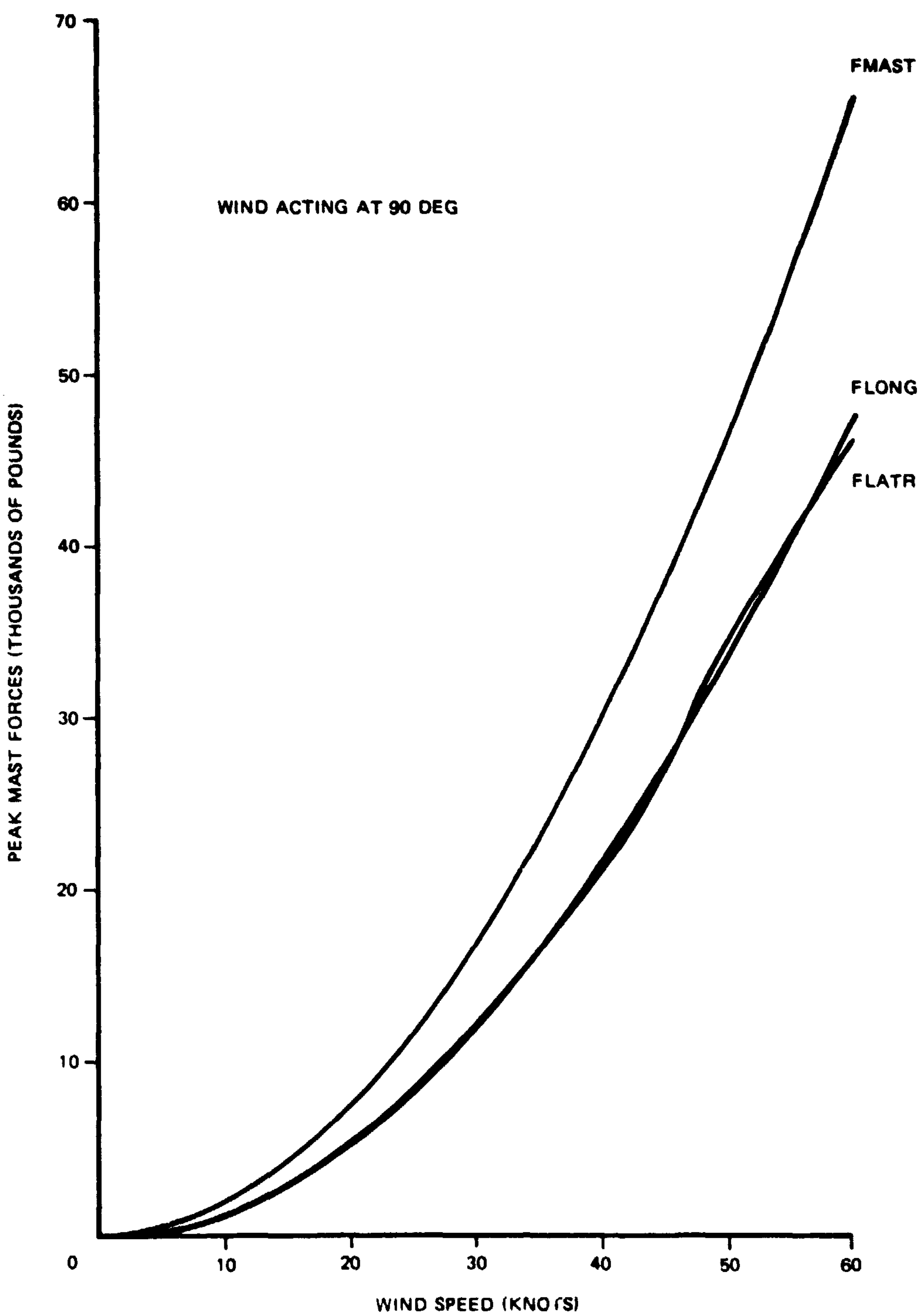

Figure 5-10 - Peak Mast Forces versus Wind Speed for Bow Moored MPA

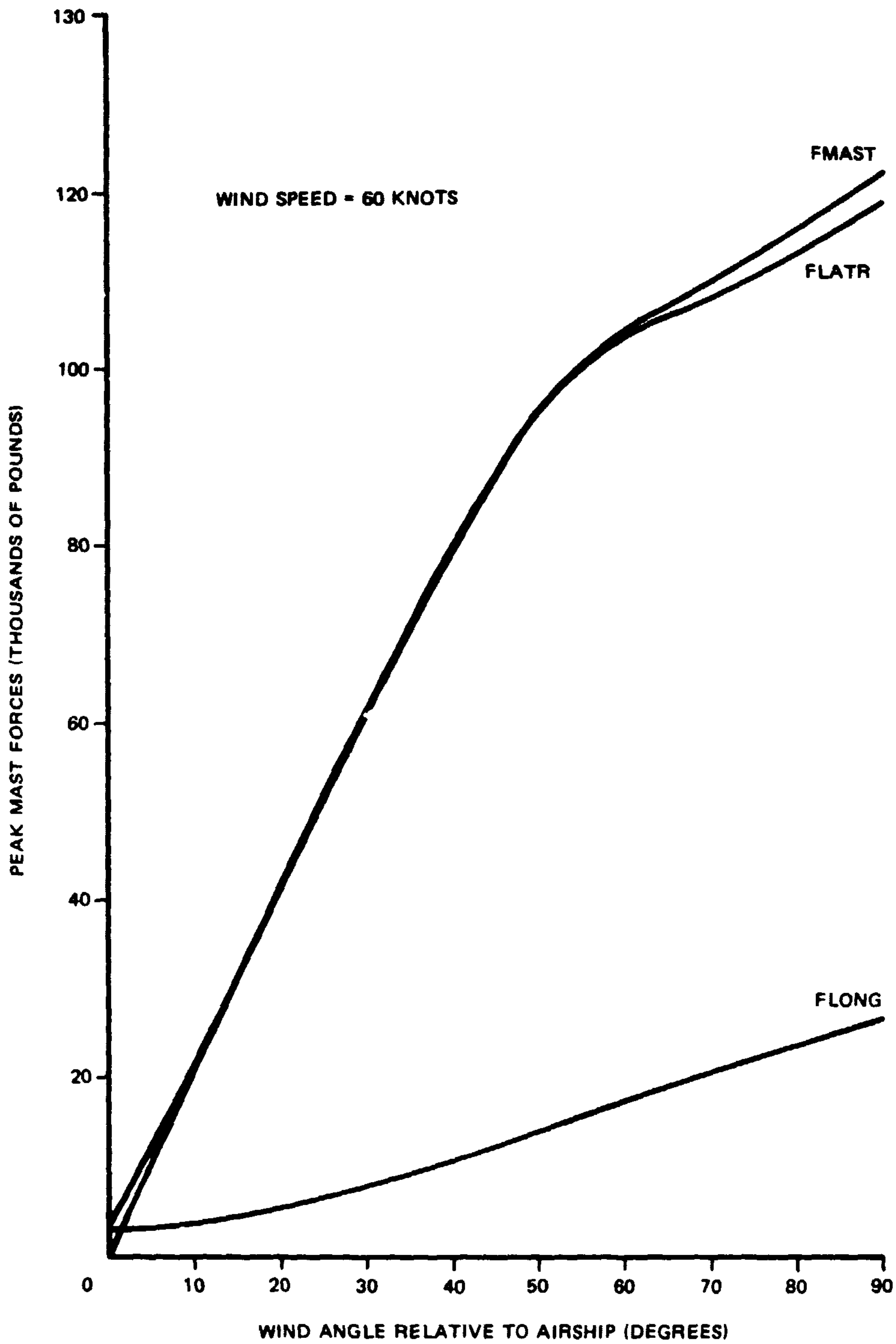

Figure 5-11 - Peak Mast Forces versus Wind Angle for Belly Moored MPA

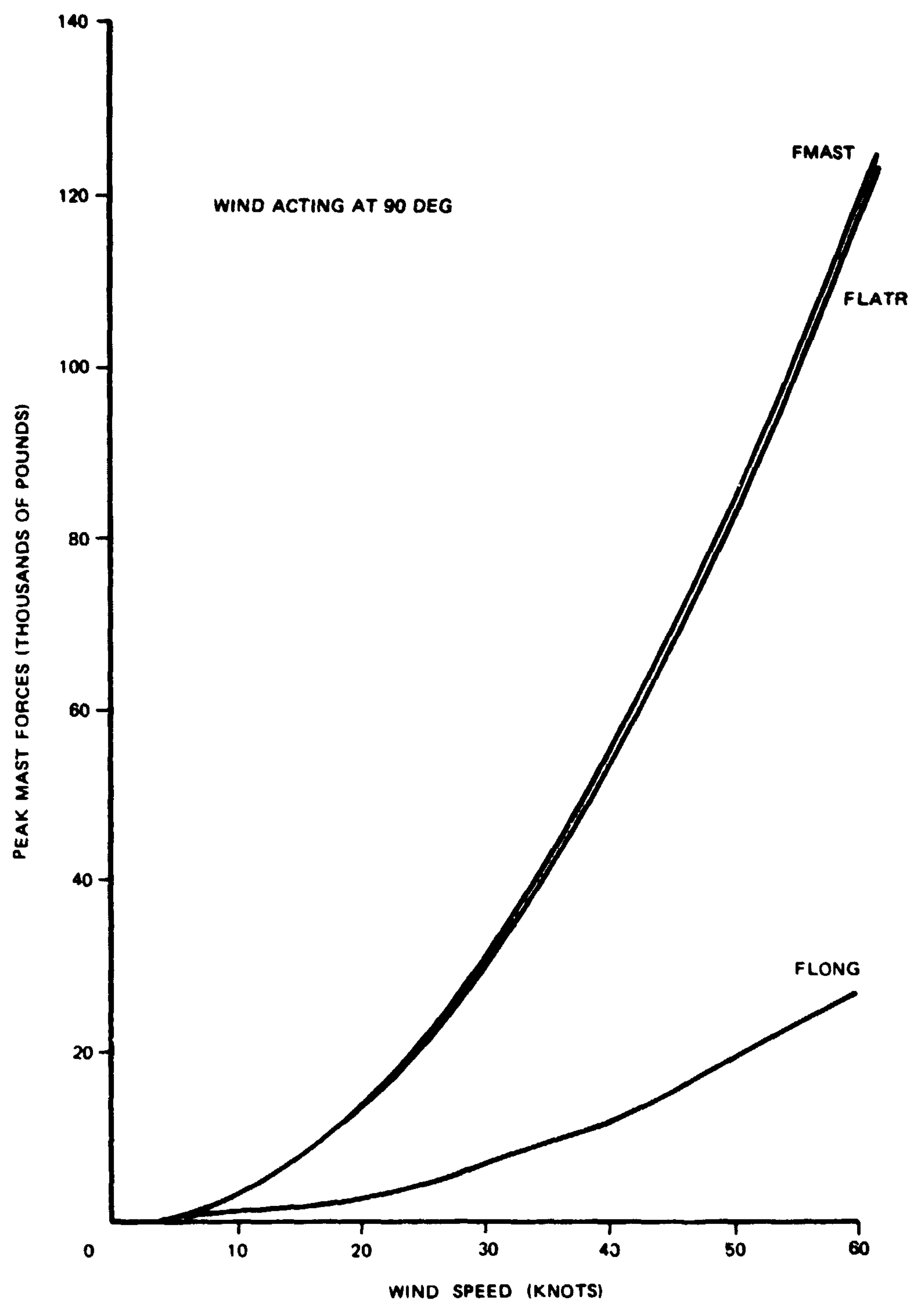

Figure 5-12 - Peak Mast Forces versus Wind Speed
for Belly Moored MPA

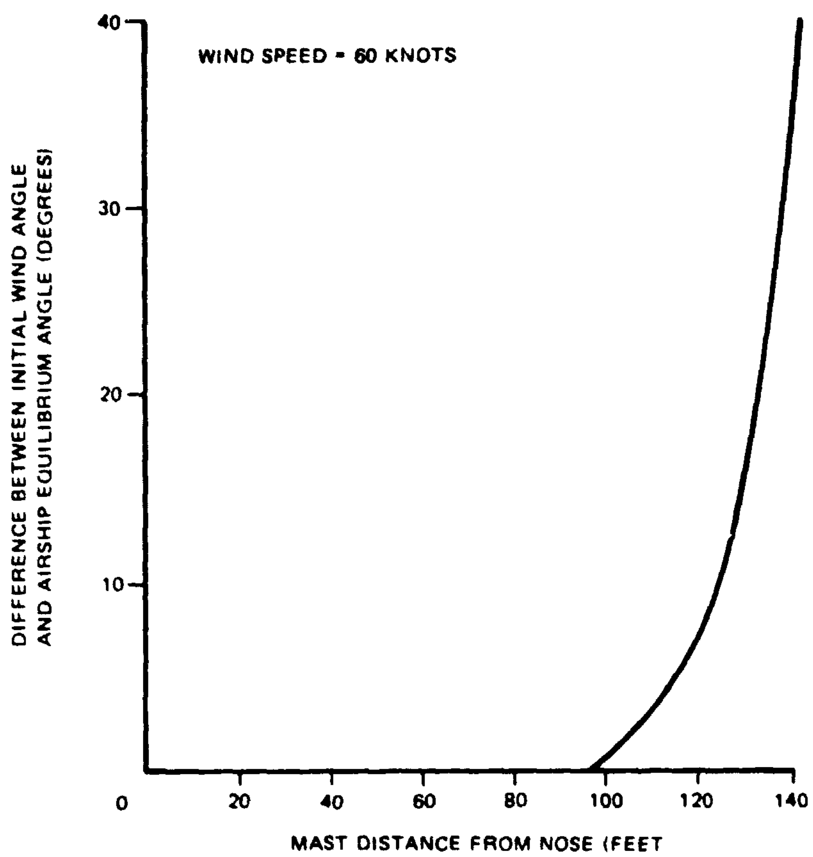

Figure 5-13 - Equilibrium Position with Respect to Mast Location

SECTION VI - IMPACTS OF VEHICLE DESIGN ON GROUND HANDLING

1. TAIL CONFIGURATION

Tests were conducted by the David Taylor Model Basin (DTMB) to determine the effects of varying tail configurations on a conventional airship hull (Reference 29). The following empennage configurations were investigated:

1. Conventional
2. Modified conventional
3. X-type
4. Modified X-type
5. Inverted Y-type
6. Modified inverted Y-type
7. End-plated

The various empennage configurations are compared in Table 6-1. Stability and control derivatives for each empennage configuration were determined experimentally and are reported in Reference 29.

Aerodynamic derivatives of particular interest in the ground handling case are zero lift drag coefficient (C_{D_o}), side force-slope in yaw (C_{y_ψ}), and yaw moment-slope in yaw (C_{n_ψ}). Table 6-2 compares these derivatives for the various empennage configurations. The conventional or cruciform configuration is used as a basis for comparison and is given a designated value of 100.

The following conclusions are apparent based on Table 6-2:

1. Zero lift drag coefficient is a minimum for the two inverted Y configurations.
2. The end-plated tail has excessive drag as tested.
3. Static directional stability (C_{n_ψ}) is a maximum and approximately equal for the X-type and end-plated fins.

The dynamic stability of the various configurations was also analyzed in Reference 29. Dynamic stability was judged on the basis of the following stability criteria:

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TABLE 6-1 - COMPARISON OF FULL-SCALE EMPENNAGE GEOMETRIC CHARACTERISTICS

A = ASPECT RATIO = $\frac{b^2}{S_t + S_e}$, S_t = EXPOSED EMPENNAGE AREA, S_e = INCLUDED HULL AREA,
ℓ_t = C.B. TO C.P. —— $\ell_{t(H)}$ = C.B. TO HINGE LINE —— $E = \frac{\text{FLAP AREA}}{S_t}$
ALL DIMENSIONS IN FEET —— DRAWINGS NOT TO SCALE.

MODEL DESIGNATION	VERTICAL	HORIZONTAL
CONVENTIONAL	A = 1.62 S_t = 1040 E = .249 ℓ_t = 106 $\ell_{t(H)}$ = 127.1	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1
MODIFIED CONVENTIONAL NO LOWER FIN	A = 1.76 S_t = 636 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1
X-TYPE (45°)	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1 [FINS ROTATED TO VERTICAL]	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1 [FINS ROTATED TO HORIZONTAL]
MODIFIED X-TYPE (37.5°)	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1 [FINS ROTATED TO VERTICAL]	A = 1.76 S_t = 1272 E = .269 ℓ_t = 106.4 $\ell_{t(H)}$ = 127.1 [FINS ROTATED TO HORIZONTAL]
INVERTED Y-TYPE (30°)	A = 1.66 S_t = 2513 E = .265 ℓ_t = 102.9 $\ell_{t(H)}$ = 127.1 [LOWER FINS ROTATED 60° DOWN]	A = 1.61 S_t = 1668 E = .265 ℓ_t = 102.9 $\ell_{t(H)}$ = 127.1 [LOWER FINS ROTATED 30° UP]
MODIFIED INVERTED Y-TYPE UPPER FIN IDENTICAL WITH 45° FIN	A = 1.76–1.66 S_t = 2304 E = .267 ℓ_t = {106.4, 102.9} $\ell_{t(H)}$ = 127.1 [LOWER FINS ROTATED 60° DOWN]	A = 1.66 S_t = 1668 E = .265 ℓ_t = 102.9 $\ell_{t(H)}$ = 127.1 [LOWER FINS ROTATED 30° UP]
END-PLATED SYMMETRICAL DOUBLE END-PLATES	A = 3.3 S_t = 1456 E = .238 ℓ_t = 116.9 $\ell_{t(H)}$ = 125.7	A = 8.3 S_t = 964 E = .262 ℓ_t = 108.9 $\ell_{t(H)}$ = 126.7

FOR PURPOSE OF COMPARISON, EMPENNAGE IS ASSUMED ROTATED INTO HORIZONTAL AND VERTICAL PLANES.

TABLE 6-2 - COMPARISON OF MEASURED STABILITY DERIVATIVES FOR VARIOUS TAIL CONFIGURATIONS (BASED ON 1/48-SCALE DTMB WIND TUNNEL TESTS)

Configuration	Conventional	Modified conventional	X-type	Modified X-type	Inverted Y-type	Modified inverted Y-type	End-plated
C_{D_o}	100	100	100	100	94	94	114
C_{y_ψ}	100	88	142	116	129	121	129
C_{n_ψ}	100	103	76	86	84	87	78

$$I = m' - \left(\frac{n'm'' + m'n''}{2kx}\right)$$

$m' = C_{n_\psi}$ per radian

$n' = C_{y_\psi}$ per radian

$m'' = C_{n_r} \left(V/V^{1/3}\right)$ per radian per sec

$n'' = C_{y_r} \left(V/V^{1/3}\right)$ per radian per sec

k_x = longitudinal inertia coefficient (24)

Dynamic stability of a configuration exists when the index is negative; that is, I is less than or equal to 0. Based on the measured and estimated derivatives at small angles of yaw, the stability criteria for each configuration are given in Table 6-3.

TABLE 6-3 - COMPUTATION OF DYNAMIC STABILITY CRITERIA FOR VARIOUS TAIL CONFIGURATIONS

Configuration	Conventional	Modified conventional	X-type	Modified X-type	Inverted Y-type	Modified inverted Y-type	End-plate
Directional stability							
m'	1.032	1.09	0.823	0.952	0.861	0.891	0.715
n'	0.768	0.712	0.982	0.849	0.928	0.908	0.886
m"	1.95	1.154	2.195	1.67	1.985	1.795	1.51
n"	1.2	0.685	1.365	1.01	1.235	1.095	0.91
2kx	2.195	2.195	2.195	2.195	2.195	2.195	2.195
I	-0.213	0.372	-0.661	-0.134	-0.464	-0.34	-0.192

Based on Table 6-3, the following conclusions can be drawn:

1. The modified conventional empennage (lower fin left off) is directionally unstable.
2. The modified X-type empennage has marginal directional stability.
3. The inverted Y-type configuration is less stable than the X-type empennage.
4. The end-plated configuration has only marginal directional stability.

With regard to ground handling qualities, the data of Reference 29 indicate that the inverted Y configuration is very suitable. Directional stability characteristics are better than for the conventional cruciform type but not as good as the X-type. Drag is less with the Y configuration than the X-type or cruciform. Both the X-type and inverted Y-type configurations have good tail ground clearance qualities as opposed to the cruciform tail. The inverted Y has the further advantage of having the best (lowest) snow accumulation characteristics. The only configuration that appears to be absolutely unacceptable from a ground handling standpoint is the modified conventional tail due to its directional instability.

2. EFFECT OF BUOYANCY RATIO

Buoyancy ratio (β) is defined as the static lift divided by the gross weight of the airship. The design value of β for this MPA is 0.66.

With the airship moored at the bow and free to swing, any shifting of the prevailing wind sets up a yaw angle, which causes the airship not only to weathervane but also to kite. If the wind shifts less than 90 degrees, the negative lift due to pitch and static heaviness in combination with the metacentric moment opposes the kiting tendency and defines maximum kiting angle for a given yaw angle. As the yaw angle is reduced by weathervaning, the airship is forced to the ground. If the wind shifts more than 90 degrees (a tail-to-wind condition), both the lift due to yaw and the lift due to pitch may cause the airship to kite to large angles. If the wind shift and velocity are severe enough, high impact loads may result on contact with the ground (References 38 and 41).

In order to prevent any damage caused by kiting, the following alternatives exist:

1. Apply an anti-kiting moment sufficient either to prevent or limit kiting for all weather conditions. This can be accomplished by:
   a. Decreasing the buoyancy ratio by adding weight to the car
   b. Attaching a weight to the stern handling lines, leaving the airship free to weathervane
   c. Applying up deflection of the elevator before kiting and varying elevator deflection during kiting
   d. Trimming the airship tail-heavy with ballonet
2. Tie the tail to a stern riding-out car anchored to circular rails
3. Increase the load capacity of the landing gear and its supporting structure to withstand all reasonable impact loads which may be experienced
4. Moor the airship to a high mast

The anti-kiting moment, which is applied by adding weight to the car, is limited by the capacity of the landing gear. Should kiting occur in spite of this static heaviness, the impact velocity on contact with the ground is thereby increased.

The concept of attaching a weight to the stern lines culminated in the development of the Terra-Tire anti-kiting device by Goodyear (see Figure 6-1). The anti-kiter was 10-1/2 feet long, 11 feet wide, and approximately 6 feet high. It weighed 10,300 pounds completely loaded with shot and 5465 pounds without shot.

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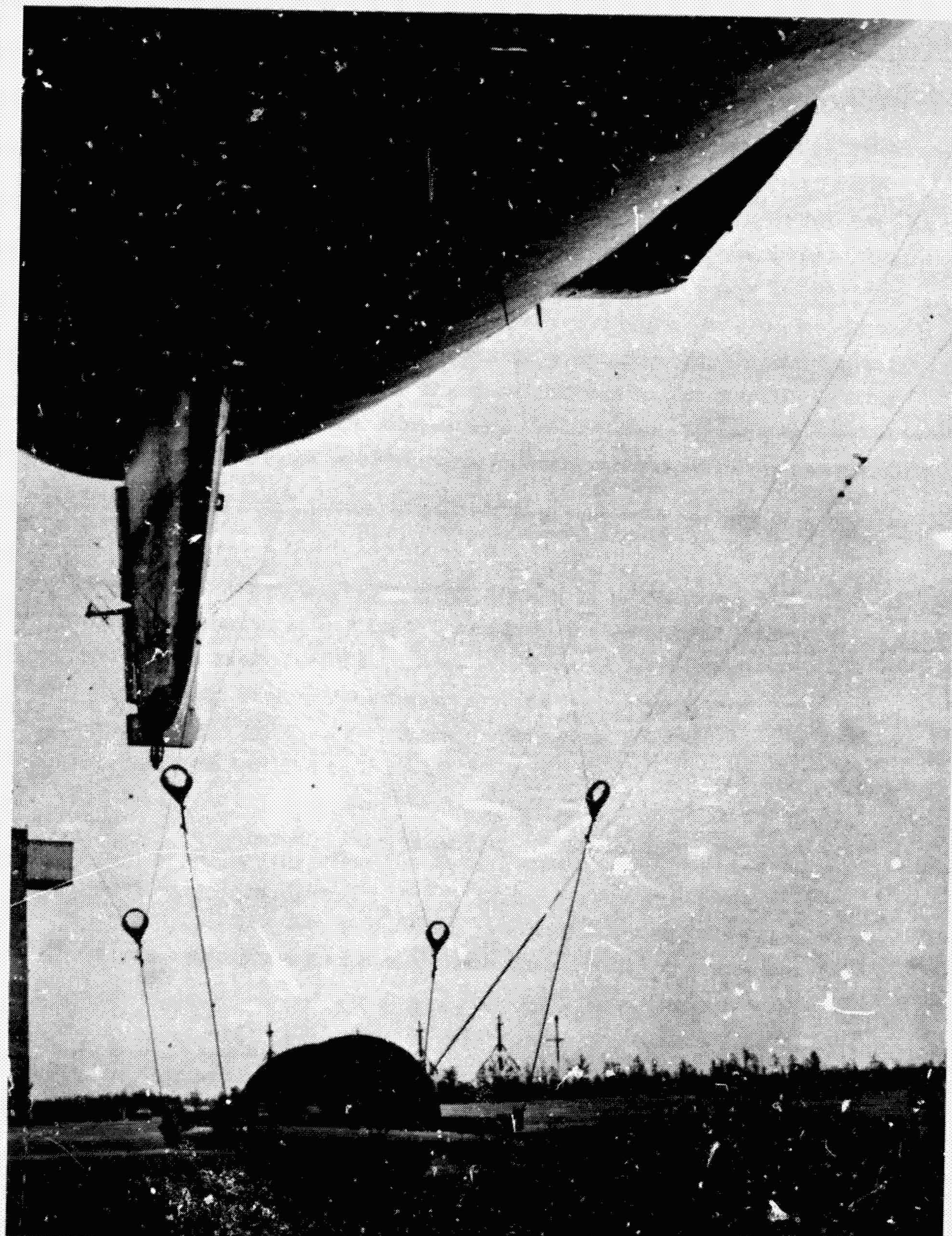


Figure 6-1 - Terra-Tire Anti-Kiting Device

The unit consisted of a tubular steel frame, which would carry 2600 pounds of shot when filled, with slack-absorbing springs through which passed the attaching cables, and all mounted on two 60 x 42 x 18.00 Terra-Tires. The capacity of each Terra-Tire was 6000 pounds with a pressure of 10 psi. The anti-kiter was attached to the stern bridles of the airship by quick disconnects and bridle sheaves at the end of the cable which passed through the slack absorber. Approximately 90 inches of vertical travel were absorbed by the springs before they bottomed and allowed the anti-kiter to leave the ground. A shot bag frame allowed the addition or removal of 2240 pounds of weight. The anti-kiter also incorporated a retractable tow hitch, retractable screw hand crank, and retractable stowage stand. Unfortunately, the anti-kiter suffered from the same problem as adding weight to the car. It did not entirely prevent kiting and resulted in considerable damage when it recontacted the ground.

The provision of a tail car anchored to rails appears to be too costly for nonrigid airship operations.

In winds greater than 25 knots, proper use of the elevators can be quite effective to prevent or limit kiting and to reduce ground contact speeds should kiting occur. By fully deflecting the elevators up, kiting can be appreciably delayed and reduced. However, to minimize landing gear loads in high winds, the elevators should not be deflected full up until the airship starts to kite. After the maximum kiting angle is attained, the ground contact velocity can be reduced by holding down the elevator.

Consequently, effective use of the elevators requires that they should be controlled either manually or automatically during kiting. In low winds (less than 20 knots), the elevators have limited effectiveness and should be kept in neutral.

The anti-kiting moment due to trimming the airship tail down will not greatly reduce kiting. Should the airship kite, this moment increases the impact velocity slightly.

The added weight needed to increase the gear strength can reduce the performance in flight noticeably. Some solution may be obtained by the installation of special ground handling gears, which can be removed for flight.

The aerodynamic forces that cause kiting in shifting winds are basically due to ground effects. Consequently, by mooring the airship to a high mast, kiting tendencies can be reduced. The kiting that remains while moored high is less likely to result in damage. However, the overall disadvantages associated with high mast mooring greatly outweigh this particular attribute.

The solution that appears to provide the best overall results is to maintain the airship at equilibrium, but slightly heavy while at the mast. When the airship is fully restrained, a lower buoyancy ratio would be preferred in order to resist the overturning moment. However, as shown in Figure 6-2, the effects of reducing β are not that substantial. In fact, a decrease in buoyancy ratio from 1.0 to 0.5 in a 60-knot wind condition results in only about a 10-percent reduction in the maximum upward vertical force.

3. ENVELOPE AND SUSPENSION SYSTEM WEIGHT

The weight of the suspension system is a function of the suspended load. In a conventional airship, the suspended load is approximately 50 percent of the gross weight, where the gross weight is the product of the displaced volume and the local air density. For standard atmosphere, the suspended load is (0.5) (0.0765)V. The suspension system is normally designed to carry an additional acceleration factor of 0.5g. The design suspension system load is defined as L_s, where

$$L_s = (1.5)(0.5)(0.0765)V$$

$$= 0.0574V \qquad (25)$$

and the suspension system weight, W_s, is

$$W_s = C_{ws}\, L_s$$

$$= C_{ws}\,(0.0574V) \qquad (26)$$

The coefficient C_{ws} varies somewhat with configuration and load distribution between internal and external systems. An average has been used (see Table 6-4).

Restraining the airship by rigidly attaching the car to the ground results in the airload acting on the envelope being transferred by the suspension system to the car and ground in addition to the nominal suspended load. These loads are added vectorally to define the resultant suspension system load's magnitude and direction. These forces are identified in Figure 6-3. All forces are acting in the same plane. Their definitions are:

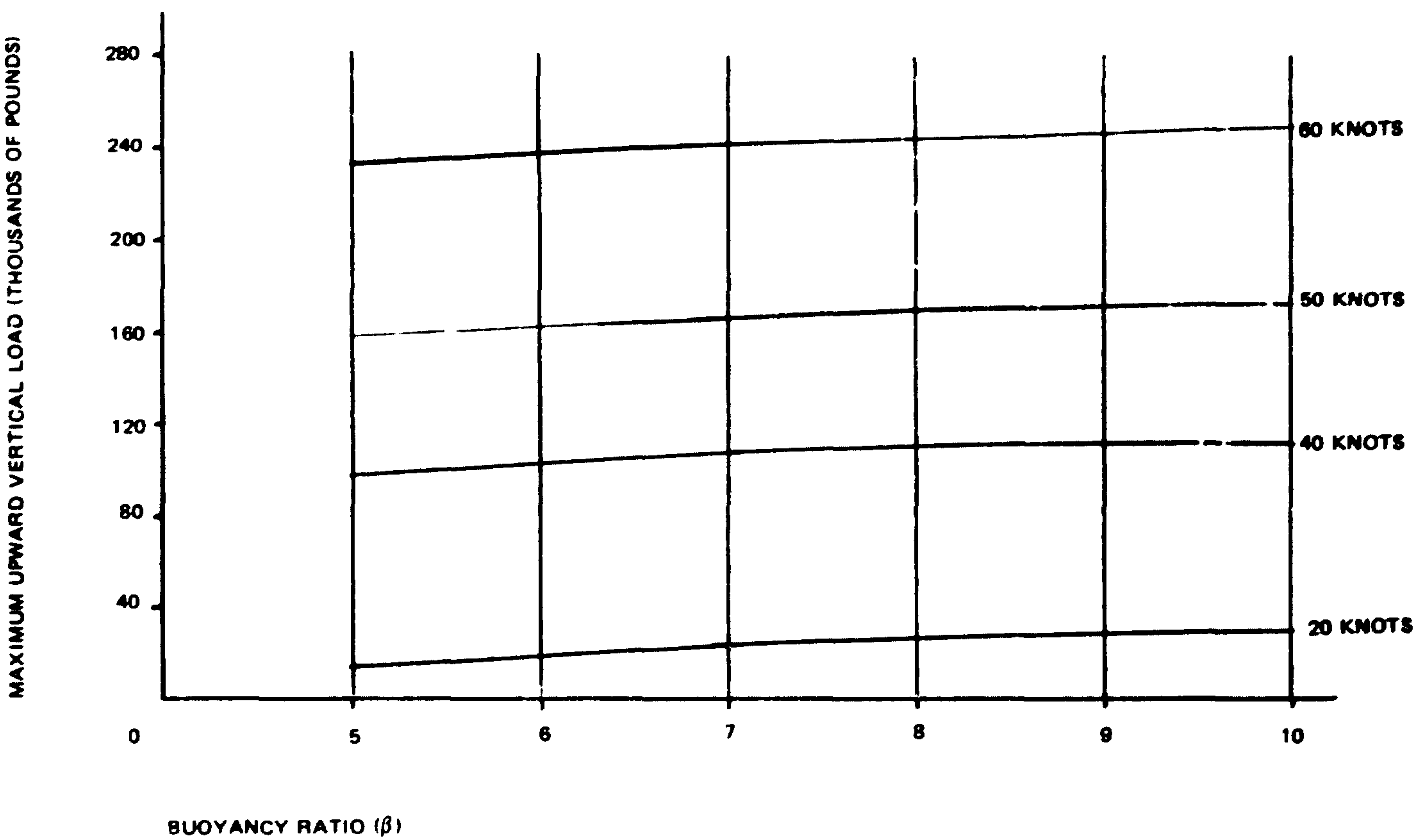


Figure 6-2 - Buoyancy Ratio versus Maximum Upward Vertical Load for Fully Restrained MPA

F_y = effective horizontal component of external wind loads

F_z = effective vertical component of external wind loads

P_{ds} = static lift load $\left(= \frac{L_s}{1.5}\right)$

P_s = resultant load

θ_s = direction of resultant load

ϕ = location of internal suspension curtain

TABLE 6-4 - SUSPENSION SYSTEM WEIGHT COEFFICIENT (C_{ws})

Ship	Volume (ft^3)	W (lbs)	C_{ws} (Actual)	W' (lbs)
ZS2G-1	650,000	1001	0.0268	910
ZPG2	975,000	1269	0.0227	1365
ZPG2W	975,000	1359	0.0243	1365
ZPG3W	1,465,000	2000	0.0238	2051
		Mean	0.0244	

Note: W is the actual suspension weight of the airship. W' is the weight defined by the product of the mean value of C_{ws} and (0.0574V).

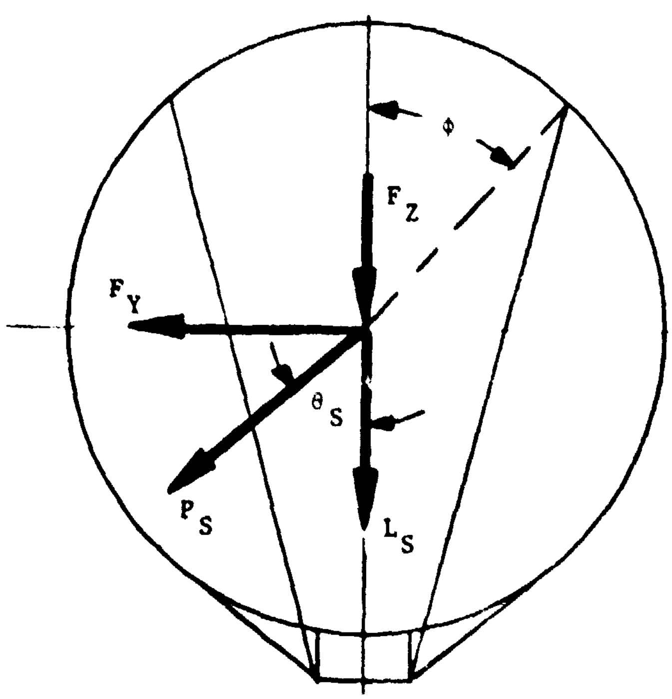


Figure 6-3 - Suspension System Forces for Total Restraint System

Assume the pitching and yawing moments are reacted by linearly varying loads over the length of the suspension system. The average increase in load (f_{AVG}) over one-half the length of the suspension system of length, L, is defined as:

$$f_{AVG} = \frac{3M}{L^2} \tag{27}$$

The length, L, of the suspension system is estimated at 55 percent of the overall length of the ship. The ship length, L_m, is related to the volume by

$$L_m = \left(\frac{4\lambda^2 V}{\mu \pi}\right)^{1/3} \tag{28}$$

where λ is the length-to-diameter ratio and μ is the prismatic coefficient. Appropriate values for the MPA are $\mu = 0.643$ and $\lambda = 4.37$. Inserted in the above equation:

$$L_M = \left(\frac{4(4.37)^2 V}{0.643\pi}\right)^{1/3}$$

$$= 3.36V^{1/3}$$

Since $$L = 0.55L_m,$$

therefore $$L = 1.85V^{1/3}$$

The average increase in the load component on the suspension system is

$$F_i'' = f_{AVG}\, L$$

$$= \frac{3M}{L}$$

Since $$M = C_i qV,$$

where C_i is the pitching or yawing moment coefficient.

Therefore:

$$F_i'' = \frac{3C_i qV}{1.85V^{1/3}}$$

$$= 1.62\; C_i qV^{2/3} \tag{29}$$

The total design vertical load component is defined as:

$$F_v = F_z + P_{ds} \tag{30}$$

where

$$F_z = F_z' + F_z''$$

$$= \left(C_z q V^{2/3}\right) + \left(1.62 C_m q V^{2/3}\right)$$

$$= \left(C_z + 1.62 C_m\right) q V^{2/3}$$

and

$$F_y = F_y' + F_y''$$

$$= \left(C_y q V^{2/3}\right) + \left(1.62\, C_n q V^{2/3}\right)$$

$$= \left(C_y + 1.62\, C_n\right) q V^{2/3}$$

Now,

$$P_s = \overrightarrow{F_v} + \overrightarrow{F_y}$$

$$= \left|\overrightarrow{P_{ds} + (C_z + 1.62\, C_m) q V^{2/3}}\right| + \left|\overrightarrow{(C_y + 1.62\, C_n) q V^{2/3}}\right|$$

$$= \left|\overrightarrow{\frac{0.0574V}{1.5} + (C_z + 1.62\, C_m) q V^{2/3}}\right| + \left|\overrightarrow{C_y + 1.62\, C_n) q V^{2/3}}\right|$$

$$= qV^{2/3}\left[\overrightarrow{\left(\frac{0.0383V^{1/3}}{q} + C_z + 1.62\, C_m\right)} + \overrightarrow{\left(C_y + 1.62\, C_n\right)}\right]$$

Using a NASA standard atmosphere,

$$q = \frac{(KT)_w^2}{295.1} \tag{31}$$

where $(KT)_w$ is the wind velocity, and substituting in the above equation,

$$P_s = 0.00339\, (KT)_w^2\, V^{2/3} \left[\overrightarrow{\left(\frac{11.293\, V^{1/3}}{(KT)_w^2} + C_z + 1.62\, C_m\right)} + \overrightarrow{\left(C_y + 1.62\, C_n\right)}\right] \tag{32}$$

Therefore, referring again to Figure 6-3,

$$\theta_s = \mathrm{Tan}^{-1} \frac{(C_y + 1.62\,C_n)}{\left[\dfrac{11.293\ V^{1/3}}{(KT)_w^2} + C_z + 1.62\,C_m\right]} \qquad \text{for } (KT)_w \neq 0 \tag{33}$$

If $(KT)_w$ is equal to zero, then $\theta_s = 0$.

The load in the heavily loaded side of the suspension system, $P_{s/2}$, for values of θ_s equal to or less than ϕ is:

$$P_{s/2} = \frac{P_s}{2}\left(\frac{\mathrm{Sin}\ \theta_s}{\mathrm{Sin}\ \phi} + \frac{\mathrm{Cos}\ \theta_s}{\mathrm{Cos}\ \phi}\right) \tag{34}$$

When θ is greater than ϕ, the load on one-half the suspension system is assumed to be P_s. If it is assumed that the airship is free to roll, the centerline plane of the suspension system will align itself with the vector, P_s, and the load on each half of the suspension system is $0.5\ P_s$.

Since the weight of the suspension system is proportional to the load in the suspension system, the suspension system weight multiplier, K_{ws}, can be defined as:

$$K_{ws} = \frac{2P_{s/2}}{L_s} \tag{35}$$

For $\theta_s \leq \phi$,

$$K_{ws} = \frac{P_s}{L_s}\left(\frac{\mathrm{Sin}\,\theta_s}{\mathrm{Sin}\ \phi} + \frac{\mathrm{Cos}\ \theta_s}{\mathrm{Cos}\ \phi}\right)$$

$$= \frac{0.00339(KT)_w^2\ V^{2/3}}{0.0574\ V}\left[\overrightarrow{\left(\frac{11.293\ V^{1/3}}{(KT)_w^2} + C_z + 1.62\,C_m\right)} + \overrightarrow{\left(C_y + 1.62\,C_n\right)}\right] \cdot \left(\frac{\mathrm{Sin}\ \theta_s}{\mathrm{Sin}\ \phi} + \frac{\mathrm{Cos}\ \theta_s}{\mathrm{Cos}\ \phi}\right)$$

$$= 0.0591 \frac{(KT)_w^2}{V^{1/3}} \left[\overrightarrow{\left(\frac{11.293\, V^{1/3}}{(KT)_w^2} + C_z + 1.62\, C_m\right)} + \overrightarrow{\left(C_y + 1.62\, C_n\right)} \right] \bullet$$

$$\left(\frac{\sin\theta_s}{\sin\phi} + \frac{\cos\theta_s}{\cos\phi}\right) \qquad (36)$$

For $\theta_s > \phi$,

$$K_{ws} = \frac{2(0.00339)(KT)_w^2\, V^{2/3}}{0.0574\, V} \left[\overrightarrow{\left(\frac{11.293\, V^{1/3}}{(KT)_w^2} + C_z + 1.62\, C_m\right)} + \overrightarrow{\left(C_y + 1.62\, C_n\right)} \right]$$

$$= 0.1181 \frac{(KT)_w^2}{V^{1/3}} \left[\overrightarrow{\left(\frac{11.293\, V^{1/3}}{(KT)_w^2} + C_z + 1.62\, C_m\right)} + \overrightarrow{\left(C_y + 1.62\, C_n\right)} \right] \qquad (37)$$

In conventional airship design, side loads are very limited and are assumed negligible. Typical values of ϕ are approximately 30 degrees. Total restraint of an airship introduces substantial side forces, however, that result in flattening the suspension system plane. A value of ϕ = 40 degrees is selected to account for this. Now, using this value of ϕ and the airship volume of 875,000 cubic feet, Equation 37 can be solved at various yaw angles and various speeds. The results are given in Table 6-5.

TABLE 6-5 - SUSPENSION SYSTEM WEIGHT FACTOR (K_{ws})

$(KT)_w$ (knots)	Yaw angle (deg)					
	60 deg		90 deg		120 deg	
	θ_s	K_{ws}	θ_s	K_{ws}	θ_s	K_{ws}
10	8.07	1.19	11.91	1.19	11.43	1.12
20	21.60	2.14	34.18	2.13	36.30	1.86
30	30.66	3.73	49.05	3.65	55.11	3.07
40	35.67	5.97	56.73	5.87	65.06	4.92
50	38.50	8.82	60.83	8.77	70.33	7.41
60	40.20	12.31	63.21	12.37	73.35	10.50

The suspension system weight for a restrained airship would be impacted by the weight factor defined above so that the system weight, W_s, is

$$W_s = C_{ws} L_s K_{ws} \tag{38}$$

As previously defined, $C_{ws} = 0.0244$ and $L_s = (0.0574)V$. Defining the weight fraction, $\%W_s$, as the suspension system percent of the gross lift, and using 0.06 lb/cu ft as the nominal lift of helium (gross lift equals 0.06V),

$$\%W_s = \frac{0.0244\ (0.0574)V}{0.06V} K_{ws} \tag{39}$$

$$= 2.334\ K_{ws}$$

Results of Equation 39 combined with the maximum values of K_{ws} in Table 6-5 are given in Table 6-6.

TABLE 6-6 - SUSPENSION SYSTEM WEIGHT FRACTION

$(KT)_w$ (knots)	Maximum K_{ws}	$\% W_s$
10	1.19	2.78
20	2.14	5.00
30	3.73	8.71
40	5.97	13.94
50	8.82	20.59
60	12.37	28.87

Table 6-6 indicates that the suspension system weight increases from the 2.33 percent of the conventional airship gross static lift to almost 9 percent at 30 knots and 29 percent at 60 knots.

The effect of total restraint mooring on the envelope weight is a function of how the increase in suspension system strength is obtained. The increase in suspension system strength can be obtained by either increasing the size of a fixed number of suspension systems or increasing the number of suspension systems.

If the number of suspension systems is increased by the required factor, the load per envelope attachment line is constant. Therefore, there is no increase in envelope weight.

If a fixed number of suspension systems is increased in strength by the required factor, the envelope structural weight is increased by some factor. The envelope structural weight is the envelope weight minus ballonets, airlines, patches, fairings, etc. The envelope structural weight is a function of the maximum design velocity of the airship and is not directly controlled by the suspended load effects. The structural weight fraction of conventional ships designed to fly 75 knots is 12.5 percent of the gross lift. The airship experiences loads that produce fabric stress greater than that required to carry the suspended load. A factor greater than the required factor of safety is inherent in the envelope structural weight with respect to the strength required to carry the suspended load. This factor varies with several design parameters: speed, configuration, pitch angle, gas valve size, and ascent and descent rate. The factor is estimated to be 2.25 for a 75-knot airship. The envelope weight fraction is increased by the ratio of the suspension system weight factor to the 2.25 inherent factors in the envelope for a conventional suspension configuration and suspended load.

$$K_{we} = \frac{K_{ws}}{2.25} = 0.44\ K_{ws} \qquad (40)$$

$$\%W_e = 12.5\ K_{we} \qquad (41)$$

The total weight fraction for the structural envelope plus the suspension system is the algebraic sum of $\%W_e$ and $\%W_s$ as shown in Table 6-7. Whereas the ($\%W_e + \%W_s$) for a conventional airship is 14.83 percent, the weight penalty associated with a restrained airship is considerably higher. Depending on the wind speed, the end result would vary from a significant decrease in payload capability to being too heavy to fly. For those conditions below the dotted line in Table 6-7, alternate airship designs would require consideration.

Graphic representations of the data in Tables 6-6 and 6-7 are shown in Figure 6-4.

Regardless of the type of airship (non-rigid, semi-rigid, or rigid), the transference of large lateral forces through the airship will require sufficient structure to accommodate the load. It is anticipated that any vehicle designed on this premise will result in structural weights similar to those predicted above.

TABLE 6-7 - ENVELOPE WEIGHT FRACTIONS FOR FIXED NUMBER OF SUSPENSION SYSTEMS

$(KT)_w$ (knots)	K_{ws}	K_{we}	$\%W_e$	$\%W_s$	$\%W_e + \%W_s$
0	1.00	0.44	12.5	2.33	14.83
10	1.19	0.52	12.5	2.78	15.28
20	2.14	0.94	12.5	5.00	17.50
30	3.73	1.64	20.5	8.71	29.21
40	5.97	2.63	32.88	13.94	46.82
50	8.82	3.88	48.50	20.59	69.09
60	12.37	5.44	68.00	28.87	96.87

For the concept of directly attaching the envelope to an anchor system as opposed to securing the control car, there appears to be little structural weight advantage. Since the weight of a structure is a linear function of the load in the structure, the external catenary system would have approximately the same impact as the internal system defined above. The loads will be identical, and any improvement in the geometric position of the system is offset by the increased length to ground.

Assuming a more optional location of the attachment between the envelope and the restraining system, the envelope weight penalty may be somewhat less than determined for the rigid car restraint.

Even assuming that part of the restraint system can be detached and not become part of the airborne ship weight, incorporating such a system will, depending on design wind speed, vary from a significant decrease in payload capability to being too heavy to fly.

4. PROPULSION UNITS

In terms of ground handling operations, the placement of the propulsion units has both advantages and disadvantages. On the positive side, the large vertical clearance distance between the propellers and the ground add an additional

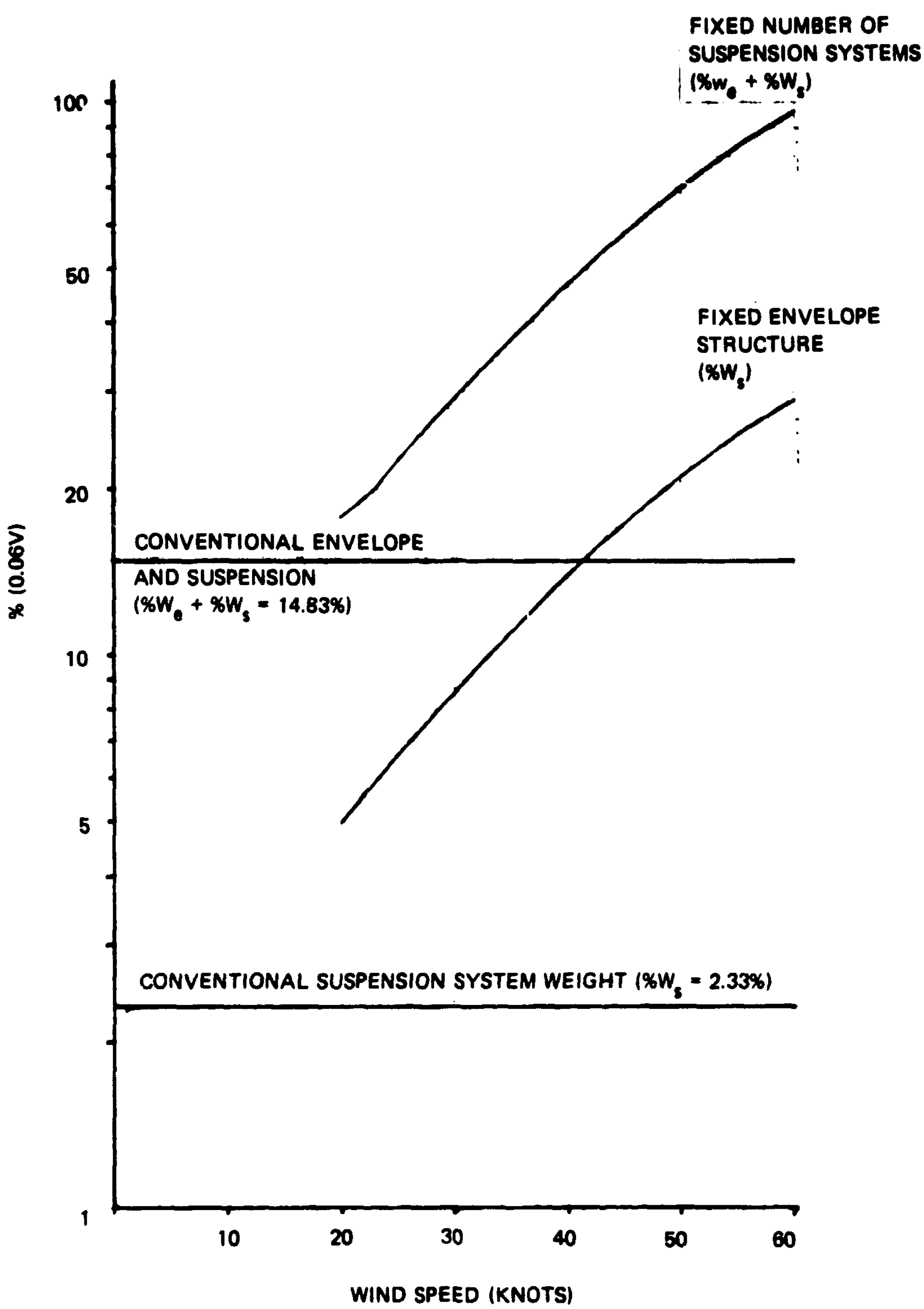


Figure 6-4 - Effect of Complete Vehicle (Total) Restraint Mooring on Suspension System and Envelope Weight dimension of safety for ground handling personnel and equipment. The engines can be kept running in order to provide thrust without jeopardizing other operations.

A disadvantage of the propulsion unit placement relates to servicing the engines. With the airship on a mast, maintenance of the propulsion system is limited to minor overhaul. Access to the forward engines is gained from the car, to the air duct, through the cross-beam tunnel to the engine cowl. For access to the stern engine, the nose pendant cable is payed out of the mooring cap to permit mechanical mules, with constant tension winches, to pull and hold the stern of the airship down to ground level. With the engine in the vertical attitude, a work platform is latched to the support structure for maintenance. This permits the airship to weathervane to some degree when tensions in the winch cables are reduced. In a hangar, major overhaul should be no problem. The vehicle may be tied down to minimize movement and positioned such that the maximum engine height above ground level is 25 feet. On a comparable basis, the DC-10 fin engine exceeds a ground height of 35 feet.

The selection of the Allison GMA-500 engines for the MPA was premised on an evaluation of proposed maritime missions as defined in Reference 15. This choice was not impacted by any consideration of ground handling operation.

The attribute that the powerplants should exhibit to aid in ground handling is the ability to supply sufficient thrust to enable the airship to taxi or hold a position on the ground. This capability would significantly reduce the need for superfluous personnel and equipment. This topic, however, falls within the realm of overall airship performance analysis and is beyond the scope of this report.

SECTION VII - OPERATIONAL CHARACTERISTICS AND COSTS

1. GENERAL

As previously indicated in this report, four mooring concepts are investigated for the MPA:

1. Bow mooring
2. Belly mooring
3. Complete vehicle (total) restraint
4. Hangar systems

For each mooring concept, a series of system attributes is reviewed encompassing ground handling manpower and equipment requirements, mooring area requirements, impact on maintenance procedures, environmental considerations, and mooring system mobility.

In order to assess the alternatives, certain operational assumptions are made. These assumptions are not intended as design criteria but rather as reference points for ground handling applications. The major assumed features are:

1. The MPA is capable of VTOL operation.
2. The MPA is capable of taxiing.
3. Aerodynamic lift on the MPA with empennage is approximately 8500 pounds.
4. The crew is composed of not fewer than four members.

2. SITE CONSIDERATIONS

a. General

The selection and operation of an airship mooring site depends on a number of physical constraints imposed by the geography of the area. The principal geographic factors are topography, soil type, site size and shape, and weather conditions.

b. Topography

Fundamental to selecting a mooring site is consideration of site topography. Ideally, a smooth, flat, level surface of appropriate size will be available; realistically, such a site will rarely be found in a remote environment. Certain civil engineering functions will then be required in order to convert the available area to a suitable mooring site. These functions will typically involve using a bulldozer to provide a generally smooth, flat area free from significant relief differences and stumps. The degree to which this must be accomplished is defined by the mooring styles.

c. Soil Conditions

The ability of a soil to support a given load is paramount in the provision of a mooring site both in terms of a load applied by the airship through its landing gear and the forces incurred at any mast anchor points.

The California Bearing Ratio (CBR) test serves as a standard procedure for determining load bearing capability. The CBR number is a ratio of the unit load (psi) required to generate a certain penetration in the test sample to a standard unit load (Reference 30). The CBR is generally used to rate the predicted performance of soils. Table 7-1 gives typical ratings (Reference 30).

TABLE 7-1 - TYPICAL CBR RATINGS

CBR No.	General Rating	Typical Soil Types
0-3	Very Poor	Clays of high plasticity, some silts
3-7	Poor to Fair	Same as above
7-20	Fair	Low plasticity clays, inorganic silts, fine sands
20-50	Good	Silty, sandy, or clayey grounds
>50	Excellent	Well graded gravels with few fines

More empirical data has been developed by industry, particularly with respect to the "holding power" of ground anchors. In essence, a soil probe was developed for field testing to provide instant access to anchor design charts. A typical soil classification system is shown in Table 7-2 (Reference 31).

The use of single-helix anchors appear to be appropriate for the mooring systems considered in this report. These anchors would be installed with a hand-held portable pipethreader adapted for this purpose. Due to the torque limitations on this equipment, the efficiency of setting the anchors drops quickly above the eight-inch helix size. It can be either electrically or gas driven. The anchors have differently sized helixes available mounted on a 1.25-inch rod. Various attributes of these anchors are given in Table 7-3 (Reference 31).

TABLE 7-2 - SOIL CLASSIFICATION DATA

Class	Description of Soil
1	Solid Bed Rock
2	Dense Clay; Compact Gravel; Dense Fine Sand; Laminated Rock; Slate; Schist; Sandstone
3	Shale; Broken Bed Rock; Hardpan; Compact, Clay-Gravel Mixtures
4	Gravel, Compact Gravel and Sand; Claypan
5	Medium-Firm Clay; Loose Sand and Gravel; Compact Coarse Sand
6*	Soft-Plastic Clay; Loose Coarse Sand; Clayey Silt; Compact Fine Sand
7	Fill; Loose Fine Sand; Wet Clays; Silt
8**	Swamp; Marsh; Saturated Silt; Humus

*Includes areas only seasonally wet with slow drain as in fairly flat terrain.

**Install anchors deep enough, by the use of extensions, to penetrate a Class 5, 6, or 7 underlying the Class 8 Soil.

TABLE 7-3 - CHARACTERISTICS OF SINGLE-HELIX SCREW ANCHORS

Helix Diameter (in.)	Area (sq in.)	Unit Weight (lb)	Holding Strength by Soil Class (lb)*			
			4	5	6	7
6	50	35.0	13,000	11,000	9,000	6,000
10	78	41.5	15,000	13,000	10,000	7,000
11-5/16	100	45.2		15,000	13,000	10,000
13-1/2	143	51.6		17,000	15,000	12,000
15	176	61.6		20,000	17,000	14,000

*Refer to Table 7-2 for soil classes.

The forces developed at the landing gear when the airship lands or when it is moved and its resisting rolling moment must also be addressed. Landing gear and tire arrangements and types are sensitive to the bearing strength of the contacted surface. Table 7-4 gives the recommended maximum tire pressures for various landing surfaces (Reference 32).

TABLE 7-4 - TIRE PRESSURE RECOMMENDATIONS

Landing Surface	Max Tire Pressure (psi)
Aircraft carrier deck	>200
Large military airport pavement	200
Large civil airport pavement	120
Small tarmac runway; good foundation	70-90
Small tarmac runway; poor foundation	50-70
Temporary metal runway	50-70
Hard grass, depending on soil	45-60
Wet, boggy grass	30-45
Hard desert sand	40-60
Soft, loose, desert sand	25-35

d. Site Size and Shape

The size of a landing and mooring area needed to support one MPA should be determined based on the minimum width that will permit an airship to land without damaging any airship components, obscurring visibility, or causing ingestion in the engines from blowing soil and debris due to dynamic pressure. The airship mooring style must also be considered.

For those mooring systems with rotational capabilities (bow and belly), the required circular land area was generated based on a radius equal to the distance from the stern to the mast plus 50 feet. In developing the minimum area requirements, it was assumed that - under certain conditions - it would not be necessary to completely clear the area of brush under the aft portion of the ship. It was arbitrarily assumed that a clearance of 20 feet be obtained in any event. Thus, for bow mooring, a point on the underside of the envelope 220 feet from the nose is 20 feet above ground. This 220 feet represents the absolute minimum radius acceptable for a bow mooring circle. For belly mooring, the same approach was taken, but under no circumstance should the radius be less than one-half the ship's length plus 50 feet. Figure 7-1 illustrates this requirement.

The amount of blowing soil and debris that is generated while the engines are operating is a function of the soil type, soil strength, and amount of vegetation. If soil erosion becomes a problem due to vegetation degradation, steps should be taken to minimize its effect through soil consolidation and stabilization with either chemical or soil cement treatments. Cost would vary considerably depending on the extent of the problem. While various concepts exist for landing mats, they would be uneconomical for MPA applications unless a specific long-term site on previously unprepared soil was a dictum.

e. Weather Conditions (References 34 to 36)

The major weather factor influencing MPA mooring capabilities is wind. Strong gusts attacking a moored airship at large angles with respect to the centerline axis can impart tremendous loads that either must be handled by the envelope and suspension system or transferred to the mooring mast. Failure in either mode could lead to catastrophy.

An investigation into extreme wind distributions in the United States (Reference 40) indicates that the annual predicted extreme wind speed at a point 30 feet

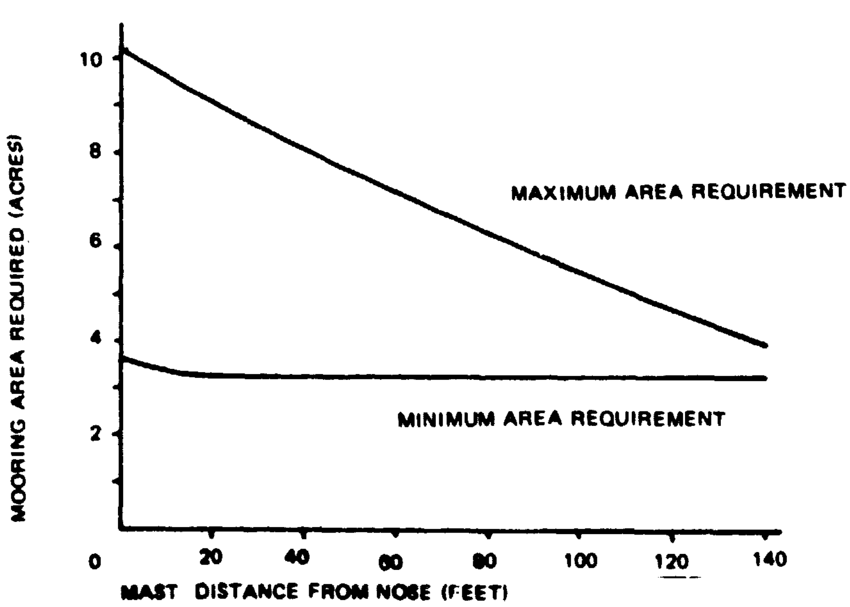


Figure 7-1 - Land Requirements for Mooring Systems with Rotational Capability above ground, based on a 10-year mean recurrence interval for the East Coast, ranges from 75 to 85 mph (65 to 74 knots). The Gulf Coast is generally restricted to 70 mph (61 knots), while the West Coast maximum is approximately 60 mph (52 knots). A pocket of very high winds in excess of 90 mph (78 knots) exists along the west coast of Washington (see Figure 7-2). Peak gust speeds at the 30-ft elevation would be 30 percent higher than these values.

In order to compare the relative merits of the various mooring techniques, a reference wind velocity of 69 mph (60 knots) is selected that approximates the predicted annual extreme in most coastal areas.

The buildup of snow or ice on a moored airship is a critical problem. Due to the immense size of the surface of the airship, relatively small depths can impact a significant load on the envelope system and landing gear. Assuming that the snow buildup occurs over one-fourth of the total envelope area and based on an average snow density of eight pounds per cubic foot, each inch of accumulated snow adds 10,000 pounds of weight.

Figure 7-2 - Annual Extreme Wind Speeds (mph)

The problem of snow removal has been investigated for many years, but as yet no completely satisfactory solution has been generated. Some approaches that have been tried or hypothesized are as follows:

1. Scraping and brushing, a technique using a rope, was slow and required constant attention during storms. Rope action also chafed the envelope, and the development of larger airships precluded its use.
2. Vibration met with limited success. The major problem of inducing a vibration in the envelope was difficult to satisfy.
3. Envelope distortion was discarded due to the potential of fabric damage. It would not have been effective for snow.
4. External heat required too much power and equipment, and the problem was compounded by inaccessibility to upper envelope surfaces.
5. Super heating the helium was experimented with but was not further developed despite its apparent feasibility.
6. Chemical systems, the application of substances to reduce adhesion or act as freeze depressants, have been effective.
7. Water systems have also been used. The most widely used technique was to attempt to spray the snow from the envelope. Though this approach has some limitations it remained the recommended approach of the Navy and is presently prescribed for the Goodyear public relations airship fleet.

Though other weather factors can adversely affect the operation of an airship mooring system, none have the capability of impacting the airship and mooring equipment in the same manner as high, off-angle winds or large accumulations of snow or ice.

3. BOW MOORING

a. Structural Requirements

Fundamental to the design of a mast for a bow mooring system is the load transference from the airship through the nose to the mast. This minimizes the magnitude of the mooring loads on the envelope or suspension system. In the most extreme case as defined in this report (a 60-knot wind attacking at 90 degrees to the centerline axis), the maximum forces are approximately 48,000 pounds for FLATR and 45,000 pounds for FLONG. The maximum resultant force (FMAST), which in this instance coincides with the maximum FLONG, equals 66,000 pounds. Both the maximum moment developed by the forces and the determination of the ultimate axial load are of critical design importance.

The peak vertical force on the mast is determined by summing the system forces - the aerodynamic load and the force created by the pitching moment. The result, based on Table 4-2, is a net upward vertical force of 40,000 pounds that must be restrained.

A tubular aluminum mast has been selected to satisfy the design criteria. It would be constructed in two sections.

The top half, equipped with the mast head and mooring cup, would have a 16-inch outside diameter and a one-inch wall thickness. The lower half dimensions would be 14 inches and 0.75 inch, respectively. The baseplate diameter is six feet. At a point three feet from the top of the mast, 20 cables would emanate. These cables would be attached to ground anchors placed on the circumference of a circle of radius 35 feet about the mast; this would result in anchors every 11 feet. The cables are one-half inch in diameter and 59 feet long, with an ultimate load requirement of 21,000 pounds.

In order to provide bending support, cables are also provided at the midpoint of the mast. Ten would be required; these cables would be attached to the same anchors as above but at 22-foot placements. Each cable is 41 feet long with a diameter of 5/16 inch. Ultimate load is 9800 pounds (see Figure 7-3).

Tests conducted by Goodyear have shown that ground anchor holding strength is additive. That is, a set of two anchors holding a single cable will develop double the resistance of a single anchor. For this particular case, the eight-inch single-helix anchor (see Table 7-3) used in tandem would be sufficient in Class 5 or better soils.

b. Mooring Area Requirements

The bow mooring concept requires a large tract of land. For the MPA with an effective required radius of 375 feet, this land amounts to a cleared area of 10 acres.

In a previously unprepared site, it may be possible to take advantage of the ground clearance in the aft portion of the airship. This could effectively reduce the cleared area to the minimum amount indicated in Figure 7-1.

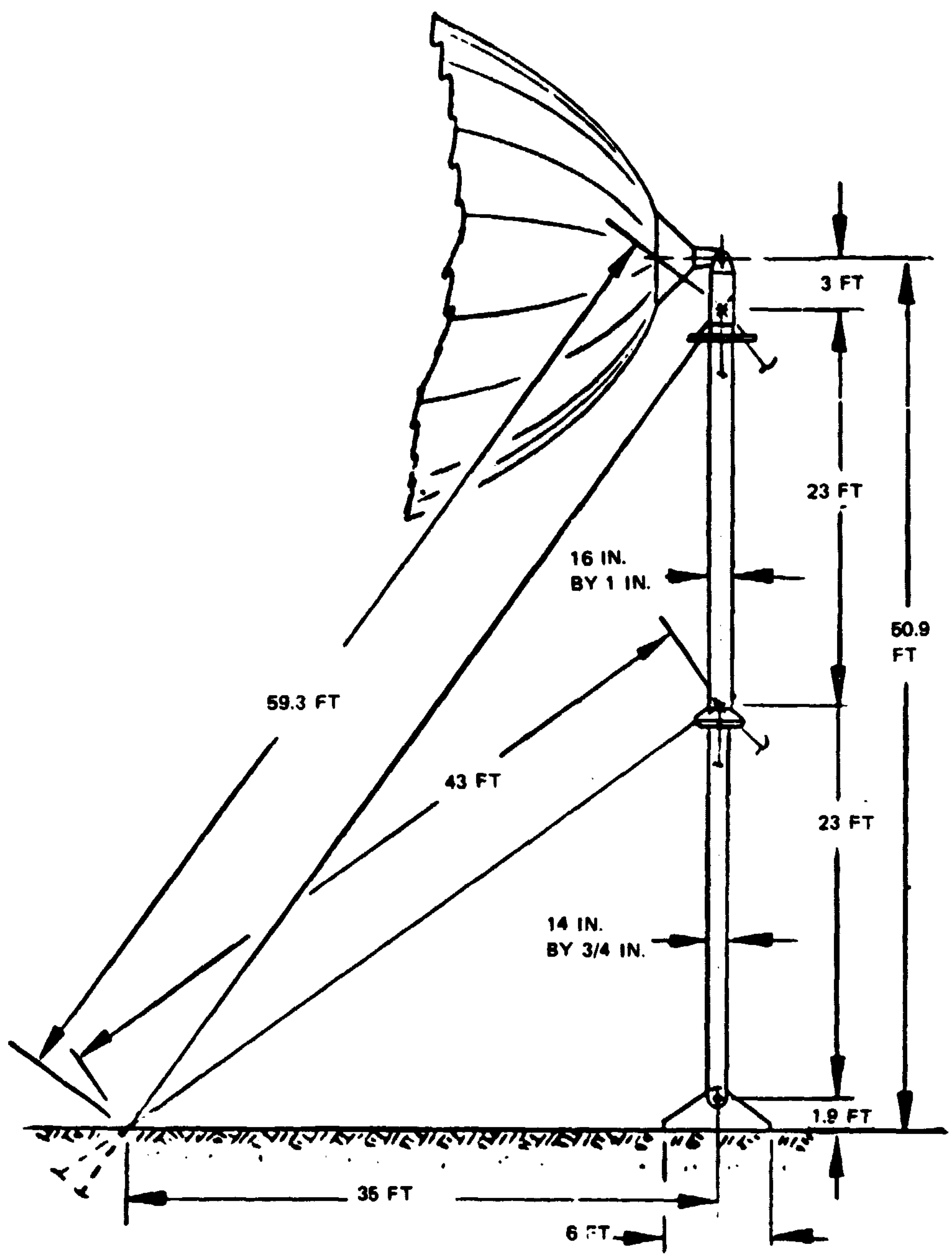


Figure 7-3 - Bow Mooring Mast Arrangement

c. Operational Concept and Requirements

The operational sequence for establishing a base begins with the MPA delivering the mast, mast baseplate, anchors, portable power drive system, winch, ancillary tools, and a two-man crew. The airship then departs the area temporarily while the mast baseplate is centrally located in the field and all anchors installed. The mast is drawn toward the baseplate with the winch, and all cables (slack) are attached to their respective anchors. The mast is hoisted to a vertical position atop the baseplate by the winch and a block and tackle. All guy cables are then secured. Total estimated time for this effort is six to eight hours. The airship lands near the mast and taxis toward it. When the airship is sufficiently close, a noseline is attached to a line leading through the mooring cup, through the mast to the winch. The vehicle is then drawn into the mast and secured in position.

To unmast the airship, the nose pin is manually removed, and the MPA can then move up and away from the mast. The mast is removed by reversing the installation sequence. The anchors can be removed and reused. The mast is stowed under and attached to the car during flight.

d. System Mobility

The provision of a large ground support team with associated equipment is inconsistent with the mission goals of the MPA. The airship and its crew must be capable of establishing a base without assistance, provided the topography and soil conditions are conducive. Two main system attributes are prerequisites for such operations: (1) the ability of the airship to land unaided and temporarily hold a position on the ground (that is, low-speed controllability) and (2) the ability of the airship to transport all necessary mooring equipment.

The first attribute must be assumed as a capability at this point. In the second, however, the total weight of the mooring system must exceed the load-carrying capabilities of the airship. The total useful load defined for the MPA is 22,504 pounds.

A weight breakdown of the ground equipment used for the bow mooring system is given in Table 7-5. By carrying this equipment, the useful load of the MPA would be reduced to 16,680 pounds.

TABLE 7-5 - EQUIPMENT WEIGHT FOR BOW MOORING SYSTEM

Item	Estimated Weight (lb)
Mast head	325
Mast	2388
Cables and fittings	911
Baseplate	400
Anchors (40)	1400
Winch	200
Tool kits and power drive	200
Total	5824

e. Environmental and Maintenance Considerations

The bow mooring concept meets the wind load criteria of sustaining a 60-knot gust that hits the envelope perpendicular to its centerline axis. Although still susceptible to snow loads, this mooring system approaches the all-weather capability feature that would be required for any operator.

Maintenance service for the engines is addressed in Section VI. Any major work will necessitate the use of a hangar.

f. Costs

Total acquisition cost of a bow mooring system is estimated at $375,000. This cost is based on historical records maintained within Goodyear and is tempered by a parametric extension of the costs associated with the Goodyear public relations fleet.

4. BELLY MOORING

a. Structural Requirements

A mooring mast placed at any location other than the bow necessitates assessing the rolling moment effects on the airship as well as on the mooring system. The critical areas are: (1) the point of attachment for the mooring mast to the airship; (2) the landing gear; and (3) the mast and anchors. The operational capability of a belly mooring concept is limited by the least capable of these areas. For this analysis, a mast position 75 feet from the nose has been selected. This position coincides with the plane of the forward engines and does not interfere with the location of the forward ballonet. In addition, the car is assumed to be equipped with a tricycle landing gear. The forward gear is 104 feet from the nose, while the aft gear is 148 feet from the nose. Lateral displacement varies from 10 to 30 feet.

In order to secure a mast to the underside of the airship, all forces occurring at that point must be distributed over a sufficiently large envelope area so that the strength limits of the fabric are not exceeded. For the case of the mast at a point 75 feet from the nose, the maximum FMAST is 121,000 pounds. Since the design limit for the fabric is 150 pounts per inch, a total external catenary curtain of 67 feet would be required on each side of the airship to accommodate this load. It is unlikely that the force could be evenly distributed over such a length, even if the curtain could be physically placed. An alternative would be to provide an internal curtain to support this point. Again, however, the physical arrangement of the system is inhibited by the forward ballonet and the support structure for the engines. In view of the above, significant redesign of the airship would be required. Assuming this redesign is feasible, an acceptable mooring suspension system would weigh approximately 2700 pounds more than the weight required for the standard suspension system, based on the findings of Section 6.3.

The forces required to resist the overturning moment of the airship are substantial. Figure 7-4 shows the relationship between wind speed and the force required at a single gear point to maintain the ship in equilibrium with respect to rolling. At 60 knots, this force is 67,000 pounds when the aft gears are at the widest spacing.

In order to scope the magnitude of this force, a preliminary support truss and landing gear were designed for the MPA. Using the maximum load indicated above at a distance 30 feet from center and using tires similar to those used on the ZPG-3W, the result was a 16-wheel landing gear and a support structure weight in excess of 10,000 pounds (see Figure 7-5). This result is unacceptable. Even by going to a higher rated tire that would possibly result in a castering two-tired gear, the structural weight penalty would still exist.

A more realistic approach would be to offset the landing gear 10 feet on each side and use two wheels per side. The allowable load would be 12,600 pounds at 45 psi, which would permit mooring on a grassy surface (see Table 7-4).

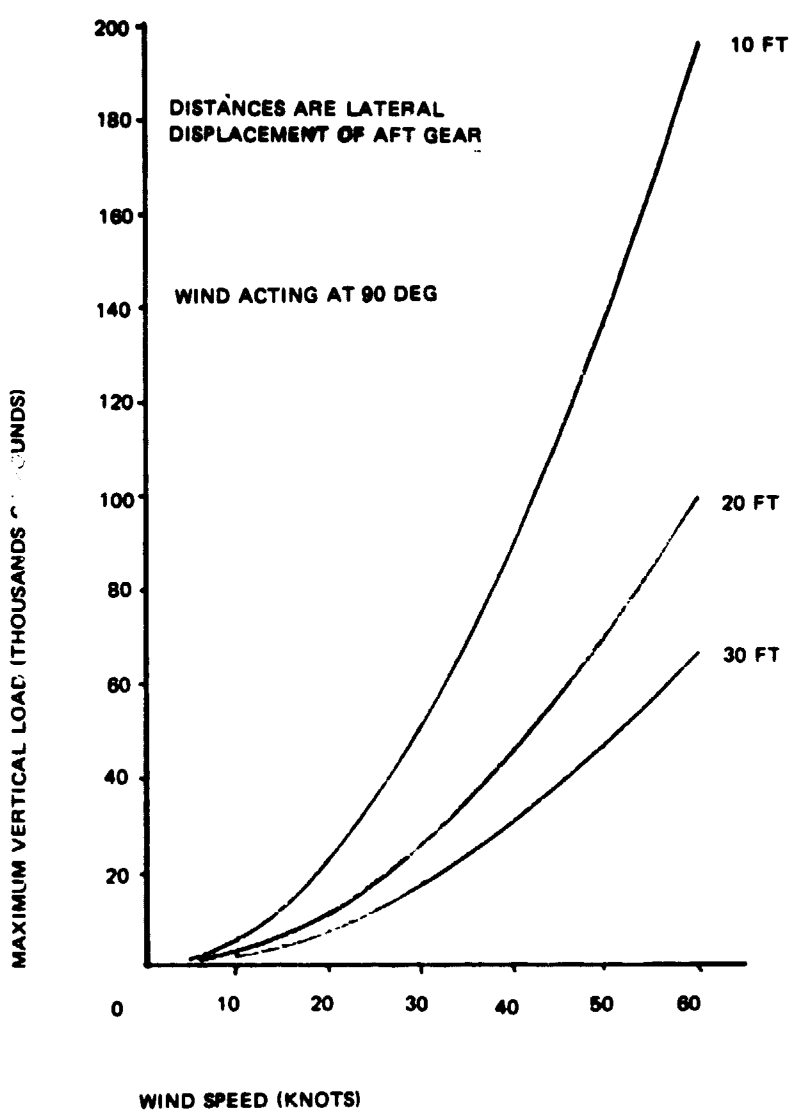
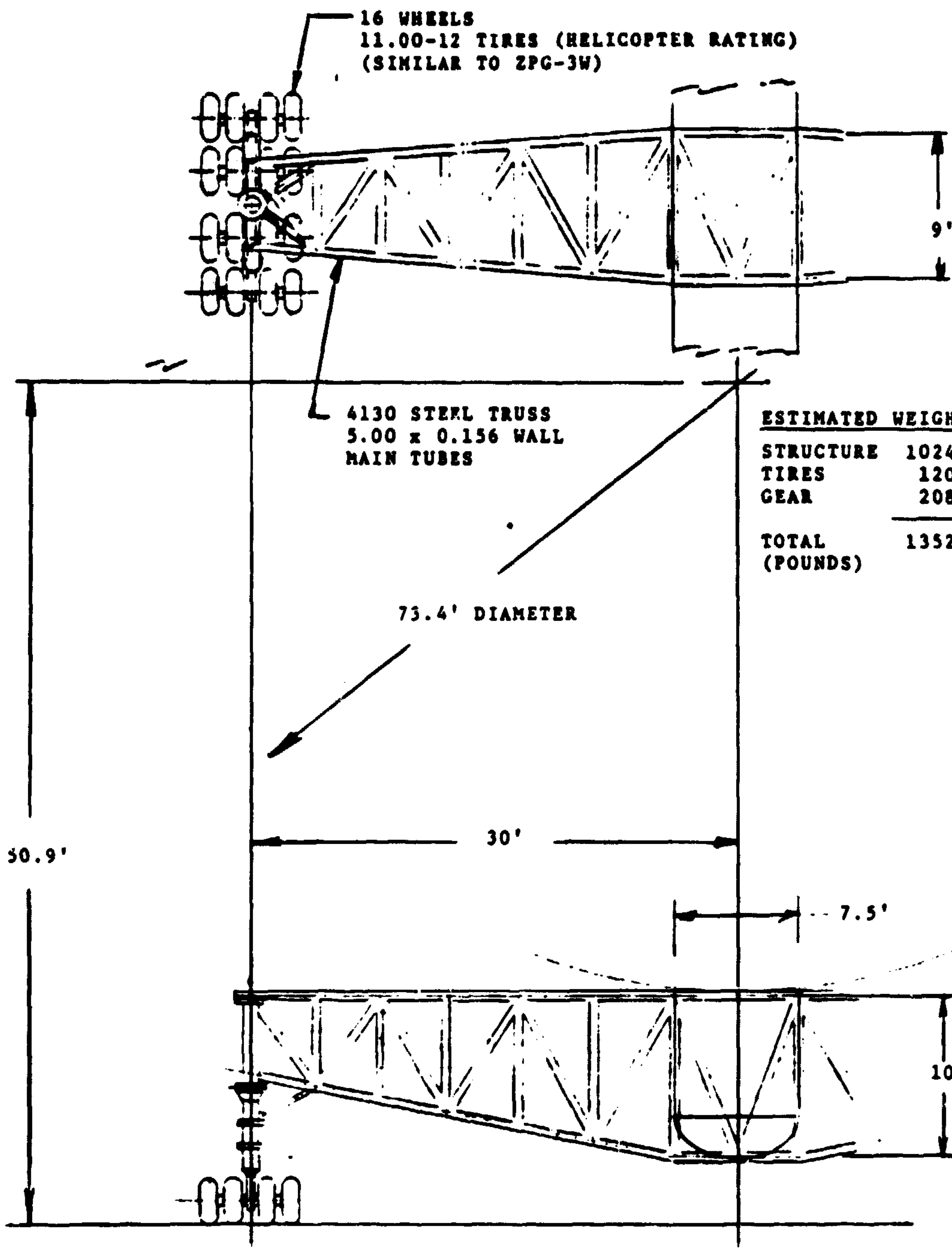


Figure 7-4 - Wind Speed Versus Landing Gear Load for Belly-Moored MPA



ESTIMATED WEIGHT	
STRUCTURE	10240
TIRES	1200
GEAR	2080
TOTAL (POUNDS)	13520

Figure 7-5 - Hypothetical Landing Gear and Truss Configuration

If a more substantial surface was available, the allowable load would be increased to 25,200 pounds per gear at a tire pressure of 68 psi. These values correspond to maximum wind speeds of 15 and 21 knots, respectively.

Based on the original design requirements of withstanding a 60-knot wind afting at 90 degrees to the main axis and using the same approach used for the bow mast, a tubular aluminum mast with the following dimensions could withstand the predicted FMAST of 121,000 pounds: 14.3 feet high, 18 inches outside diameter, wall thickness of 0.75 inches. For a 20-cable arrangement, an ultimate cable load of 33,300 pounds must be restrained. Referring to Table 7-3, a pair of 13.5-inch-diameter single-helix screw anchors would be required. Recall, however, that the capability of the hand-held power drive unit is limited. It therefore might be more feasible to use three of the eight-inch anchors at each point. For the purpose of comparison to other systems, it will be assumed that the larger units are used.

b. Mooring Area Requirements

As indicated in Figure 7-1, the recommended mooring area for the MPA belly moored at a point 75 feet from the nose is approximately 6.4 acres. Under certain conditions, this area could be reduced to 3.3 acres provided vertical clearances were maintained.

c. Operations and Mobility

Procedurally, belly mooring is similar to bow mooring. The mast is somewhat easier to erect due to its shorter length, but additional work would be necessary to install the anchors.

The weight summary for the belly mooring concept is given in Table 7-6. This concept is 567 pounds lighter than the bow mooring system.

TABLE 7-6 - EQUIPMENT WEIGHT FOR BELLY MOORING SYSTEM

Item	Estimated Weight (lb)
Mast head	400
Mast	1016
Cables and fittings	657
Baseplate	720
Anchors (40)	2064
Winch	200
Tool kits and power drive	200
Total	5257

d. Environmental and Maintenance Considerations

As indicated previously, the belly mooring concept is severely limited by the rolling moment. This limitation would drive the design and substantially reduce the structural requirements indicated above. Maintenance procedures for bow mooring would also apply to this concept.

e. Costs

The acquisition cost of a belly mooring system would approximate that of the bow mooring system. However, significant changes to the airship also must be considered. These changes include the provision of a tricycle landing gear and associated structure, a belly mooring patch, and substantial suspension system enhancements. In addition, this concept could also deteriorate airship performance due to increased weight and drag.

5. COMPLETE VEHICLE (TOTAL) RESTRAINT

a. Structural Requirements

A major problem in assessing complete vehicle restraint for the MPA is to define an attachment point. Unlike the heavy-lift airship designs that incorporate a massive interconnecting structure, the MPA is equipped solely with a control car that is not structurally designed to handle large ground handling loads.

There are two possible approaches to consider. The first is to assume that the airship car is firmly fixed to the ground by cable or other mechanical attachment device. If no changes were made to the envelope or suspension system, there would be little resistance to the rolling moment and the airship would be destroyed in any significant cross wind. If a suspension system was installed to compensate for the load developed by a 60-knot wind, it would weigh 15,060 pounds, an increase of 13,850 pounds (refer to Table 6-5). This weight would diminish the useful load to 8654 pounds, about equal to the dynamic lift, which would significantly inhibit airship operations.

If the suspension system design was left unchanged and the envelope structure improved, the results would be even worse. At 60 knots, the envelope would weigh more than [illegible]5,000 pounds (see Table 6-6).

A compromise is to relax the wind-speed requirement to where the added structural weight of the suspension system is tolerable. At 20 knots, for example, the weight of the suspension would be slightly more than double the normal, or 2600 pounds. This additional weight probably could be tolerated, but additional structural development would still be required for the car.

The second approach would be to develop a quad-gear arrangement similar to the tricycle gear setup for belly mooring. Unfortunately, this arrangement suffers from the same weight problems and hence is disregarded.

b. Mooring Area Requirements

The complete vehicle (total) restraint concept is the most frugal in terms of land requirements. A rectangular area with the dimensions of vehicle length plus 100 feet by vehicle width plus 100 feet would probably suffice, assuming the VTOL characteristics of the MPA. The total area would be 1.8 acres.

c. Operational Concept

Operationally, the MPA could follow a routine similar to the bow and belly mooring concepts. A small ground party crew would have to set anchors in place prior to bringing the ship in for mooring. Since the airship would normally land into the wind, the anchors should be arranged to accommodate this. This approach is sensitive to changes in wind direction.

d. Costs

Due to the absence of a need for large amounts of ground handling hardware, the complete vehicle (total) restraint system has some economic advantage. Even at the comparatively low wind speed of 20 knots, however, the car structure and suspension system must be improved. The costs of these modifications as well as the reduction in airship operating capabilities due to increased weight would have to be included in a comprehensive system cost analysis.

6. HANGAR SYSTEMS

a. Operational Concept and Requirements

Both the conventional and air-supported hangars defined in Section I would conduct airship operations in a manner similar to those developed by the Navy and currently practiced by Goodyear. In essence, the airship would enter and leave a hangar with the assistance of a mobile mast and two ground handling mules. The function of this equipment is to prevent cross winds at the hangar door from causing a collision between the airship and the hangar. This operation is detailed in Item 2c of Section I.

Equipment needs at the hangar associated with ground handling are:

1. Mobile mooring mast
2. Mast tractor
3. Two ground handling mules
4. Water ballast system
5. Auxiliary power unit for the mast
6. Mobile service vehicle
7. Fire-fighting equipment
8. Mooring circle

As an airship mooring concept, a hangar is unequaled. It provides all-weather protection and facilitates maintenance and servicing operations.

b. Additional Utility for Airship Operations Support

Given the investment requirement for the construction of a hangar, its use cannot be restricted to simply housing the airship. Complete airship assembly, erection, component testing, and overhaul work could be accommodated. Such operations would require significantly more equipment, however, such as:

1. Test stand equipment
2. Magirus ladders
3. Scaffolding
4. Ground cloths
5. Inflation net
6. Rope racks
7. Ballonet ladders
8. Fin slings
9. Suspended work platforms
10. Helium supply
11. Helium purifier
12. Inflation tunnels
13. Bosun's chairs
14. Pressure watch blowers
15. Engine handling equipment
16. All necessary tools

Since the above equipment does not specifically encompass the realm of ground handling, it is not included in the cost estimate.

c. Additional Support for Other USCG Operations

Should a hangar be erected, its cost effectiveness is enhanced by additional utility. Since an immediate buildup of an airship fleet is impossible, there will be significant time periods when the hangar is unoccupied by an airship. During these times, use by other USCG vehicles is recommended. Characteristics of these aircraft are given in Table 7-7. Dimensionally, there is no problem.

TABLE 7-7 - USCG AIRCRAFT CHARACTERISTICS

Model	HH3F	HC130B	HC130H	HC131A	HU25A	HH65A
Length	73'0"	97'9"	98'9"	74'8"	56'3"	43'9"
Width/span (including rotor)	62'0"	132'7"	132'7"	91'9"	53'6"	38'4"
Height	18'1"	36'6"	38'6"	27'3"	17'5"	12'6"
Max gross weight (lb)	22,050	135,000	155,000	67,000	32,000	8400

The 150-foot door opening would permit access by any of the aircraft. Similarly, height and length restrictions are not compromised.

There would be significant economic benefit to maintaining a hangar for all operations rather than limiting its use to airships through more effective use of personnel and equipment.

d. Costs

The hangar erection costs and equipment acquisition costs are detailed below (see Table 7-8). The conventional hangar cost is based on the description in Section III and was provided by A&F Building Systems of Houston, Texas. This firm designed and built the existing Goodyear hangar in Houston.

The air-supported hangar cost is based on a clear height equal to the conventional hangar (128 feet) and a width of 500 feet (4 to 1 ratio). The length is 425 feet. Unit cost estimate provided by ESI for materials and erection is $6 per square foot for a long-term material. This estimate is assumed to include all necessary hardware and equipment but is exclusive of a foundation pad, whose cost is estimated at $325,000.

In both cases, land acquisition and clearing costs are not considered.

TABLE 7-8 - HANGAR SYSTEM COSTS

Item	Estimated Cost ($1981)		
Building erection			
Conventional	6,100,000		
Air supported			1,600,000
Equipment			
Mooring mast		965,000	
Mast tractor		90,000	
Mules (2)		759,000	
Ballast system		7,000	
APU		21,000	
Service vehicle		21,000	
Mooring circle		96,000	
Fire-fighting equipment		84,000	
Totals	8,053,000		3,553,000

8. OPERATIONAL SCENARIO SUITABILITY

As indicated in Item 2d of Section VII, high winds and snow can severely impact ground handling operations. Some of the record wind speeds for domestic coastal sites are well beyond proposed design limits. However, due to advanced weather-prediction techniques, it is unlikely that an airship would remain in an area scheduled for such inclement conditions.

The ability of maritime patrol airships to survive is well documented. The history of their use during World War II lends credibility to their predicted ability to operate in a wide variety of environmental circumstances. This ability is best demonstrated by the identification of the World War II airship operational wings: Airship Wing One operated off the East Coast and was headquartered at Lakehurst (see Figure 7-6); Wing Two covered the Caribbean with headquarters in Richmond, Florida; Houma, Louisiana; and Jamaica; Wing Three covered the West Coast with headquarters at Tillimook, Moffett Field, and Santa Ana; Wing Four consisted of two squadrons and protected the South Atlantic from its headquarters in Brazil; and Wing Five covered the lower Antilles from an operating base in Trinidad.

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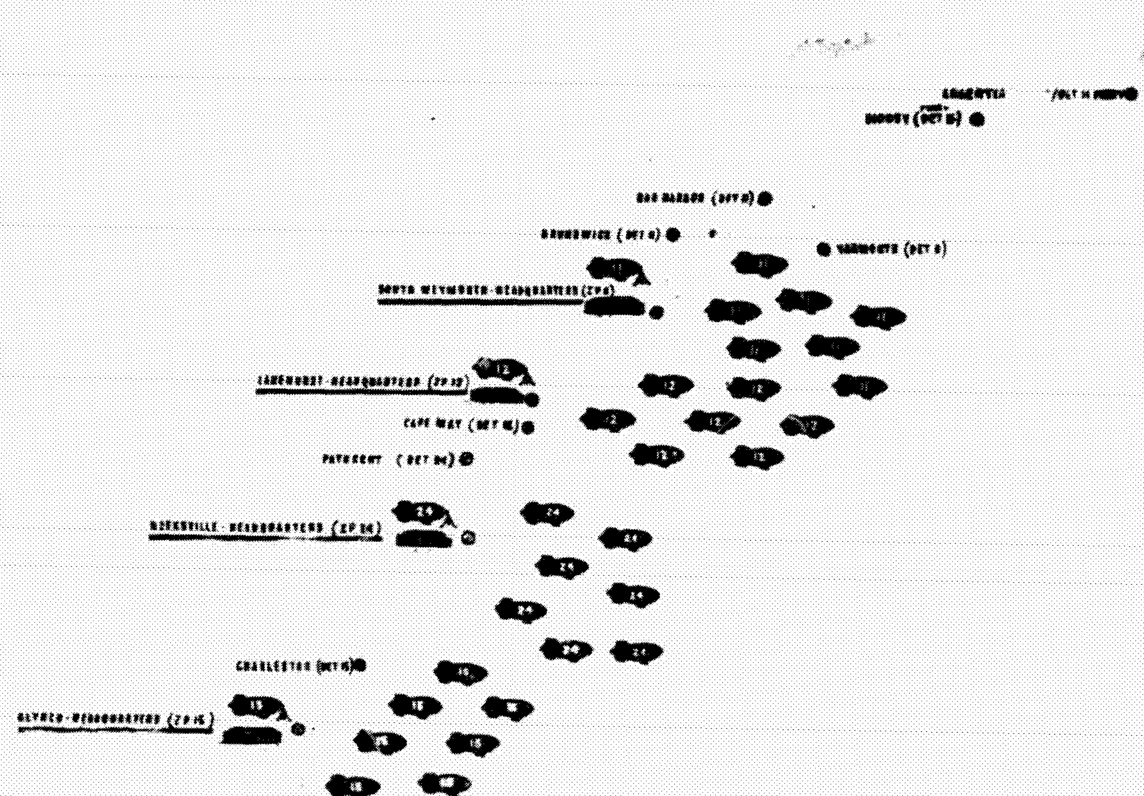
Headquarters, Lakehurst, N. J.



SQUADRONS		MAIN OPERATING BASE
ZP-11	8 airships	Naval Air Station, South Weymouth, Massachusetts
ZP-12	8 airships	Naval Air Station, Lakehurst, New Jersey
ZP-24	8 airships	Naval Air Station, Weeksville, North Carolina
ZP-15	8 airships	Naval Air Station, Glynco, Georgia

Figure 7-6 - Fleet Airship Wing One Deployment
During World War II

In 1944, a squadron was deployed to North Africa to patrol the Western Mediterranean and Straits of Gibraltar. These ships were the first non-rigids tc make a transatlantic flight. An airship utility squadron headquartered in Key West provided many service and utility operations, including ASW training.

9. PERMANENT VERSUS REMOTE BASE REQUIREMENTS

Two distinct levels of basing exist within the realm of MPA operations (see Table 7-9). Level I, which would serve as the home base or headquarters, would be the maintenance depot equipped with a spare parts inventory to handle all service functions. A mooring circle would be established with a paved surface, permanently installed anchors, and mast baseplate. A hangar is optional.

TABLE 7-9 - LEVELS OF MPA BASES

Level	Attribute
I	Permanent base; operational headquarters
II	Remote base; MPA commutes daily to mission site

Level II would constitute a base away from the headquarters. It would typically be a site that did not require any clearing or leveling prior to establishing the base. An open field near a small airport would be a candidate location. From this site, the MPA would travel daily to the mission site. The mast would remain erected at this location for the duration of the mission. Similar to operating from a Level I base, an MPA could service several mission sites from a single location.

10. CONCEPT SUMMARY

a. General

The key attributes of each mooring concept (bow, belly, and complete vehicle restraint) are assessed below with respect to their predicted operational effectiveness. Hangars are discussed separately.

b. Attributes

(1) Manpower

A basic premise of the MPA is that it will permit the ground handling function to be executed by members of the flight crew. The basis for this statement is that the MPA has substantially improved low-speed controllability over previous airships and is also capable of VTOL and taxiing. Thus, for all concepts examined, a ground crew party of two men (from an airship complement of four men) properly equipped could perform the necessary tasks.

(2) Equipment

For both the bow- and belly-mooring concepts, a full complement of mast, baseplate, and ancillary equipment is required. This equipment would always be assigned to the airship. The airship associated with total restraint would have substantially less equipment as an integral part of its inventory but is much more dependent on engineering services that must be undertaken in advance of the airship's arrival. Spontaneous mooring is therefore precluded.

(3) Impact on Vehicle Empty Weight

Assuming that the operational design speed of 60 knots must be attained with each concept, the effect of this speed on the vehicle's empty weight can be estimated.

For bow mooring, no additional envelope or suspension system weight would be required since all mooring loads are transferred directly to the mast. The only adverse impact would be the weight of the mooring equipment that would become an integral part of the airship in the ferry mode. During mission execution, however, there would be no weight penalty since all ground handling equipment would be off-loaded.

The belly mooring concept is impacted by ground equipment loads similar to those indicated above. This approach is further impacted, however, by additional weight requirements for the suspension system, envelope, and landing gear assemblies. The probability of advancing a vehicle design based on large wind loads and belly mooring (heavy-duty gear assemblies; complex catenary system to support mast/airship interface point) is remote.

Complete vehicle (total) restraint mooring would result in extremely large weight penalties for high-wind conditions. Even at reduced wind speeds where the additional suspension weight requirements are smaller, substantial improvements to the car's structure would be needed.

(4) Mooring Area Requirements

The amount of cleared land required for effective ground handling varies from a maximum of 11 acres for a barrier to a minimum of 1.8 acres for a fully restrained airship. Some savings can be realized in those concepts with rotational capability by only partially clearing the area to maintain vertical clearance requirements in the aft portion of the airship.

(5) Maximum Wind Speed

For the MPA vehicle specified in Section II, there are identifiable wind-speed limitations for each mooring concept.

A bow-moored MPA is capable of withstanding 60 knots at 90 degrees with the ground equipment specified. As the wind direction approaches colinearity to the airship, the allowable wind speed increases dramatically.

The belly-mooring concept cannot withstand wind speeds in excess of 15 knots on a grassy surface or 21 knots on a paved surface. The critical element is the landing gear, but the development of an effective mooring point on the underside of the envelope and the retention capability of the ground anchors also are limiting factors.

The totally restrained airship is limited by its envelope and suspension system capabilities to 20 knots, but this speed would likely be further diminished by structural limitations of the car.

(6) System Mobility

The transportability of the bow- and belly-mooring systems is implicit in their designs. The masts, complete with guy cables, would be attached to the car with all support equipment stowed as required. Thus, each airship would have a mooring system as an integral vehicle component. The total restraint system may need some advance preparation to provide suitable anchor systems since the screw anchors described for mast retention would not be sufficient.

(7) Cost

The costs of building a mast for either bow or belly mooring are approximately $375,000. However, the belly-moored airship would require additional features that would impact both its initial cost and its operational costs due to increased weight and drag. The cost of the complete vehicle restraint system depends on the method of securing the airship to the ground.

c. Hangar Systems

Though not specifically a mooring system, the hangars defined herein represent the ultimate approach to protecting an airship on the ground. However, moving an airship to and from the hangar necessitates additional mobile equipment, which in fact represents a bow mooring operation. Total minimum manpower is six (two per mule, one on the mast tractor, and one supervisor).

Despite operational similarities, the costs of the two hangar systems are considerably different. The lower purchase price of the air-supported structure must be assessed in the light of a shorter life (material is good for only five to six years) and the development required for moving an airship through a large opening in the structure without seriously impacting the support system.

d. Rating

Since all mooring concepts represent some degree of risk, the preferred approach to mooring is the use of a hangar. Unfortunately, the large cost and immobility of such a structure are major detriments. The impact of the former can diminish somewhat by using it to house and service other vehicles.

The bow-mooring concept is the only approach that fulfilled the operational wind load requirements without adversely affecting the overall MPA design. There was no weight penalty associated with this concept, although some adverse performance effects in the ferry mode could result due to the overall weight of the mooring equipment. The large land area associated with the bow mooring is a disadvantage.

A distant third in terms of overall effectiveness is the belly-mooring concept. The structural integrity of the system is jeopardized at wind speeds in excess of 15 knots. In addition, this concept would suffer from performance degradation due to increased airship weight.

The complete vehicle (total) restraint approach has only limited applicability as defined above due to structural weight implications.

Table 7-10 summarizes the key attributes of each mooring concept.

TABLE 7-10 - MOORING CONCEPT SUMMARY

	Hangars	Bow Moored	Belly Moored	Complete Restraint
Ground personnel	6	2	2	2
Equipment	Building, mobile mast, mules, etc	Mast, baseplate, anchors, winch, tools, etc	Same as for bow moored	Anchors, cables, etc
Impacts on vehicle empty weight	None	The additional weight of the equipment can be off-loaded prior to missions; hence, little impact	Additional weight for suspension and landing gear; mooring equipment same as for bow moored	Large increase in suspension system or envelope weight
Landing area (acres)	>10	10	6.4	1.8
Maximum wind speed (knots)	>60	60	15 (21)*	$\leq$20
Limiting feature	Cost; immobility	Mast and anchor strength	Landing gear; suspension system	Vehicle empty weight
System mobility	Immobile	Mobile	Mobile	May require advance preparations
Permanent/remote	Permanent	Both	Both	Both
Rating	1	2	3	4

*15 knots on grassy surface; 21 knots on paved surface.

SECTION VIII - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. HISTORICAL REVIEW

The development of ground handling systems for lighter-than-air vehicles has evolved from man-handling to the mechanized state established for large non-rigid Navy airships in the 1950's. Throughout the nearly 200 years since the Montgolfier brothers first ascended in a hot-air balloon, a plethora of mooring techniques have been attempted. Of all these efforts, however, the bow-mooring concept has consistently represented the optimum approach for securing airships on the ground. Though marine capabilities have been demonstrated, they have not been further developed.

2. VEHICLE CONCEPT

The baseline vehicle for this study was the ZP-3G maritime patrol airship developed by Goodyear Aerospace for NADC (Reference 15). It has a tri-rotor propulsion system with the forward engines supported on a structure above and ahead of the control car and the aft engine mounted on the stern. The envelope volume is 875,000 cubic feet.

3. MOORING SYSTEM ALTERNATIVES

Several mooring alternatives were described and assessed: bow mooring, belly mooring, center point mooring, complete vehicle (total) restraint mooring, hangar systems, and maritime systems. After preliminary investigation, it was determined that center point mooring and all maritime systems did not warrant additional investigation.

4. STRUCTURAL ANALYSIS OF A FULLY RESTRAINED AIRSHIP

An investigation of airship empty weights versus wind velocity was undertaken for the two vehicle concepts but was limited to a static condition in which envelope deformation was not considered. Previously defined aerodynamic coefficients that are based on experimental data for various airship models were found to have sufficient correlation to be applicable to the vehicle being considered. The coefficients appear to be insensitive to fineness ratio.

A static analysis of the mooring loads developed in a fully restrained airship was defined and coded for a computer program. Results indicate that the lateral loads are the most significant followed by vertical and longitudinal.

5. DYNAMIC ANALYSIS OF A MASTED AIRSHIP

In order to extend the results of the static analysis to encompass the dynamic effects of an airship rotating about a mast, a segmented approach was taken to determine the overall forces acting on the airship. For each segment, the various forces were computed and then summed to yield results for the entire airship. Calculations were performed by a computer simulation model in which the airship physical properties, mooring mast location, and wind information were input. Results of this model, presented graphically, indicate that the mast forces increase as the mast location moves from the airship nose toward the center point. For both bow- and belly-mooring concepts, mast forces increase due to increased wind speeds and increased yaw angles. The airship equilibrium position was found to be colinear with the wind provided the mast is no further than 100 feet from the nose.

6. IMPACT OF VEHICLE DESIGN ON GROUND HANDLING

With respect to ground handling qualities, the X-type empennage configuration is very suitable, with good ground clearance qualities. It also has the advantage of having good (low) snow accumulation characteristics.

The effect of buoyancy ratio on the vertical forces of a fully restrained airship is also addressed at various wind speeds.

When mooring, attempts are made to exclude ground handling loads from acting on the envelope and suspension system by transferring the loads to a mast. If this opportunity is not provided, however, the envelope and suspension system must be structurally capable of withstanding these forces. This results in a severe weight penalty due to increases in envelope fabric strength or increased size or quantity of catenary cables. Operationally, this would result in a serious degradation of airship performance efficiency.

Propulsion unit selection should address the need for sufficient power requirements for ground handling purposes. Unit placement in this particular design makes engine servicing somewhat inconvenient unless hangared.

7. OPERATIONAL CHARACTERISTICS AND COSTS

The main factors to consider in the establishment of a mooring site are the local topography, soil conditions, weather conditions, and the mooring concept.

The site topography will dictate the overall suitability of a mooring location. Significant relief would not be tolerable, and the site would require extensive renovation.

Soil conditions and bearing strength will ultimately define the operational limits of the mooring systems. The ability of the soil to withstand loads at landing gear contact points and to develop sufficient strength from anchors is of paramount importance. Similarly, the landing site's resistance to degradation through erosion must be addressed.

The two weather factors that most severely affect airship mooring are wind and snow. This analysis has attempted to quantify wind loads and minimize their effects through the use of the appropriate mooring concept. Snow loads, however, will require additional study since no completely effective means of snow removal has been developed.

Four mooring concepts were examined: bow-mooring; belly-mooring; complete vehicle (total) restraint; and hangars.

Bow mooring is the most conventional and is designed to hold the airship at the nose, thus permitting it to rotate. Loads are transferred through the airship to the mast so that mooring loads do not act as the design loads on the vehicle. While it does permit the airship to rotate, belly mooring results in significant loads due to the rolling moment that must be resisted. Some structural penalty would be involved with this concept. Complete vehicle (total) restraint mooring offers distinct disadvantages since extreme envelope and suspension system weight penalties would accrue, <u>if</u> a satisfactory means of attachment could be developed for high wind speeds.

Hangar systems are the optimum approach although construction and operating costs are major factors.

For the non-hangar systems, bow mooring is preferred, despite the large land area requirements. The attributes that distinguish it as most attractive are: load transference to the mast and hence no design impact on the airship; ability to withstand extreme wind speeds; transportability; and relative ease of installation.

In terms of permanent versus remote temporary basing, two levels exist: (1) a permanent base to serve as the operational headquarters and (2) a remote base from which the airship commutes on a daily basis to the mission site. Another advantage of the bow-mooring system is that it is applicable to each of these levels without needing any mooring equipment changes relative to base location. The only elements that would probably be required in a permanent base would be a paved mooring area with anchors permanently installed.

8. RECOMMENDATIONS

As a result of the findings of this study, the following recommendations for additional study are suggested:

1. Future design studies to further develop and enhance a transportable bow-mooring mast system
2. Additional study of snow and ice removal as well as identification of critical operational limits in cold weather areas
3. More detailed analysis of wind load effects that will examine the overall airship reactions to these forces: wind accelerative impacts, envelope deformation, landing gear deflections, other structural deflections
4. Additional study of the dynamic effects on a moored airship, including kiting effects
5. Additional study of ground anchors and enhancement of their holding power capabilities

SECTION IX - LIST OF SYMBOLS

Symbol	Definition
C_l	Rolling moment coefficient
C_m	Pitching moment coefficient
C_n	Yawing moment coefficient
C_x	Axial force coefficient
C_y	Lateral force coefficient
C_z	Vertical force coefficient
C_{ws}	Suspension system weight coefficient
F_{latr}	Total lateral force
F_{long}	Total longitudinal force
F_{mast}	Total resultant force
F_{x_i}	Axial force on element i
F_{y_i}	Lateral force on element i
I_{cg}	Moment of inertia about center of gravity, including virtual mass
I_y	Moment of inertia about mast, including virtual mass
$(KT)_D$	Design velocity (knots)
$(KT)_W$	Wind velocity (knots)
L_{cg}	Center of gravity location along X
L_i	Element location along X
L_m	Mast location along X
m	Mass of airship, including virtual mass
P'_s	Resultant force in suspension system
V_T	Instantaneous relative wind velocity at element i
V_w	Prevailing wind velocity

Symbol	Definition
W_s	Suspension system weight
β	Buoyancy ratio
θ	Airship heading
$\dot{\theta}$	Angular velocity about the mast
$\ddot{\theta}$	Angular acceleration about the mast
λ	Length-to-diameter ratio
μ	Prismatic coefficient
ψ	Wind azimuth angle
ρ	Air density

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APPENDIX A - ADDED MASS FORCES

1. INTRODUCTION

The treatment of added mass forces in the literature is inadequate even in the following references:

1. "Hydrodynamics," by Sir Horace Lamb
2. The Complete Expressions for Added Mass of Rigid Body Moving in an Ideal Fluid," by F. H. Imlay

Several articles were published in the literature with erroneous concepts and conclusions; some appeared as recently as July 1981. Even for the topics that were adequately treated, the approaches were obsolete in the following sense:

1. The approaches were not easily amenable for extensions
2. A modern-day airplane aerodynamicist was unfamiliar with the notation and the approaches

Thus, a comprehensive approach is presented here for the treatment of added mass forces. The advantages of the approach are as follows:

1. The limitations and assumptions are clear.
2. A modern-day aerodynamicist can easily read and follow the treatment.
3. Formulation is appealing because the existing fluid dynamics programs can be used for calculation of added mass constants of arbitrary three-dimensional bodies on digital computers.
4. Formulation can easily be extended to elastic bodies.
5. In addition to the gross added mass coefficients, the distribution of the added masses can also be obtained.

Finally, six examples are carefully selected to demonstrate the concepts. Some may clear up the erroneous assumptions that exist in the literature.

2. EQUATIONS OF MOTION AND INVISCID FLOWS

The governing equations of motion of inviscid flows are given by

<u>Continuity equation</u>: $$\frac{D\rho}{Dt} + \rho \operatorname{div} \underset{\approx}{Q} = 0 \qquad \text{(A-1)}$$

<u>Momentum equation</u>: $$\frac{D\underset{\approx}{Q}}{Dt} = - \frac{\operatorname{grad} p}{\rho} \qquad \text{(A-2)}$$

$$\underline{\text{Energy equation:}}\ \frac{D}{Dt}\left[\frac{a^2}{\gamma-1} + \frac{Q^2}{2}\right] = \frac{1}{\rho}\frac{\partial p}{\partial t} \tag{A-3}$$

where:
- ρ = fluid density
- $\underset{\sim}{Q} = \underset{\sim}{i}\,u + \underset{\sim}{j}\,v + \underset{\sim}{k}\,w$ = total velocity vector
- $\frac{D}{Dt} = \frac{\partial}{\partial t} + \underset{\sim}{Q} \cdot \text{grad}$
- a = speed of sound
- γ = ratio of specific heats
- p = pressure

For potential flows (barotropic irrotational flows), Equations A-1 to A-3 boil down to the following nonlinear potential flow equation:

$$\nabla^2\phi - \frac{1}{a^2}\left[\frac{\partial^2\phi}{\partial t^2} + \frac{\partial Q^2}{\partial t^2} + \underset{\sim}{Q} \cdot \text{grad}\left(\frac{Q^2}{2}\right)\right] = 0 \tag{A-4}$$

where:
- Q = grad ϕ
- $Q^2 = \underset{\sim}{Q} \cdot \underset{\sim}{Q}$
- a = speed of sound
- ∇ = Laplace operator $= \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ in cartesian system

The boundary conditions of the problem are:

1. At each point of the solid-fluid surface, at every instant, the component normal to the surface of the relative velocity between the fluid and the solid must vanish.
2. The conditions at infinity are to be specified. Further, it is required that the velocity due to the motion of the body be finite or zero at infinity.

The equation of the surface of a three-dimensional arbitrary body moving in a time-dependent fashion can be written as

$$F\ (x, y, z, t) = 0 \tag{A-5}$$

The first boundary condition can then be written mathematically as

$$\frac{\partial F}{\partial t} + \underset{\sim}{Q} \cdot \text{grad } F = 0 \tag{A-6}$$

Equations A-4 to A-6 are valid for incompressible and compressible fluid flows including subsonic, transonic, supersonic, and hypersonic unsteady flows. For incompressible flows, the nonlinear potential flow equation (Equation A-4) reduces to

$$\nabla^2 \phi = 0 \tag{A-7}$$

The most general flow that is governed by the Laplace equation is unsteady, incompressible, irrotational, and large disturbance flows. There is no unsteady term in the Laplace equation, but the time dependency comes through the boundary condition given by Equation A-6.

For small disturbances, the nonlinear potential flow equation can be linearized to the following equation

$$\nabla^2 \phi' - \frac{1}{a_\infty^2} \left[\frac{\partial^2 \phi'}{\partial t^2} + 2\,U \frac{\partial^2 \phi'}{\partial x \partial t} + U^2 \frac{\partial^2 \phi'}{\partial x^2} \right] = 0 \tag{A-8}$$

where ϕ' is perturbation velocity potential over the steady-state velocity vector $\tilde{Q} = \tilde{i}\,U$ and a_∞ is free-stream speed of sound. It can be observed from Equation A-8 that only incompressible flows can be represented by Laplace's equation even for steady flows.

Consider a region, R, that is enclosed by a surface, S, and that contains only fluid in motion. The kinetic energy, T, of the fluid in R is given by

$$T = \iiint_R \frac{\rho Q^2}{2}\, d\tau = \iiint_R \frac{\rho(|\text{grad}\ \phi|)^2}{2}\, d\tau \tag{A-9}$$

The first form of Green's theorem says

$$\iiint_R (\psi\ \nabla^2\phi + \text{grad}\ \psi \cdot \text{grad}\ \phi)\, d\tau = \iint_S \psi \frac{\partial \phi}{\partial n}\, dS \tag{A-10}$$

Substituting the above result (after specializing $\psi = \phi$) in Equation A-9 yields

$$T = \frac{1}{2}\iint_S \rho\phi \frac{\partial \phi}{\partial n}\, dS - \frac{1}{2} \iiint_R \rho\phi\nabla^2\phi \tag{A-11}$$

If the flow is governed by Laplace's equation ($\nabla^2\phi = 0$), then Equation A-11 becomes

$$T = \frac{1}{2}\iint_S \rho\, \phi \frac{\partial \phi}{\partial n}\, dS \tag{A-12}$$

Since the governing equation and the boundary conditions for the flows under consideration are linear, one can seek a solution for ϕ in the following form for a body moving in incompressible potential flow by virtue of linearity and time variable separability of the problem:

$$\phi = \sum_{i=1}^{6} u_i\,(t)\;\phi_i\,(x,y,z) \tag{A-13}$$

where u_1, u_2, u_3, u_4, u_5, and u_6 are linear and angular velocities about an arbitrary system axes that is neither an inertial space nor a set of body axes. Substituting Equation A-13 into A-12 yields

$$T = \frac{1}{2}\rho \iint_S \left[\left(\sum_{i=1}^{6} u_i\,\phi_i\right)\left(\sum_{j=1}^{6} u_j \frac{\partial \phi_j}{\partial n}\right)\right] dS \tag{A-14}$$

Interchanging summation and integration in the above equation:

$$T = \frac{1}{2}\sum_{i=1}^{6}\sum_{j=1}^{6} u_i\, u_j\, \rho \iint_S \phi_i \frac{\partial \phi_j}{\partial n}\, dS \tag{A-15}$$

or

$$T = \frac{1}{2}\sum_{i=1}^{6}\sum_{j=1}^{6} u_i\, u_j\, M_{ij} \tag{A-16}$$

where

$$M_{ij} = \rho \iint_S \phi_i \frac{\partial \phi_j}{\partial n}\, dS \tag{A-17}$$

The second form of Green's theorem says

$$\iiint_R (\psi\, \nabla^2\phi - \phi\, \nabla^2 \psi)\, d\tau = \iint_S (\psi \frac{\partial \phi}{\partial n} - \phi \frac{\partial \psi}{\partial n})\, dS \tag{A-18}$$

If ϕ and ψ are both harmonic functions, then Equation A-18 becomes

$$\iint_S (\psi \frac{d\phi}{\partial n} - \phi \frac{\partial \psi}{\partial n})\, dS = 0 \tag{A-19}$$

The application of Equation A-19 to Equation A-17 yields

$$M_{ij} = M_{ji} \tag{A-20}$$

The kinetic energy given by Equation A-16 can be expressed in matrix form as

$$T = \frac{1}{2} \left\{ u_i \right\}^{tr} \left[M_{ij} \right] \left\{ u_j \right\} \tag{A-21}$$

The matrix $[M_{ij}]$ is known as added mass matrix. This matrix is symmetric by virtue of Equation A-20. The Lagrange equation of a rigid body referred to an arbitrary system axes is

$$\left\{ F_i \right\} = \frac{d}{dt} \left\{ \frac{\partial T}{\partial u_i} \right\} + [\omega] \left\{ \frac{\partial T}{\partial u_i} \right\}, \ i = 1,2,3 \tag{A-22}$$

$$\left\{ F_j \right\} = \frac{d}{dt} \left\{ \frac{\partial T}{\partial u_j} \right\} + [\omega] \left\{ \frac{\partial T}{\partial u_j} \right\} + [V] \left\{ \frac{\partial T}{\partial u_i} \right\}, \ j = 4,5,6 \tag{A-23}$$

where

$$u_1 = u;\ u_2 = v;\ u_3 = w;\ u_4 = p;\ u_5 = q;\ u_6 = r \tag{A-24}$$

$$[V] = \begin{bmatrix} 0 & -w & v \\ w & 0 & -u \\ -v & u & 0 \end{bmatrix}; \ [\omega] = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \tag{A-25}$$

Expanding Equations A-22 and A-23

$$F_1 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_1} \right) - r \frac{\partial T}{\partial u_2} + q \frac{\partial T}{\partial u_3} \tag{A-26}$$

$$F_2 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_2} \right) + r \frac{\partial T}{\partial u_1} - p \frac{\partial T}{\partial u_3} \tag{A-27}$$

$$F_3 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_3} \right) - q \frac{\partial T}{\partial u_1} + p \frac{\partial T}{\partial u_2} \tag{A-28}$$

$$F_4 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_4} \right) - r \frac{\partial T}{\partial u_5} + q \frac{\partial T}{\partial u_6} - w \frac{\partial T}{\partial u_2} + v \frac{\partial T}{\partial u_3} \tag{A-29}$$

$$F_5 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_5} \right) + r \frac{\partial T}{\partial u_4} - p \frac{\partial T}{\partial u_6} + w \frac{\partial T}{\partial u_1} - u \frac{\partial T}{\partial u_3} \tag{A-30}$$

$$F_6 = \frac{d}{dt} \left(\frac{\partial T}{\partial u_6} \right) - q \frac{\partial T}{\partial u_4} + p \frac{\partial T}{\partial u_5} - v \frac{\partial T}{\partial u_1} + u \frac{\partial T}{\partial u_2} \tag{A-31}$$

Substituting Equations A-16 and A-20 in Equations A-26 to A-31:

$$
\begin{aligned}
F_1 = {} & \dot{u}\,M_{11} + \dot{v}\,M_{12} + \dot{w}\,M_{13} + \dot{p}\,M_{14} + \dot{q}\,M_{15} + \dot{r}\,M_{16} \\
& - r\,u\,M_{12} - r\,v\,M_{22} - r\,w\,M_{23} - r\,p\,M_{24} - r\,q\,M_{25} - r^2\,M_{26} \\
& + q\,u\,M_{13} + q\,v\,M_{23} + q\,w\,M_{33} + q\,p\,M_{34} + q^2\,M_{35} + q\,r\,M_{36}
\end{aligned}
\tag{A-32}
$$

$$
\begin{aligned}
F_2 = {} & \dot{u}\,M_{12} + \dot{v}\,M_{22} + \dot{w}\,M_{23} + \dot{p}\,M_{24} + \dot{q}\,M_{25} + \dot{r}\,M_{26} \\
& + r\,u\,M_{11} + r\,v\,M_{12} + r\,w\,M_{13} + r\,p\,M_{14} + r\,q\,M_{15} + r^2\,M_{16} \\
& - p\,u\,M_{13} - p\,v\,M_{23} - p\,w\,M_{33} - p^2\,M_{34} - p\,q\,M_{35} - p\,r\,M_{36}
\end{aligned}
\tag{A-33}
$$

$$
\begin{aligned}
F_3 = {} & \dot{u}\,M_{13} + \dot{v}\,M_{23} + \dot{w}\,M_{33} + \dot{p}\,M_{34} + \dot{q}\,M_{35} + \dot{r}\,M_{36} \\
& - q\,u\,M_{11} - q\,v\,M_{12} - q\,w\,M_{13} - q\,p\,M_{14} - q^2\,M_{15} - q\,r\,M_{16} \\
& + p\,u\,M_{12} + p\,v\,M_{22} + p\,w\,M_{23} + p^2\,M_{24} + p\,q\,M_{25} + p\,r\,M_{26}
\end{aligned}
\tag{A-34}
$$

$$
\begin{aligned}
F_4 = {} & \dot{u}\,M_{14} + \dot{v}\,M_{24} + \dot{w}\,M_{34} + \dot{p}\,M_{44} + \dot{q}\,M_{45} + \dot{r}\,M_{46} \\
& - r\,u\,M_{15} - r\,v\,M_{25} - r\,w\,M_{35} - r\,p\,M_{45} - r\,q\,M_{55} - r^2\,M_{56} \\
& + q\,u\,M_{16} + q\,v\,M_{26} + q\,w\,M_{36} + q\,p\,M_{46} + q^2\,M_{56} + q\,r\,M_{66} \\
& - w\,u\,M_{12} - w\,v\,M_{22} - w^2\,M_{23} - w\,p\,M_{24} - w\,q\,M_{25} - w\,r\,M_{26} \\
& + v\,u\,M_{13} + v^2\,M_{23} + v\,w\,M_{33} + v\,p\,M_{34} + v\,q\,M_{35} + v\,r\,M_{36}
\end{aligned}
\tag{A-35}
$$

$$F_5 = \dot{u} M_{15} + \dot{v} M_{25} + \dot{w} M_{35} + \dot{p} M_{45} + \dot{q} M_{55} + \dot{r} M_{56}$$

$$+ r u M_{14} + r v M_{24} + r w M_{34} + r p M_{44} + r q M_{45} + r^2 M_{46}$$

$$- p u M_{16} - p v M_{26} - p w M_{36} - p^2 M_{46} - p q M_{56} - p r M_{66}$$

$$+ w u M_{11} + w v M_{12} + w^2 M_{13} + w p M_{14} + w q M_{15} + w r M_{16}$$

$$- u^2 M_{13} - u v M_{23} - u w M_{33} - u p M_{34} - u q M_{35} - u r M_{36}$$

(A-36)

$$F_6 = \dot{u} M_{16} + \dot{v} M_{26} + \dot{w} M_{36} + \dot{p} M_{46} + \dot{q} M_{56} + \dot{r} M_{66}$$

$$- q u M_{14} - q v M_{24} - q w M_{34} - q p M_{44} - q^2 M_{45} - q r M_{46}$$

$$+ p u M_{15} + p v M_{25} + p w M_{35} + p^2 M_{45} + p q M_{55} + p r M_{56}$$

$$- v u M_{11} - v^2 M_{12} - v w M_{13} - v p M_{14} - v q M_{15} - v r M_{16}$$

$$+ u^2 M_{12} + u v M_{22} + u w M_{23} + u p M_{24} + u q M_{25} + u r M_{26}$$

(A-37)

In the special case where u_1, u_2, u_3, u_4, u_5, and u_6 refer to a coordinate system with the center at the center of mass, Equations A-35 to A-37 reduce to the following:

$$F_4 = \dot{u} M_{14} + \dot{v} M_{24} + \dot{w} M_{34} + \dot{p} M_{44} + \dot{q} M_{45} + \dot{r} M_{46}$$

$$- r u M_{15} - r v M_{25} - r w M_{35} - r p M_{45} - r q M_{55} - r^2 M_{56}$$

$$+ q u M_{16} + q v M_{26} + q w M_{36} + q p M_{46} + q^2 M_{56} + q r M_{66}$$

(A-38)

$$F_5 = \dot{u} M_{15} + \dot{v} M_{25} + \dot{w} M_{35} + \dot{p} M_{45} + \dot{q} M_{55} + \dot{r} M_{56}$$

$$+ r u M_{14} + r v M_{24} + r w M_{34} + r p M_{44} + r q M_{45} + r^2 M_{46}$$

$$- p u M_{16} - p v M_{26} - p w M_{36} - p^2 M_{46} - p q M_{56} - p r M_{66}$$

(A-39)

$$F_6 = \dot{u} M_{16} + \dot{v} M_{26} + \dot{w} M_{36} + \dot{p} M_{46} + \dot{q} M_{56} + \dot{r} M_{66}$$

$$- q u M_{14} - q v M_{24} - q w M_{34} - q p M_{44} - q^2 M_{45} - q r M_{46}$$

$$+ p u M_{15} + p v M_{25} + p w M_{35} + p^2 M_{45} + p q M_{55} + p r M_{56}$$

(A-40)

The analysis performed so far leads to the following conclusions.

1. When a body is moving in an inviscid incompressible fluid (which is at rest otherwise) and a velocity potential can be defined for the resulting disturbance flow field, then the fluid forces that arise due to accelerations and due to certain velocity product terms are given by Equations A-26 to A-31. The coefficients in these equations are called as added masses and inertias (also known as apparent or virtual).
2. The added mass and inertia coefficients can be put into matrix form of order 6 X 6 as shown in Equation A-21. This added mass matrix is symmetric by virtue of Equation A-20 and hence there are 21 independent coefficients.
3. Some of the added mass or inertia coefficients will be zero when the body has certain geometrical properties. In the case of a body with mutually orthogonal planes of symmetry, the number of coefficients will be as follows: one plane of symmetry, 12 coefficients; two planes of symmetry, 8 coefficients; three planes of symmetry, 6 coefficients; and cyclic symmetry, 1 coefficient.

The unsteady Bernoulli's equation for incompressible flows can be written as

$$\frac{p}{\rho} + \frac{q^2}{2} + \frac{\partial \phi}{\partial t} = F(t) \qquad \text{(A-41)}$$

The function $F(t)$ may be eliminated from the right side of Equation A-41 by redefining the velocity potential. Thus, ϕ may be replaced by $[\phi - \int F(t)\,dt]$ without altering the velocity field in any respect. Hence, Equation A-41 can be written as

$$\frac{p}{\rho} + \frac{q^2}{2} + \frac{\partial \phi}{\partial t} = \text{constant} \tag{A-42}$$

The added masses are acceleration dependent aerodynamic forces; hence, for determination of these forces, Equation A-42 can be written as

$$\frac{p}{\rho} + \frac{\partial \phi}{\partial t} = \text{constant} \tag{A-43}$$

Differentiate the governing differential equation of motion given by Equation A-7 with respect to t

$$\frac{\partial^3 \phi}{\partial t \partial x^2} + \frac{\partial^3 \phi}{\partial t \partial y^2} + \frac{\partial^3 \phi}{\partial t \partial z^2} = 0 \tag{A-44}$$

Substitute Equation A-43 in Equation A-44, then

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{A-45}$$

The boundary condition of the problem can be written on the surface of the body as

$$(\underset{\sim}{Q} - \underset{\sim}{Q_S}) \cdot \underset{\sim}{n} = 0 \tag{A-46}$$

or

$$\underset{\sim}{Q} \cdot \underset{\sim}{n} = \text{grad}\ \phi \cdot \underset{\sim}{n} = \frac{\partial \phi}{\partial n} = \underset{\sim}{Q_S} \cdot \underset{\sim}{n} \tag{A-47}$$

where $\underset{\sim}{Q}$ = velocity vector of the fluid

$\underset{\sim}{Q_S}$ = velocity vector of the surface of the body

Differentiate Equation A-47 with respect to t

$$\frac{\partial^2 \phi}{\partial t \partial n} = \frac{\partial}{\partial t} (\underset{\sim}{Q_S} \cdot \underset{\sim}{n}) \tag{A-48}$$

Perform gradient operation on Equation A-43 and take dot product with unit vector n

$$\left[\frac{\text{grad}\ p}{\rho} + \text{grad}\left(\frac{\partial \phi}{\partial t}\right)\right] \cdot \underset{\sim}{n} = 0 \tag{A-49}$$

or

$$\frac{1}{\rho}\ \frac{\partial p}{\partial n} + \frac{\partial^2 \phi}{\partial t \partial n} = 0 \tag{A-50}$$

Compare Equations A-48 and A-50.

$$\frac{\partial p}{\partial n} = -\rho \frac{\partial}{\partial t} (\underset{\sim}{Q_S} \cdot \underset{\sim}{n}) \tag{A-51}$$

Let $Q_{nS} = \underset{\sim}{Q_S} \cdot \underset{\sim}{n}$ = normal velocity of the body surface

Then $\frac{\partial Q_{nS}}{\partial t} = \frac{\partial}{\partial t} (\underset{\sim}{Q_S} \cdot \underset{\sim}{n}) = a_{nS}$ = normal acceleration of the body surface.
Then Equation A-51 can be written as

$$\frac{\partial p}{\partial n} = -\rho\, a_{nS} \tag{A-52}$$

The solution of Equations A-45 and A-52 gives the pressure distribution due to the acceleration of body. The integration of this pressure gives the acceleration-dependent aerodynamic forces or added mass coefficients. To solve this problem, ρ and a_{nS} must be specified. If the accelerations are specified in the direction other than the normal directions, the normal accelerations have to be computed.

If accelerations are specified as $\dot{u} = 1$, $\dot{v} = 0$, $\dot{w} = 0$, $\dot{p} = 0$, $\dot{q} = 0$, and $\dot{r} = 0$, then the corresponding pressure distribution can be obtained by solving Equations A-45 and A-52. In solving this problem, the unit acceleration $\dot{u}$ has to be resolved in the normal direction according to Equation A-52. By integrating this pressure and the moments due to this pressure, the forces defined in Equations A-32 to A-37 can be obtained. These forces are related to added mass coefficients as shown below.

$$F_1 = M_{11};\ F_2 = M_{12};\ F_3 = M_{13};\ F_4 = M_{14};\ F_5 = M_{15};\ F_6 = M_{16}$$

Similarly, by specifying different sets of body accelerations, the remaining added mass coefficients can be determined. The sets of problems to be solved to determine the 21 added mass coefficients are given below.

Accelerations	Added Mass Coefficients
1. $\dot{v} = \dot{w} = \dot{p} = \dot{q} = \dot{r} = 0;\ \dot{u} = 1$	$M_{11}, M_{12}, M_{13}, M_{14}, M_{15}, M_{16}$
2. $\dot{u} = \dot{w} = \dot{p} = \dot{q} = \dot{r} = 0;\ \dot{v} = 1$	$M_{22}, M_{23}, M_{24}, M_{25}, M_{26}$
3. $\dot{u} = \dot{v} = \dot{p} = \dot{q} = \dot{r} = 0;\ \dot{w} = 1$	$M_{33}, M_{34}, M_{35}, M_{36}$
4. $\dot{u} = \dot{v} = \dot{w} = \dot{q} = \dot{r} = 0;\ \dot{p} = 1$	M_{44}, M_{45}, M_{46}
5. $\dot{u} = \dot{v} = \dot{w} = \dot{p} = \dot{r} = 0;\ \dot{q} = 1$	M_{55}, M_{56}
6. $\dot{u} = \dot{v} = \dot{w} = \dot{p} = \dot{q} = 0;\ \dot{r} = 1$	M_{66}

For solution of the above sets of problems, the normal accelerations are to be specified. They can be obtained as described below. If F $(x,y,z) = 0$ is the body surface equation, then the unit outward drawn normal is given by:

$$n = \frac{\text{grad } F}{|\text{grad } F|} \qquad \text{(A-53)}$$

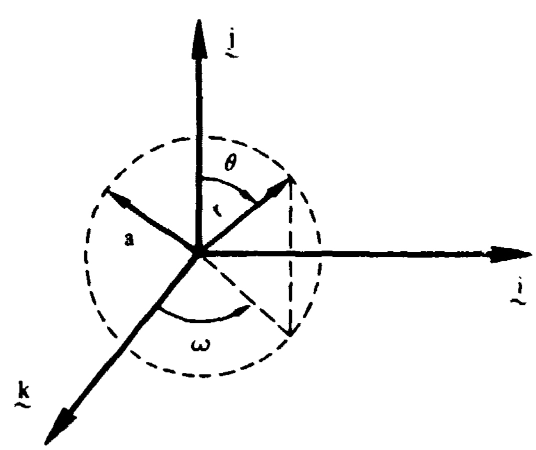
Let linear acceleration vector of the origin O relative to the stationary fluid at infinity be $\dot{\underset{\sim}{Q}}$ and let body angular acceleration be $\dot{\underset{\sim}{\omega}}$. If the position vector of a point on the body is $\underset{\sim}{r}$ and the outward normal is $\underset{\sim}{n}$, then the normal acceleration at the body surface is:

$$a_{nS} = (\ddot{\underset{\sim}{Q}} + \dot{\underset{\sim}{\omega}} \times \underset{\sim}{r}) \cdot \underset{\sim}{n} \qquad \text{(A-54)}$$

Example 1: Sphere Problem for Validation of the Formulation

For application of the above formulation, consider a sphere of radius, a,

$$F\ (r,\ \theta,\ \omega) = r - a = 0$$



The unit vector is given by:

$$\underset{\sim}{n} = \frac{\nabla F}{|\nabla F|} = \underset{\sim}{i} \sin\theta \cos\omega + \underset{\sim}{j} \sin\theta \sin\omega + \underset{\sim}{k} \cos\theta \qquad \text{(A-55)}$$

The normal acceleration of the body is given by:

$$a_{nS} = (\dot{\underset{\sim}{Q}} + \dot{\underset{\sim}{\omega}} \times \underset{\sim}{r}) \cdot \underset{\sim}{n} \tag{A-56}$$

	Acceleration	Normal acceleration
1.	$\dot{v} = \dot{w} = \dot{p} = \dot{q} = \dot{r} = 0,\ \dot{u} = 1$	$a_{nS_1} = \sin\theta \cos\omega$
2.	$\dot{u} = \dot{w} = \dot{p} = \dot{q} = \dot{r} = 0,\ \dot{v} = 1$	$a_{nS_2} = \sin\theta \sin\omega$
3.	$\dot{u} = \dot{v} = \dot{p} - \dot{q} = \dot{r} = 0,\ \dot{w} = 1$	$a_{nS_3} = \cos\theta$
4.	$\dot{u} = \dot{v} = \dot{w} - \dot{q} = \dot{r} = 0,\ \dot{p} = 1$	$a_{nS_4} = 0$
5.	$\dot{u} = \dot{v} = \dot{w} = \dot{p} = \dot{r} = 0,\ \dot{q} = 1$	$a_{nS_5} = 0$
6.	$\dot{u} = \dot{v} = \dot{w} = \dot{p} = \dot{q} = 0,\ \dot{r} = 1$	$a_{nS_6} = 0$

From the boundary condition,

$$\left.\frac{\partial p}{\partial n}\right|_{r=a} = -\rho\, a_{nS}$$

$$\left.\begin{aligned}
\frac{\partial p_1}{\partial n} &= -\rho \sin\theta \cos\omega \\
\frac{\partial p_2}{\partial n} &= -\rho \sin\theta \sin\omega \\
\frac{\partial p_3}{\partial n} &= -\rho \cos\theta \\
\frac{\partial p_4}{\partial n} &= 0 \\
\frac{\partial p_5}{\partial n} &= 0 \\
\frac{\partial p_6}{\partial n} &= 0
\end{aligned}\right\} \tag{A-57}$$

The governing equation (Laplace's equation) in spherical coordinates is given by:

$$\sin\theta \frac{\partial}{\partial r}\left(r^2 \frac{\partial p}{\partial r}\right) + \frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial p}{\partial\theta}\right) + \frac{1}{\sin} \frac{\partial^2 p}{\partial\omega^2} = 0 \tag{A-58}$$

Three solutions for this equation can be written as:

$$\left.\begin{aligned} p_1 &= \frac{1}{2} k \frac{a^3}{r^2} \sin\theta \cos\omega \\ p_2 &= \frac{1}{2} k \frac{a^3}{r^2} \sin\theta \sin\omega \\ p_3 &= \frac{1}{2} k \frac{a^3}{r^2} \cos\theta \end{aligned}\right\} \tag{A-59}$$

where k is an arbitrary constant.

The validity of the above solutions can be verified by substituting these into the Laplace's equation.

The radial derivatives of these solutions are given by:

$$\left.\begin{aligned} \left.\frac{\partial p_1}{\partial n}\right|_{r=a} &= -k \sin\theta \cos\omega \\ \left.\frac{\partial p_2}{\partial n}\right|_{r=a} &= -k \sin\theta \sin\omega \\ \left.\frac{\partial p_3}{\partial n}\right|_{r=a} &= -k \cos\theta \end{aligned}\right\} \tag{A-60}$$

The comparison of Equations A-60 and A-57 gives:

$$k = \rho \tag{A-61}$$

Substituting Equation A-61 into Equation A-59 gives,

$$
\begin{aligned}
p_1 &= \frac{1}{2}\rho \text{ a sin } \theta \text{ cos } \omega \\
p_2 &= \frac{1}{2}\rho \text{ a sin } \theta \text{ sin } \omega \qquad \text{(A-62)} \\
p_3 &= \frac{1}{2}\rho \text{ a cos } \theta
\end{aligned}
$$

Integrate over the body surface,

$$F_1 = \int_0^{2\pi}\int_0^{\pi} - p_1 \sin\theta \cos\omega \, r^2 \sin\theta \, d\theta \, d\omega$$

$$F_2 = \int_0^{2\pi}\int_0^{\pi} - p_2 \sin\theta \sin\omega \, r^2 \sin\theta \, d\theta \, d\omega$$

$$F_3 = \int_0^{2\pi}\int_0^{\pi} - p_3 \cos\theta \, r^2 \sin\theta \, d\theta \, d\omega$$

By substituting A-62 into the above equations gives

$$F_1 = F_2 = F_3 = \frac{2}{3}\pi\rho a^3$$

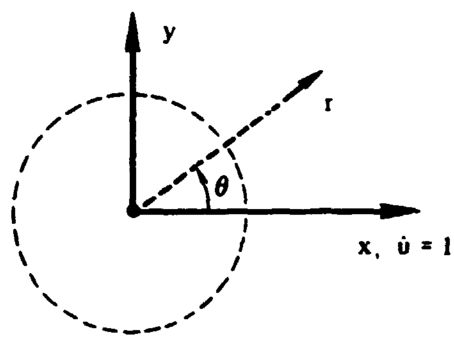
The above result agrees with the classical result, and there is only one non-zero coefficient.

Observations

The formulation presented here to determine the 21 added mass coefficients is valid and is applicable to arbitrary three-dimensional bodies. The formulation is appealing because (1) existing fluid dynamics programs can be used for calculations on digital computers and (2) the formulation can be extended to elastic bodies.

Formulation not only gives gross added mass but also added distribution.

Example 2: Two-Dimensional Circular Cylinder Accelerating in a Stationary Fluid



Laplace's equations in polar coordinates can be written as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2}=0$$

give a unit acceleration in x direction; then:

$$a_{nS} = \cos\theta$$

The boundary condition of the problem can be written as

$$\frac{\partial p}{\partial n} = \rho \cos\theta$$

The pressure function, p, can be written as

$$p = \frac{cR^2}{r}\cos\theta$$

This pressure function satisfies Laplace's equation and

$$\left.\frac{\partial p}{\partial n}\right|_{r=R} = \left.\frac{\partial p}{\partial r}\right|_{r=R} = -c\cos\theta = \rho\cos\theta$$

$$\Longrightarrow \quad \rho = -c$$

hence:

$$p = -\frac{\rho R^2}{r}\cos\theta$$

$$dF_x = \frac{\rho R^2}{R}\cos^2\theta\, R\, d\theta$$

$$F_x = \int_0^{2\pi} \rho\, R^2 \cos^2\theta\, d\theta = \rho\, \pi\, R^2 = k\, Ma$$

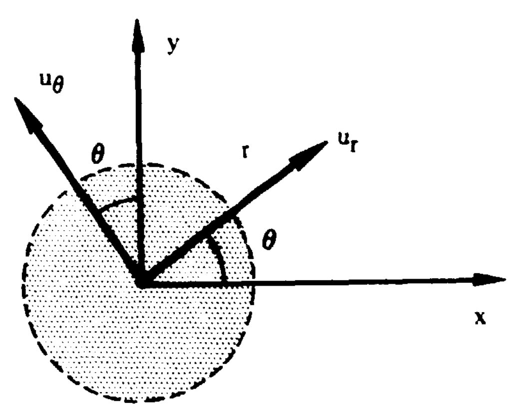
$$\text{where } k = 1;\ a = 1;\ M = \rho\, \pi\, R^2$$

Observations

This example just demonstrates the conventional added mass calculation when the body is accelerating in a fluid and the result agrees with the classical result.

Added mass distribution for this problem is also known.

Example 3: Stationary Two-Dimensional Circular Cylinder in a Fluid with a Steady Acceleration



Consider the following velocity field without the body:

$$u_x = U \text{ (constant)}$$

$$u_y = Vt$$

Convert the above velocity components in terms of polar coordinates.

$$u_r = U \cos\theta + Vt \sin\theta$$

$$u_\theta = - U \sin\theta + Vt \cos\theta$$

Flow is potential without the body since

$$\phi(r,\theta) = U r \cos\theta + Vt\, r \sin\theta$$

$$\frac{\partial\phi}{\partial r} = U \cos\theta + Vt \sin\theta = u_r$$

$$\frac{1}{r}\frac{\partial\phi}{\partial\theta} = - U \sin\theta + Vt \cos\theta = u_\theta$$

Seek an inviscid solution when the body is placed in this stream, then

$$\left.\begin{aligned} u_r &= \left(1 - \frac{R^2}{r^2}\right)(U \cos\theta + Vt \sin\theta) \\ u_\theta &= \left(1 + \frac{R^2}{r^2}\right)(- U \sin\theta + Vt \cos\theta) \end{aligned}\right\} \qquad \text{(A-63)}$$

The velocity field is chosen so that it satisfies boundary condition on the cylinder. The flow remains potential even with the body since a potential of the following form can be defined:

$$\phi(r,\theta) = \left(r + \frac{R^2}{r}\right)(U \cos\theta + Vt \sin\theta)$$

$$\frac{\partial\phi}{\partial r} = \left(1 - \frac{R^2}{r^2}\right)(U \cos\theta + Vt \sin\theta) = u_r$$

$$\frac{1}{r}\frac{\partial\phi}{\partial\theta} = \left(1 + \frac{R^2}{r^2}\right)(- U \sin\theta + Vt \cos\theta) = u_\theta$$

Unsteady Bernoulli's equation can be written as

$$\frac{\partial\phi}{\partial t} + \frac{p}{\rho} + \frac{q^2}{2} = \text{constant}$$

The pressure distribution to determine the added mass forces can be obtained from the following equation:

$$\frac{p}{\rho} + \frac{\partial\phi}{\partial t} = \text{constant}$$

$$\frac{p}{\rho} = k - \frac{\partial\phi}{\partial t} = -\left(r + \frac{R^2}{r}\right)V \sin\theta$$

$$p\Big|_{r=R} = -2\rho\ R\ V\ \sin\ \theta + k$$

$$dF_x = 2\ \rho\ R\ V\ \sin\ \theta\ \cos\ \theta\ R\ d\ \theta - k\ \cos\ \theta\ R\ d\ \theta$$

$$dF_y = 2\ \rho\ \ R\ V\ \sin^2\ \theta\ R\ d\ \theta - k\ \sin\ \theta\ R\ d\ \theta$$

$$F_x = 2\ \rho\ R^2\ V \int_0^{2\pi} \sin\ \theta\ \cos\ \theta\ d\ \theta = 0$$

$$F_y = 2\ \rho\ R^2\ V \int_0^{2\pi} \sin^2\ \theta\ d\ \theta = 2\ \rho\ \pi\ R^2\ V$$

Hence

$$F_x = 0$$

$$F_y = 2\ \rho\ \pi\ R^2\ V$$

Now compute the substantial accelerations without the body.

Without the body:

$$\underset{\sim}{Q} = \underset{\sim}{i}\ U + \underset{\sim}{j}\ Vt$$

$$\frac{DQ}{Dt} = \frac{\partial \underset{\sim}{Q}}{\partial t} + \underset{\sim}{Q} \cdot \text{grad}\ \underset{\sim}{Q} = \underset{\sim}{j}V$$

Hence:

$$F_y = \rho \pi R^2 (1 + k) \frac{D u_y}{Dt} = 2 \rho \pi R^2 V$$

$k = 1$ from Example 2

<u>Observations</u>

Flow is unsteady potential without the body.

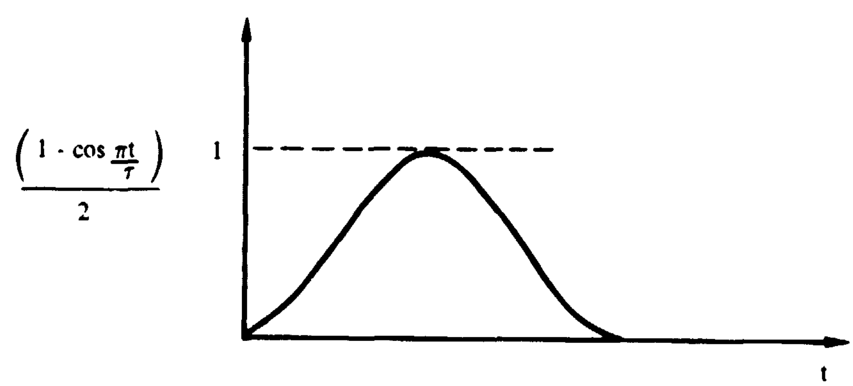
Unsteady acceleration is uniform.

Body is placed in this stream and the flow remained potential.

The acceleration-dependent aerodynamic force can be written as:

$$F_y = \underbrace{\rho \pi R^2}_{\substack{\text{Mass of the}\\ \text{fluid replaced}\\ \text{by the body}}} (\underbrace{1}_{\substack{\text{Pressure}\\ \text{gradient}\\ \text{portion}}} + \underbrace{k}_{\substack{\text{Conventional}\\ \text{added mass}\\ \text{term}}}) \underbrace{\left(\frac{D u_y}{Dt}\right)}_{\substack{\text{Substantial}\\ \text{acceleration}\\ \text{of the flow}\\ \text{without the}\\ \text{body}}}$$

<u>Example 4: Stationary Two-Dimensional Circular Cylinder in a Fluid with an Unsteady Acceleration</u>



Consider the following velocity field without the body:

$$u_x = U \text{ (constant)}$$

$$u_y = \frac{1}{2} \left(1 - \cos \frac{\pi t}{\tau}\right)$$

Define a velocity potential ϕ as:

$$\phi = Ux + \frac{1}{2}(1 - \cos\frac{\pi t}{\tau})\, y$$

$$\frac{\partial \phi}{\partial x} = U = u_x$$

$$\frac{\partial \phi}{\partial y} = \frac{1}{2}\left(1 - \cos\frac{\pi t}{\tau}\right) = u_y$$

Hence, flow is potential without the body. Convert the velocity components in terms of polar coordinates

$$u_r = U\cos\theta + \frac{1}{2}(1 - \cos\frac{\pi t}{\tau})\sin\theta$$

$$u_\theta = -U\sin\theta + \frac{1}{2}(1 - \cos\frac{\pi t}{\tau})\cos\theta$$

Place a circular cylinder in this stream and seek an inviscid solution; then:

$$u_r = \left(1 - \frac{R^2}{r^2}\right)\left[U\cos\theta + \frac{1}{2}\left(1 - \cos\frac{\pi t}{\tau}\right)\sin\theta\right]$$

$$u_\theta = \left(1 + \frac{R^2}{r^2}\right)\left[-U\sin\theta + \frac{1}{2}\left(1 - \cos\frac{\pi t}{\tau}\right)\cos\theta\right]$$

The velocity field is chosen so that it satisfies the inviscid boundary conditions on the cylinder. Define ϕ as:

$$\phi(r,\theta) = \left(r + \frac{R^2}{r}\right)\left[U\cos\theta + \frac{1}{2}\left(1 - \cos\frac{\pi t}{\tau}\right)\sin\theta\right]$$

$$\left.\begin{aligned} \frac{\partial \phi}{\partial r} &= u_r \\ \frac{1}{r}\frac{\partial \phi}{\partial \theta} &= u_\theta \end{aligned}\right\} \text{Flow remains potential}$$

$$\frac{\partial \phi}{\partial t} = r\left(1 + \frac{R^2}{r^2}\right)\frac{\pi}{2\tau}\sin\frac{\pi t}{\tau}\sin\theta$$

Pressure distribution to determine the added mass forces is

$$\left.\frac{p}{\rho}\right|_{r=R} = \frac{k}{\rho} - \frac{\partial \phi}{\partial t} = -2R\left\{\frac{\pi}{2\tau}\sin\frac{\pi t}{\tau}\right\}\sin\theta + k$$

$$\left. p\right|_R = -2\rho R\left\{\frac{\pi}{2\tau}\sin\frac{\pi t}{\tau}\right\}\sin\theta + k$$

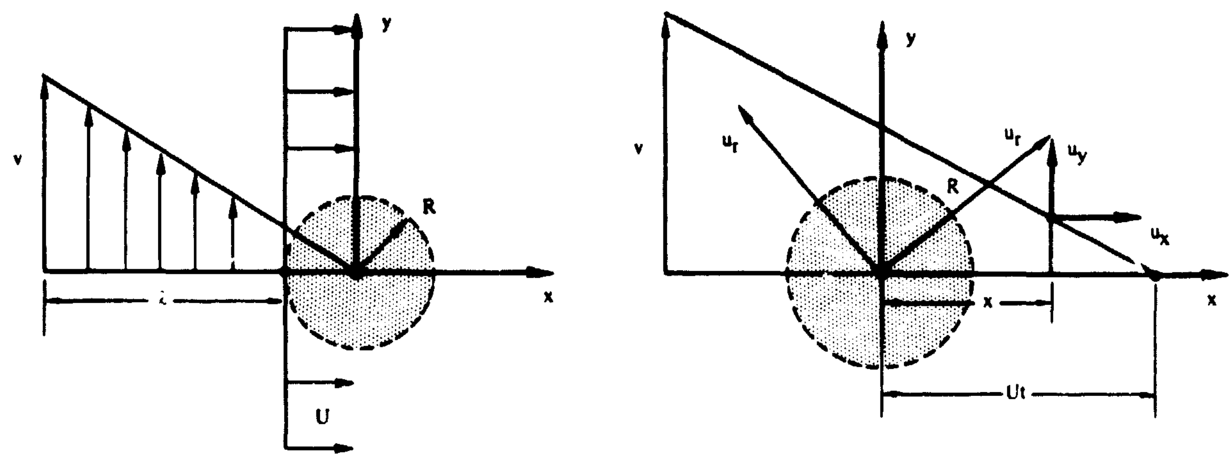
$$d F_y = \left[+2\rho R\left\{\frac{\pi}{2\tau}\sin\frac{\pi t}{\tau}\right\}\sin^2\theta - k\sin\theta\right] R\, d\theta$$

$$F_y = \pi R^2 \rho\, (1 + k)\frac{D u_y}{Dt};\; k = 1$$

Observations

Same relation holds good even for fluids with unsteady acceleration. This may not be true for nonuniform accelerations.

Example 5: Uniformly Accelerating Gust Front Penetrates a Two-Dimensional Circular Cylinder



At $t = 0$

$$u_x = U$$

$$u_y = \frac{V\,U\,t}{\ell} - \frac{Vx}{\ell}$$

Express velocity components in terms of polar coordinate.

$$u_r = U \cos\theta + \frac{V}{\ell}\,(Ut - r\cos\theta)\sin\theta$$

$$u_\theta = -\,U \sin\theta + \frac{V}{\ell}\,(Ut - r\cos\theta)\cos\theta$$

Seek an inviscid solution after the body is placed into the stream. Let:

$$u_r = U\left(1 - \frac{R^2}{r^2}\right)\left(\cos\theta + \frac{Vt}{\ell}\sin\theta - \frac{Vr}{U\ell}\,\frac{\sin 2\theta}{2}\right)$$

$U_r = 0$ when $r = R \Longrightarrow$ satisfies inviscid bounc·ᴗy condition on the cylinder.

Continuity equation: $\operatorname{diV} \underset{\sim}{Q} = 0$

or

$$\frac{\partial}{\partial r}(r\, u_r) + \frac{\partial\, u_\theta}{\partial \theta} = 0$$

$$-\frac{\partial\, u_\theta}{\partial \theta} = \frac{\partial}{\partial r}\,(r\, u_r)$$

$$-\frac{\partial\, u_\theta}{\partial \theta} = U\left(1 + \frac{R^2}{r^2}\right)\left(\cos\theta + \frac{Vt}{\ell}\sin\theta - \frac{Vr}{U\ell}\cos\theta \quad \sin\theta\right)$$

$$+ U_r\left(1 - \frac{R^2}{r^2}\right)\left(-\frac{V}{U\ell}\cos\theta\sin\theta\right)$$

$$-u_\theta = U\left(1 + \frac{R^2}{r^2}\right)\left(\sin\theta - \frac{Vt}{\ell}\cos\theta + \frac{Vr}{2\ell U}\cos^2\theta\right)$$

$$+ Ur\left(1 - \frac{R^2}{r^2}\right)\left(\frac{V\cos^2\epsilon}{2U\ell}\right)$$

Momentum equation: $\frac{D\underset{\sim}{Q}}{Dt} = -\frac{\text{grad } p}{\rho}$

$$\frac{\partial \underset{\sim}{Q}}{\partial t} + \underset{\sim}{Q} \cdot \text{grad } \underset{\sim}{Q} = \frac{\partial \underset{\sim}{Q}}{\partial t} + \text{grad}\left(\frac{Q^2}{2}\right) - \underset{\sim}{Q} \times \text{curl } \underset{\sim}{Q}$$

$$\underset{\sim}{Q} = \underset{\sim}{\rho_r}\, u_r + \underset{\sim}{\rho_\theta}\, u_\theta;\ \frac{Q^2}{2} = \frac{u^2{}_r + u^2{}_\theta}{2}$$

$$\text{grad} \equiv \underset{\sim}{\rho_r}\frac{\partial}{\partial r} + \underset{\sim}{\rho_\theta}\frac{1}{r}\frac{\partial}{\partial \theta}$$

$$\text{Curl } \underset{\sim}{Q} = \frac{1}{r}\begin{vmatrix} \underset{\sim}{\rho_r} & r\underset{\sim}{\rho_\theta} & \underset{\sim}{\rho_z} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ u_r & -u_\theta & 0 \end{vmatrix} = \frac{\underset{\sim}{\rho_z}}{r}\left[\frac{\partial(r u_\theta)}{\partial r} - \frac{\partial\, u_r}{\partial \theta}\right]$$

$$= \underset{\sim}{\rho_z}\left[\frac{u_\theta}{r} + \frac{\partial u_\theta}{\partial r} - \frac{1}{r}\frac{\partial u_r}{\partial \theta}\right]$$

$$\underset{\sim}{Q} \times \text{curl } Q = \begin{vmatrix} \underset{\sim}{\rho_r} & \underset{\sim}{\rho_\theta} & \underset{\sim}{\rho_z} \\ u_r & u_\theta & 0 \\ 0 & 0 & a_{33} \end{vmatrix}$$

$$= \underset{\sim}{\rho_r}\, u_\theta\, a_{33} - \underset{\sim}{\rho_\theta}\, u_r\, a_{33}$$

<u>Tangential momentum</u>:

$$\frac{\partial u_\theta}{\partial t} + \frac{1}{r} u_r \frac{\partial u_r}{\partial \theta} + \frac{1}{r} u_\theta \frac{\partial u_\theta}{\partial \theta} - \frac{u_\theta u_r}{r}$$

$$- u_r \frac{\partial u_\theta}{\partial r} + \frac{u_r}{r} \frac{\partial u_r}{\partial \theta} = - \frac{1}{r\rho} \frac{\partial p}{\partial \theta}$$

$$\left[- \frac{1}{\rho r} \frac{\partial p}{\partial \theta}\right]_{r=R} = \left[\frac{\partial u_\theta}{\partial t} + \frac{1}{r} u_\theta \frac{\partial u_\theta}{\partial \theta}\right]_{r=R}$$

$$\left.\frac{\partial u_\theta}{\partial t}\right|_{r=R} = \frac{2\,U\,V}{\ell} \cos\theta$$

$$\left. u_\theta \right|_{r=R} = - 2\, u\, (\sin\theta + a \cos\theta + b \cos^2\theta)$$

$$\left.\frac{\partial u_\theta}{\partial \theta}\right|_{r=R} = - 2\, U\, (\cos\theta - a \sin\theta - 2\, b \cos\theta \sin\theta)$$

$$- a = \frac{Vt}{\ell}; \quad b = \frac{VR}{2\,U\,\ell}$$

$$- \frac{1}{\rho} \left.\frac{\partial p}{\partial \theta}\right|_{r=R} = \frac{2\,UVR}{\ell} \cos\theta + 4\,U^2 (\cos\theta \sin\theta$$

$$- a \sin^2\theta - 2\, b \cos\theta \sin^2\theta + a \cos^2\theta - a^2 \cos\theta \sin\theta$$

$$- 2\, ab \cos^2\theta \sin\theta + b \cos^3\theta - ab \sin\theta \cos^2\theta$$

$$- 2\, b^2 \cos^3\theta \sin\theta)$$

$$-\frac{1}{\rho}\ p\Big|_{r=r} = \frac{2\ UVR}{\ell}\sin\theta + 4\ U^2\left(-\frac{\cos^2\theta}{2} + \frac{a}{2}\sin\theta\cos\theta\right.$$

$$-\frac{2b\sin^3\theta}{3} + \frac{a\sin\theta\cos\theta}{2} + \frac{a^2\cos^2\theta}{2}$$

$$+\frac{2ab}{3}\cos^3\theta + b\sin\theta - \frac{b\sin^3\theta}{3} + \frac{ab\cos^3\theta}{3}$$

$$\left. + \frac{2b^2\cos^4\theta}{4}\right)$$

$$-\frac{1}{\rho}\ p\Big|_R = \frac{2\ UVR}{\ell}\sin\theta + 4\ U^2\left[\frac{\cos^2\theta}{2}(a^2-1) + a\sin\theta\cos\theta\right.$$

$$\left. - b\sin^3\theta + ab\cos^3\theta + b\sin\theta + \frac{b^2}{2}\cos^4\theta\right]$$

$$F_y = -\int_0^{2\pi} p\sin\theta\ R\ d\theta$$

$$F_y = \frac{2\ UVR^2\rho}{\ell}\pi + 4\ U^2\rho\ R\left[\frac{(a^2-1)}{2}\left(-\frac{\cos^3\theta}{3}\right)\right.$$

$$+ a\frac{\sin^3\theta}{3} - \frac{b\ 3\ \theta}{8} + ab\left(-\frac{\cos^4\theta}{4}\right) + \frac{b\ \theta}{2}$$

$$\left. + \frac{b^2}{2}\left(-\frac{\cos^5\theta}{6}\right)\right]_0^{2\pi}$$

$$F_y = \frac{2\ UVR^2}{\ell}\rho\ \pi + 4\ U^2\rho\ R\frac{b}{8}2\ \pi$$

$$= \frac{2\ UVR^2\rho\ \pi}{\ell} + U^2\rho\ R\frac{VR}{2\ U\ \ell}\pi$$

$$= \frac{2\ UVR^2\rho\ \pi}{\ell} + \frac{UVR^2\rho\ \pi}{2\ell}$$

$$F_x = -\int_0^{2\pi} P \cos\theta \, R \, d\theta = \left[\frac{\rho 4 U^2 ab R 3 \theta}{8}\right]_0^{2\pi}$$

$$= 3 U^2 \pi R \rho ab$$

$$= -3 U^2 \pi R \frac{Vt}{\ell} \rho \frac{VR}{2U\ell}$$

$$F_x = -\frac{3}{2} \pi R^2 \rho \frac{V^2}{\ell^2} Ut$$

$$F_y = \frac{5}{2} \rho \pi R^2 \frac{V}{\ell} U$$

$$F_x = -\frac{3}{2} \rho \pi R^2 \frac{V^2}{\ell^2} Ut$$

Substantial acceleration without the body:

$$\underset{\sim}{Q} = \underset{\sim}{i} U + \underset{\sim}{j} \frac{V}{\ell} (Ut - x)$$

$$\frac{D\underset{\sim}{Q}}{Dt} = \frac{\partial \underset{\sim}{Q}}{\partial t} + \operatorname{grad}\left(\frac{Q^2}{2}\right) - \underset{\sim}{Q} \times \operatorname{curl} \underset{\sim}{Q}$$

$$\frac{\partial \underset{\sim}{Q}}{\partial t} = \underset{\sim}{j} \frac{V}{\ell} U$$

$$\operatorname{grad}\left(\frac{Q^2}{2}\right) = \operatorname{grad}\left\{\frac{U^2}{2} + (Ut - x)^2 \frac{V^2}{2\ell^2}\right\}$$

$$= -\frac{2 (Ut - x) V^2}{2\ell^2} \underset{\sim}{i}$$

$$\operatorname{Curl} Q = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ U & \frac{V}{\ell}(Ut-x) & 0 \end{vmatrix} = -\underset{\sim}{k} \frac{V}{\ell}$$

$$\underset{\sim}{Q} \times \text{curl}\, \underset{\sim}{Q} \quad \begin{vmatrix} \underset{\sim}{i} & \underset{\sim}{j} & \underset{\sim}{k} \\ U & \frac{V}{\ell}(Ut-x) & 0 \\ 0 & 0 & -\frac{V}{\ell} \end{vmatrix} = -\underset{\sim}{i}\frac{V^2}{\ell^2}(Ut-x) + \underset{\sim}{j}\frac{UV}{\ell}$$

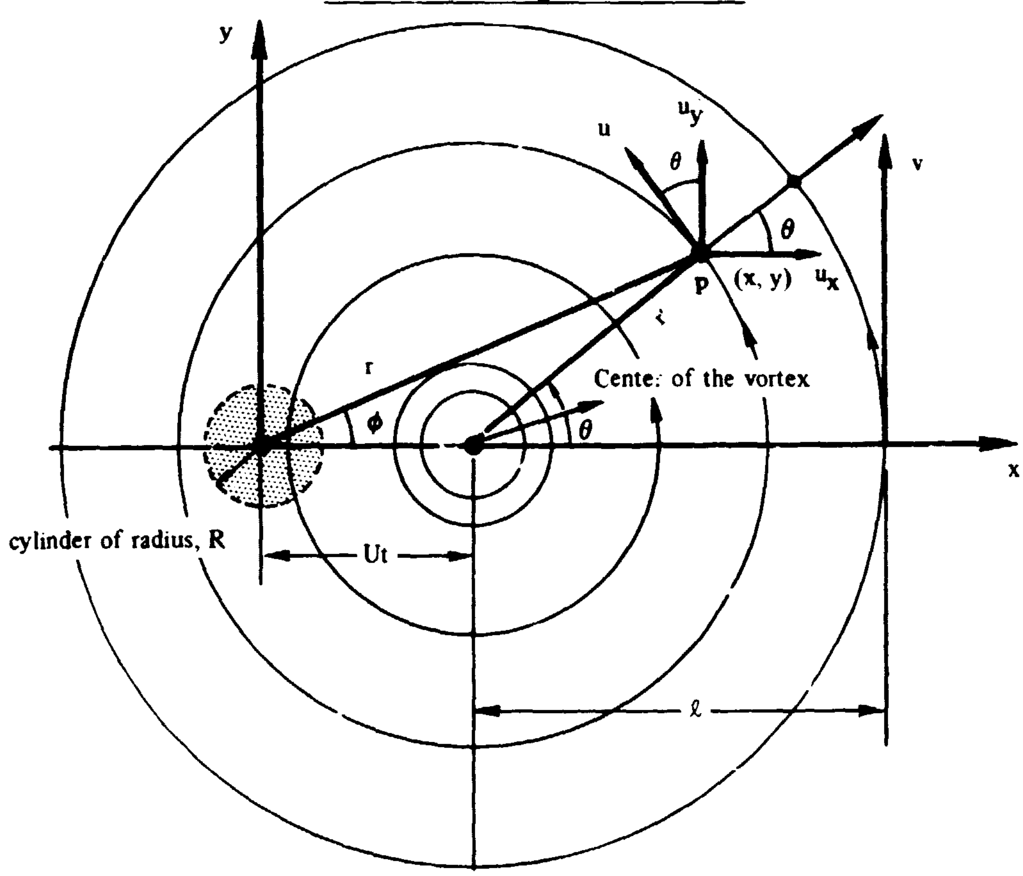
$$\frac{D\underset{\sim}{Q}}{Dt} = \underset{\sim}{j}\frac{UV}{\ell} - \underset{\sim}{i}(Ut-x)\frac{V^2}{\ell^2}$$

$$+ \underset{\sim}{i}\frac{V^2}{\ell^2}(Ut-x) - \underset{\sim}{j}\frac{UV}{\ell} = 0$$

<u>Observations</u>

Substantial accelerations of the gust front are zero. Even then, the body experiences non-zero forces.

<u>Example 6: Stationary Two-Dimensional Circular Cylinder in a Convecting Vortex Core</u>



Coordinates of point p are (x, y). Center of the coordinate system is at the center of the cylinder. At t = 0, the center of the vortex core coincides with center of the cylinder.

ℓ = radius of the vortex core

V = velocity at the edge of the vortex core

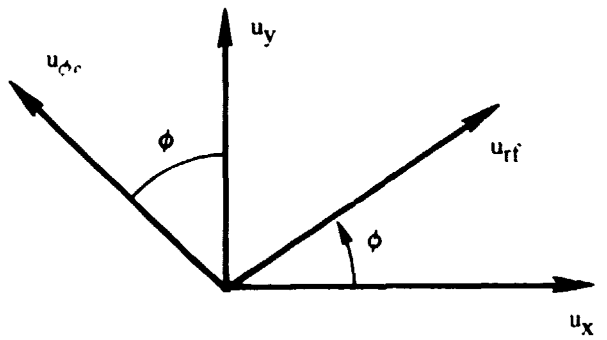
U = velocity of translating vortex

$$u = \frac{V\,r'}{\ell} = \frac{V\sqrt{(x - Ut)^2 + y^2}}{\ell}$$

$$\cos\theta = \frac{x - Ut}{\sqrt{(x - Ut)^2 + y^2}};\ \sin\theta = \frac{y}{\sqrt{(x - Ut)^2 + y^2}}$$

$$u_y = u\cos\theta = \frac{V}{\ell}(x - Ut)$$

$$u_x = U - u\sin\theta = U - \frac{Vy}{\ell}$$



$$u_{rf} = u_x\cos\phi + u_y\sin\phi$$

$$u_{\phi f} = -u_x\sin\phi + u_y\cos\phi$$

$$u_{rf} = \left(U - \frac{Vy}{\ell}\right)\cos\phi + \frac{V}{\ell}(x - Ut)\sin\phi$$

$$u_{\phi f} = -\left(U - \frac{Vy}{\ell}\right)\sin\phi + \frac{V}{\ell}(x - Ut)\cos\phi$$

$$y = r\sin\phi\ ;\ x = r\cos\phi$$

$$u_{rf} = \left(U - \frac{V\,r\sin\phi}{\ell}\right)\cos\phi + \frac{V}{\ell}(r\cos\phi - Ut)\sin\phi$$

$$= U\cos\phi - \frac{VUt}{\ell}\sin\phi$$

$$\boxed{u_{rf} = U\left(\cos\phi - \frac{Vt}{\ell}\sin\phi\right)} \tag{A}$$

$$u_{\phi f} = -\left(U - \frac{Vr\sin\phi}{\ell}\right)\sin\phi + \frac{V}{\ell}(r\cos\phi - Ut)\cos\phi$$

$$= -U\sin\phi + \frac{Vr}{\ell}\sin^2\phi + \frac{Vr}{\ell}\cos^2\phi - \frac{VUt}{\ell}\cos\phi$$

$$u_{\phi f} = -U\sin\phi + \frac{Vr}{\ell} - \frac{VUt}{\ell}\cos\phi$$

$$\boxed{u_{\phi f} = -U\left(\sin\phi + \frac{Vt}{\ell}\cos\phi\right) + \frac{Vr}{\ell}} \tag{B}$$

Velocity u_{rf} is the radial velocity in the vortex core far from the cylinder. This velocity will be modified by the presence of the cylinder in the vicinity of the cylinder so that the radial velocity on the surface of the cylinder is zero since the fluid cannot penetrate the cylinder. Hence, u_r in the vicinity of the cylinder can be written as

$$u_r = U\left(1 - \frac{R^2}{r^2}\right)\left(\cos\phi - \frac{Vt}{\ell}\sin\phi\right) \tag{C}$$

$$u_r = 0 \text{ at } r = R;\ u_r = u_{rf} \text{ at } R = 0.$$

Now, u_θ has to satisfy the continuity equation.

Continuity equation: $\operatorname{div} \underset{\sim}{Q} = 0 = \frac{\partial}{\partial r}(r\,u_r) + \frac{\partial u_\theta}{\partial\theta} = 0$

$$\frac{\partial u_\theta}{\partial\theta} = -\frac{\partial}{\partial r}(r\,u_r) = -U\left(1 + \frac{R^2}{r^2}\right)\left(\cos\phi - \frac{Vt}{\ell}\sin\phi\right)$$

$$u_\phi = -U\left(1 + \frac{R^2}{r^2}\right)\left(\sin\phi + \frac{Vt}{\ell}\cos\phi\right) + f(r)$$

$$u_\phi\Big|_{R=0} = -U\left(\sin\phi + \frac{Vt\cos\phi}{\ell}\right) + f(r)$$

Compare this equation with (B); then

$$f(r) = \frac{Vr}{\ell}$$

$$u_\phi = - U \left(1 + \frac{R^2}{r^2}\right)\left(\sin \phi + \frac{Vt}{\ell} \cos \phi\right) + \frac{Vr}{\ell} \qquad \text{(D)}$$

Momentum equation: $\dfrac{D\underset{\sim}{Q}}{Dt} = - \dfrac{\text{grad } p}{\rho}$

or

$$\frac{\partial \underset{\sim}{Q}}{\partial t} + \text{grad } \frac{Q^2}{2} - \underset{\sim}{Q} \times \text{curl } \underset{\sim}{Q} = - \frac{\text{grad } p}{\rho}$$

$$\text{grad} = \underset{\sim}{\rho_r} \frac{\partial}{\partial r} + \underset{\sim}{\rho_\phi} \frac{1}{r} \frac{\partial}{\partial \phi}$$

$$\underset{\sim}{Q} = \underset{\sim}{\rho_r}\, u_r + \underset{\sim}{\rho_\phi}\, u_\phi$$

$$\text{Curl } \underset{\sim}{Q} = \underset{\sim}{\rho_z} \left[\frac{1}{r} \frac{\partial}{\partial r} (r\, u_\phi) - \frac{\partial}{\partial \phi} (u_r)\right]$$

$$\frac{Q^2}{2} = \frac{u_r^{\,2} + u_\phi^{\,2}}{2}$$

$$\underset{\sim}{Q} \times \text{curl } \underset{\sim}{Q} = \begin{vmatrix} \underset{\sim}{\rho_r} & \underset{\sim}{\rho_\phi} & \underset{\sim}{\rho_z} \\ u_r & u_\phi & 0 \\ 0 & 0 & a_{33} \end{vmatrix}$$

$$= \underset{\sim}{\rho_r}\, u_\phi \left[\frac{1}{r} \frac{\partial}{\partial r} (r\, u_\phi) - \frac{\partial}{\partial \phi} (u_r)\right]$$

$$- \underset{\sim}{\rho_\phi}\, u_r \left[\frac{1}{r} \frac{\partial}{\partial r} (r\, u_\phi) - \frac{\partial}{\partial \phi} (u_r)\right]$$

Momentum equation can now be written as

$$\underset{\sim}{\rho_r} \left[\frac{\partial u_r}{\partial t} + \frac{1}{2} \frac{\partial}{\partial r} (u_r^{\,2} + u_\phi^{\,2}) - \frac{u_\phi}{r} \frac{\partial}{\partial r} (r\, u_\phi) + u_\phi \frac{\partial u_r}{\partial \phi}\right]$$

$$+ \underset{\sim}{\rho_\phi} \left[\frac{\partial u_\phi}{\partial t} + \frac{1}{2r} \frac{\partial}{\partial \phi} (u_r^{\,2} + u_\phi^{\,2}) + \frac{u_r}{r} \frac{\partial}{\partial r} (r\, u_\phi) - u_r \frac{\partial u_r}{\partial \phi}\right]$$

$$= - \underset{\sim}{\rho_r} \frac{1}{\rho} \frac{\partial p}{\partial r} - \underset{\sim}{\rho_\phi} \frac{1}{\rho r} \frac{\partial p}{\partial \theta}$$

Radial momentum:

$$\frac{\partial u_r}{\partial t} + \frac{1}{2}\frac{\partial}{\partial r}\left(u_r^{\,2} + u_\phi^{\,2}\right) - \frac{u_\phi}{r}\frac{\partial}{\partial r}\left(r\, u_\phi\right) + u_\phi \frac{\partial u_r}{\partial \phi}$$

$$= -\frac{1}{\rho}\frac{\partial p}{\partial r}$$

or

$$-\frac{UV}{\ell}\left(1 - \frac{R^2}{r^2}\right)\sin\phi + u_r \frac{\partial u_r}{\partial r} + u_\phi \frac{\partial u_\phi}{\partial r}$$

$$-\frac{u_\phi^{\,2}}{r} - u_\phi \frac{\partial u_\phi}{\partial r} + u_\phi \frac{\partial u_r}{\partial \phi} = -\frac{1}{\rho}\frac{\partial p}{\partial r}$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial r} = -\frac{UV}{\ell}\left(1 - \frac{R^2}{r^2}\right)\sin\phi + \left(\cos\phi - \frac{Vt}{\ell}\sin\phi\right)^2 U^2\left(1 - \frac{R^2}{r^2}\right)\left(\frac{2R^2}{r^3}\right)$$

$$-\frac{U^2}{r}\left(1 + \frac{R^2}{r^2}\right)^2\left(\sin\phi + \frac{Vt}{\ell}\cos\phi\right)^2 - \frac{V^2 r^2}{\ell^2 r}$$

$$+\frac{2V}{\ell}\, U\left(1 + \frac{R^2}{r^2}\right)\left(\sin\phi + \frac{Vt}{\ell}\cos\phi\right)$$

$$+U^2\left(1 - \frac{R^2}{r^2}\right)\left(1 + \frac{R^2}{r^2}\right)\left(\sin\phi + \frac{Vt}{\ell}\cos\phi\right)^2$$

$$-\frac{Vr}{\ell}\, U\left(1 - \frac{R^2}{r^2}\right)\left(\cos\phi - \frac{Vt}{\ell}\sin\alpha\right)$$

Radial pressure gradient equation is not required to compute the forces on the cylinder.

Tangential momentum:

$$\frac{\partial u_\phi}{\partial t} + \frac{u_r}{r}\frac{\partial u_r}{\partial \phi} + \frac{u_\phi}{r}\frac{\partial u_\phi}{\partial \phi} + \frac{u_r\, u_\phi}{r} + u_r \frac{\partial u_\phi}{\partial r}$$

$$-u_r \frac{\partial u_r}{\partial \phi} = -\frac{1}{\rho r}\frac{\partial p}{\partial \theta}$$

$$- \frac{1}{\rho r} \frac{\partial p}{\partial \theta} = \frac{\partial u_\phi}{\partial t} + \frac{u_\phi}{r} \frac{\partial u_\phi}{\partial \phi} + \overset{3}{\frac{u_r}{r} \frac{\partial u_r}{\partial \phi}} + \overset{4}{\frac{u_r u_\phi}{r}} + \overset{5}{u_r \frac{\partial u_\phi}{\partial r}} - \overset{6}{u_r \frac{\partial u_r}{\partial \phi}}$$

By observing the form of u_r

$$u_r = \left(1 - \frac{R^2}{r^2}\right)\left(\cos \phi - \frac{Vt}{\ell} \sin \phi\right),$$

one can conclude that terms 3, 4, 5, 6 do not contribute to the pressure on the cylinder.

$$- \frac{1}{\rho r} \frac{\partial p}{\partial \phi}\Big|_{r=R} = \left[\frac{\partial u_\phi}{\partial t} + \frac{u_\phi}{r} \frac{\partial u_\phi}{\partial \phi}\right]_{r=R}$$

$$u_\phi = - U \left(1 + \frac{R^2}{r^2}\right)\left(\sin \phi + \frac{Vt}{\ell} \cos \phi\right) + \frac{Vr}{\ell}$$

$$\frac{\partial u_\phi}{\partial t}\Big|_{r=R} = - U \left(1 + \frac{R^2}{r^2}\right) \frac{V}{\ell} \cos \phi\Big|_{r=R}$$

$$\frac{\partial u_\phi}{\partial t}\Big|_{r=1} = - \frac{2\ UV}{\ell} \cos \phi$$

$$u_\phi\Big|_R = - 2\ U \left[\left(\sin \phi + \frac{Vt}{\ell} \cos \phi\right) - \frac{VR}{2\ell U}\right]$$

$$\frac{\partial u_\phi}{\partial \phi}\Big|_R = - 2\ U \left(\cos \phi - \frac{Vt}{\ell} \sin \phi\right)$$

$$- \frac{\partial p}{\partial \phi}\Big|_R = \rho \Big[- \frac{2\ UV\ R}{\ell} \cos \phi + 4\ U^2 \Big(\sin \phi \cos \phi - a \sin^2 \phi$$

$$+ a \cos^2 \phi - a^2 \cos \phi \sin \phi - b \cos \phi + ab \sin \phi\Big)\Big]$$

where

$$a = \frac{Vt}{\ell}\ ;\ \ b = \frac{VR}{2\ell U}$$

$$- p\Big|_R = \rho \left[- \frac{2\,UVR}{\ell} \sin\phi + 4\,U^2 \left\{ - \frac{\cos^2\phi}{2} (1 - a^2) \right.\right.$$

$$+ \frac{a \sin\phi \cos\phi}{2} + \frac{a \sin\phi \cos\phi}{2}$$

$$\left.\left. - b \sin\phi - ab \cos\phi \right\} \right]$$

$$F_x = - \int_0^{2\pi} p \cos\phi\, R\, d\phi = - \rho\, \pi\, ab\, R = \frac{-\rho\, V^2\, t\, R^2}{2\ell^2 U} \pi \times 4\,U^2$$

$$F_x = - 2\,\rho\,\pi\, R^2\, Ut\, \frac{V^2}{\ell^2}$$

$$F_y = - \int_0^{2\pi} p \sin\phi\, R\, d\theta = - \frac{\rho\, R\, 2\,UVR}{\ell}\, \pi$$

$$- 4\,U^2\, b\, \rho\, R\, \pi \qquad - \frac{4\,U^2\, \rho\, R\, \pi\, V\, R}{2\ell U}$$

$$F_y = - \frac{2\,\rho\,\pi\, R^2\, UV}{\ell} - \frac{2\,\rho\,\pi\, R^2\, U\, V}{\ell} = - \frac{4\,\rho\,\pi\, R^2\, U\, V}{\ell}$$

$$F_x = - 2\,\rho\,\pi\, R^2\, Ut\, \frac{V^2}{\ell^2}$$

$$F_y = - 4\,\rho\,\pi\, R^2\, \frac{UV}{\ell}$$

Substantial acceleration without body

$$\frac{D\underset{\sim}{Q}}{Dt} = \frac{\partial \underset{\sim}{Q}}{\partial t} + \text{grad}\left(\frac{Q^2}{2}\right) - \underset{\sim}{Q} \times \text{curl}\, \underset{\sim}{Q}$$

$$\underset{\sim}{Q} = \underset{\sim}{i} \left(U - \frac{Vy}{\ell}\right) + \underset{\sim}{j}\, \frac{V}{\ell} (x - Ut)$$

$$\frac{\partial \underset{\sim}{Q}}{\partial t} = - \underset{\sim}{j}\, \frac{VU}{\ell}$$

$$\frac{Q^2}{2} = \frac{1}{2}\left(U - \frac{Vy}{\ell}\right)^2 + \frac{1}{2}\,\frac{V^2}{\ell^2}\,(x - Ut)^2$$

$$\text{grad}\left(\frac{Q^2}{2}\right) = \underset{\sim}{i}\,\frac{V^2}{\ell^2}\,(x - Ut) + \underset{\sim}{j}\left(U - \frac{Vy}{\ell}\right)\left(-\frac{V}{\ell}\right)$$

$$\text{Curl}\,\underset{\sim}{Q} = \begin{vmatrix} \underset{\sim}{i} & \underset{\sim}{j} & \underset{\sim}{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ U - \frac{Vy}{\ell} & \frac{V}{\ell}(x - Ut) & 0 \end{vmatrix} = \underset{\sim}{k}\left(\frac{V}{\ell} + \frac{V}{\ell}\right) = \frac{2\,V\,\underset{\sim}{k}}{\ell}$$

$$\underset{\sim}{Q} \times \text{curl}\,\underset{\sim}{Q} = \begin{vmatrix} \underset{\sim}{i} & \underset{\sim}{j} & \underset{\sim}{k} \\ U - \frac{Vy}{\ell} & \frac{V}{\ell}(x - Ut) & 0 \\ 0 & 0 & \frac{2V}{\ell} \end{vmatrix} = \underset{\sim}{i}\,\frac{2\,V^2}{\ell^2}\,(x - Ut) - \underset{\sim}{j}\,\frac{2V}{\ell}\left(U - \frac{Vy}{\ell}\right)$$

$$\frac{D\,U_x}{Dt} = \frac{V^2}{\ell^2}\,(x - Ut) - \frac{2\,V^2}{\ell^2}\,(x - Ut) = -\frac{V^2}{\ell^2}\,(x - Ut)$$

$$\frac{D\,U_y}{Dt} = y\,\frac{V^2}{\ell^2} - \frac{2\,V^2}{\ell^2}\,y = -\frac{V^2}{\ell^2}\,y$$

The right-hand side expressions of Equations A-32 to A-37 represent the fluid dynamic forces experienced by the body when it is accelerating in an incompressible inviscid fluid that is otherwise at rest. These expressions contain 21 independent coefficients called added mass coefficients (also called virtual or apparent). In the case of a body with mutually orthogonal planes of symmetry, the number of coefficients will be reduced as follows: one plane of symmetry, 12 coefficients; two planes of symmetry, eight coefficients; three planes of symmetry, six coefficients; and cyclic symmetry, one coefficient. If a body is kept stationary in an unsteady incompressible potential flow, then the body experiences unsteady forces. Part of these body forces are due to the pressure gradient that is required to be present in fluid to accelerate the flow. The remainder of the body forces accounts for the resistance resulting from the acceleration of the fluid particles induced by the body, as would be the case if the body were accelerated through an inviscid fluid at rest. If the fluid flow problem is solved directly to determine the pressure distribution and the resulting body forces, then this distinction between the pressure gradient forces and added mass force would be unnecessary. In the literature, this distinction is usually made since the added mass force can be expressed as

$$\text{Force} = k\, M\, a$$

where

k = added mass coefficient

M = mass of the fluid displaced by the body

a = acceleration of the ambient flow

The evaluation of this coefficient, k, is demonstrated in Examples 1 and 2. If all particles of the fluid are subject to the same substantial acceleration, then the total force experienced by the body can be expressed as

$$\text{Force} = (1 + k)\, M\, a$$

This fact is demonstrated in Examples 3 and 4 for steady and unsteady accelerations. In Example 5, a ramp gust front propagating with constant velocity U is considered. The substantial acceleration components of this gust front are uniform and zero. When this gust front passes over a body, then the body experiences unsteady forces that are unrelated to added mass coefficients and substantial accelerations (uniform and zero in the present example) of fluid particles of the ambient flow. In Example 6, a body is placed in a convecting vortex core; substantial accelerations of the fluid particles of the ambient flow are nonuniform in this case. In this case, the body experiences unsteady forces unrelated to added mass coefficients. The added mass coefficient approach would give wrong results, particularly when the velocity gradients are very high as in Examples 5 and 6.

APPENDIX B

AIRSHIP MOORING LOADS ANALYSIS

SIMULATION MODEL OUTPUTS

NOTES

1. The airship is submerged in the steady-state wind with given yaw angle at the initial condition. It is then released to start moving freely about the mast.
2. Refer to Figure 2-2 for airship geometric properties.

INDEX

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OF POOR QUALITY

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*****************************************
*                                       *
*    AIRSHIP MOORING LOADS ANALYSIS     *
*                                       *
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AIRSHIP CONFIGURATION DATA

** MARITIME PATROL AIRSHIP **

MOMENT OF INERTIA ABOUT CG............:	.190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:	1976.0 SLUGS
HEIGHT OF CENTER LINE.................:	50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:	143.6 FEET

MOORING STYLE

** BOW MOORED **

MAST LOCATION RELATIVE TO NOSE.......:	.0 FEET
HEIGHT OF MAST........................:	50.0 FEET
MOMENT OF INERTIA ABOUT MAST..........:	.597E 08 SLUG-FTSQ

INITIAL CONDITIONS

WIND SPEED............................:	60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:	15.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:	.0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:	.0 DEG/SEC

C-3

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OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BOW MOORED **

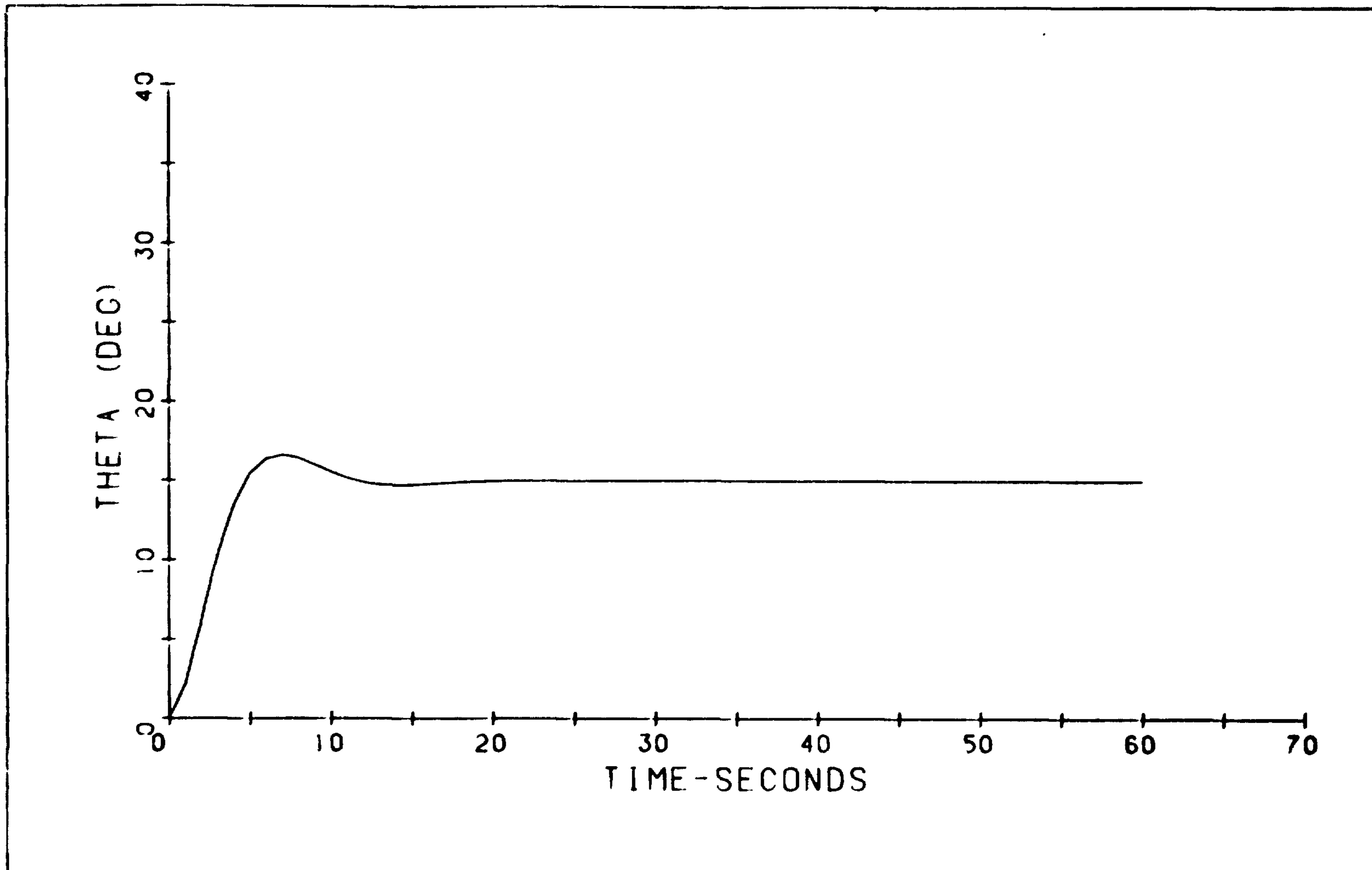
TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
.0	6.14	.00	.00	13092	4140	13731
1.0	1.69	3.53	2.13	14972	4864	15742
2.0	.04	4.28	6.16	11400	5237	12546
3.0	-.98	3.77	10.28	7182	4724	8596
4.0	-1.25	2.60	13.48	3309	3846	5074
5.0	-1.04	1.43	15.48	429	3343	3371
6.0	-.71	.56	16.44	-1227	3157	3387
7.0	-.45	-.02	16.69	-1785	3088	3567
8.0	-.21	-.35	16.49	-1759	3054	3514
9.0	-.03	-.47	16.06	-1355	3027	3316
10.0	.08	-.44	15.60	-856	3010	3130
11.0	.13	-.33	15.21	-394	2990	3016
12.0	.13	-.20	14.95	-47	2983	2984
13.0	.10	-.09	14.80	161	2980	2985
14.0	.07	-.00	14.76	248	2975	2986
15.0	.03	.05	14.79	247	2969	2979
16.0	.01	.07	14.84	196	2964	2970
17.0	-.01	.06	14.91	126	2962	2964
18.0	-.02	.05	14.97	60	2960	2960
19.0	-.02	.03	15.00	10	2959	2959
20.0	-.01	.01	15.03	-20	2960	2960
21.0	-.01	.00	15.03	-34	2959	2959
22.0	-.00	-.01	15.03	-34	2958	2958
23.0	-.00	-.01	15.02	-28	2957	2957
24.0	.00	-.01	15.01	-18	2957	2957
25.0	.00	-.01	15.01	-8	2957	2957
26.0	.00	-.00	15.00	-1	2957	2957
27.0	.00	-.00	15.00	2	2957	2957
28.0	.00	-.00	15.00	4	2957	2957
29.0	.00	.00	15.00	5	2957	2957
30.0	.00	.00	15.00	4	2956	2956
31.0	-.00	.00	15.00	2	2956	2956
32.0	-.00	.00	15.00	1	2956	2956
33.0	-.00	.00	15.00	0	2956	2956
34.0	-.00	.00	15.00	0	2956	2956
35.0	-.00	.00	15.00	0	2956	2956
36.0	-.00	-.00	15.00	0	2956	2956
37.0	-.00	-.00	15.00	0	2956	2956
38.0	.00	-.00	15.00	0	2956	2956
39.0	.00	-.00	15.00	0	2956	2956
40.0	.00	-.00	15.00	0	2956	2956
41.0	.00	-.00	15.00	0	2956	2956
42.0	.00	.00	15.00	0	2956	2956
43.0	.00	.00	15.00	0	2956	2956
44.0	.00	.00	15.00	0	2956	2956
45.0	.00	.00	15.00	0	2956	2956
46.0	.00	.00	15.00	0	2956	2956
47.0	.00	.00	15.00	0	2956	2956

** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
48.0	.00	.00	15.00	0	2956	2956
49.0	.00	.00	15.00	0	2956	2956
50.0	.00	.00	15.00	0	2956	2956
51.0	.00	.00	15.00	0	2956	2956
52.0	.00	.00	15.00	0	2956	2956
53.0	.00	.00	15.00	0	2956	2956
54.0	.00	.00	15.00	0	2956	2956
55.0	.00	.00	15.00	0	2956	2956
56.0	.00	.00	15.00	0	2956	2956
57.0	.00	.00	15.00	0	2956	2956
58.0	.00	.00	15.00	0	2956	2956
59.0	.00	.00	15.00	0	2956	2956
60.0	.00	.00	15.00	0	2956	2956

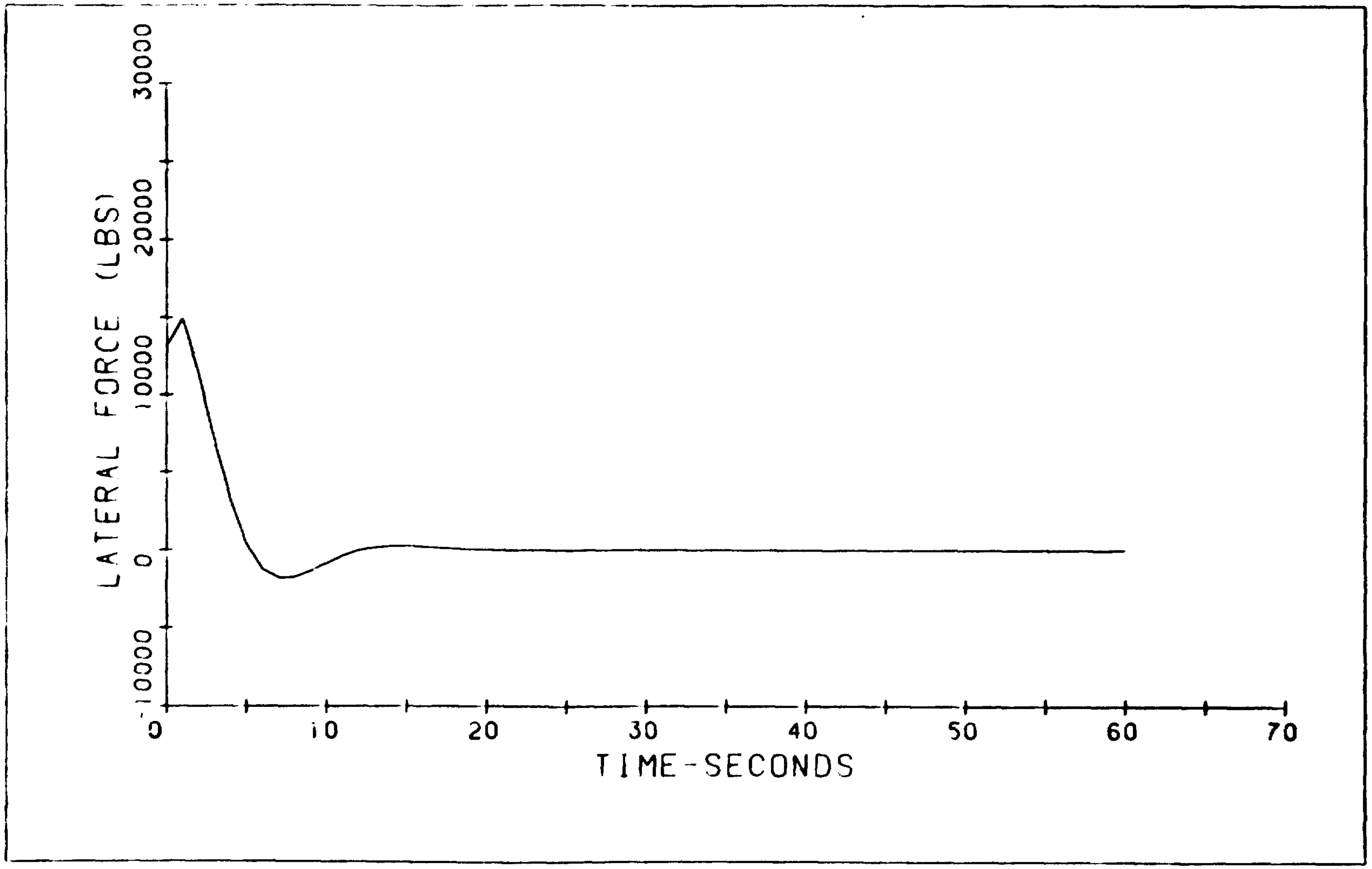
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 15°



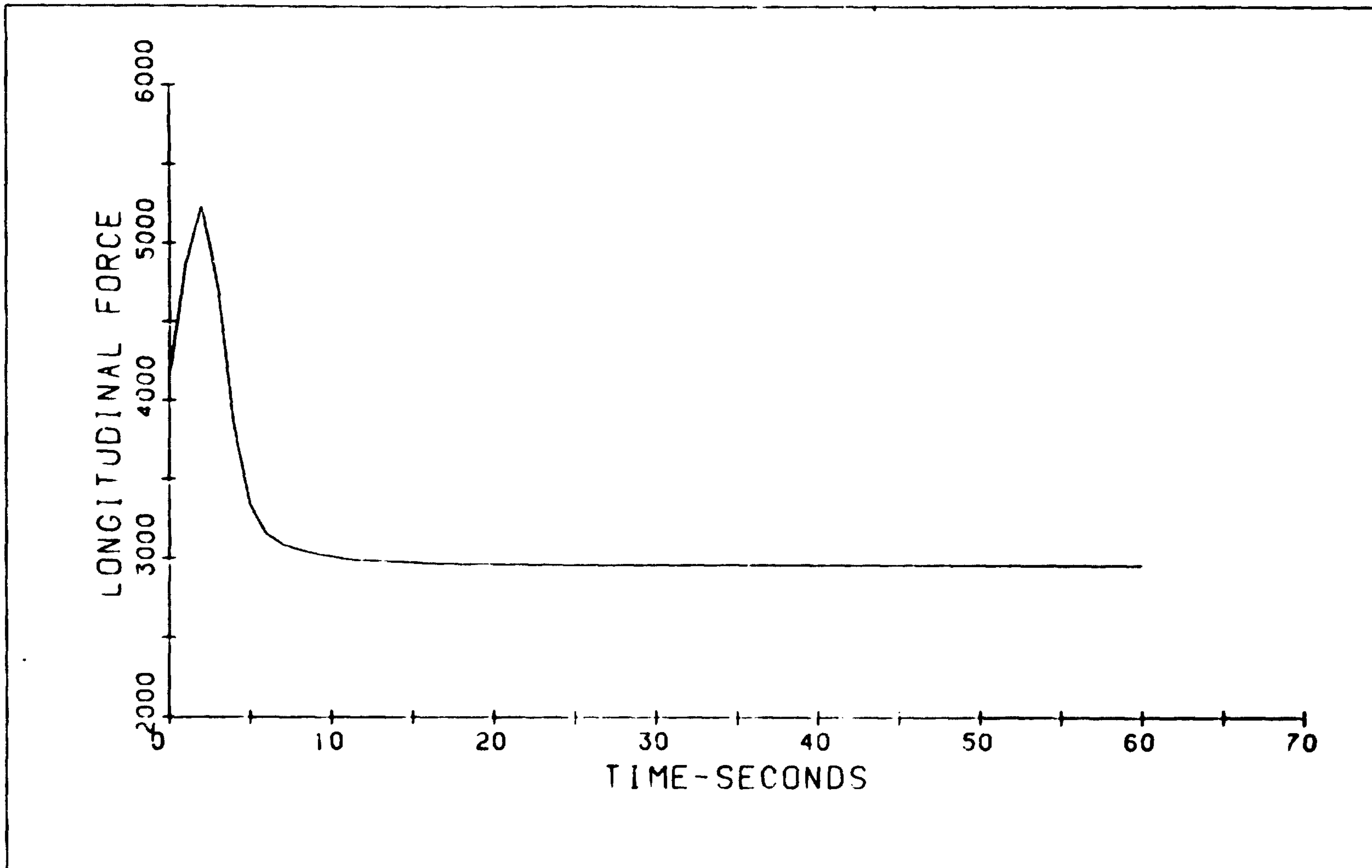
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 15°



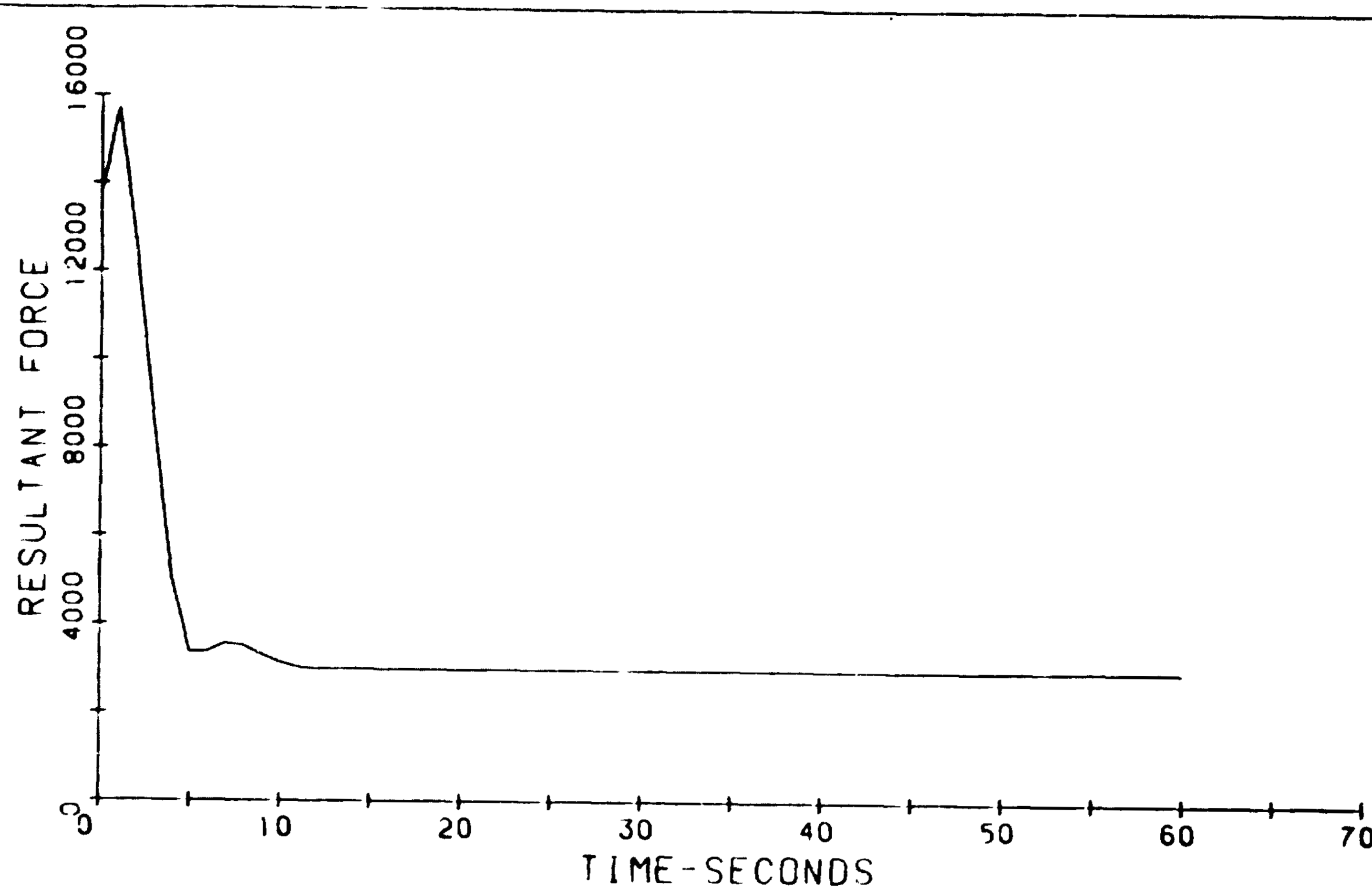
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 15°



** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 15°



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*                                       *
*     AIRSHIP MOORING LOADS ANALYSIS    *
*                                       *
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AIRSHIP CONFIGURATION DATA
--------------------------

** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET

MOORING STYLE
-------------

** BOW MOORED **
MAST LOCATION RELATIVE TO NOSE........:       .0 FEET
HEIGHT OF MAST........................:     50.0 FEET
MOMENT OF INERTIA ABOUT MAST..........: .597E 08 SLUG-FTSQ

INITIAL CONDITIONS
------------------

WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS...:     30.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
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** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
.0	14.61	.00	.00	21802	3160	22029
1.0	3.04	7.53	4.69	28078	9425	29618
2.0	-.34	8.64	13.04	22042	11395	24813
3.0	-2.27	7.16	21.10	14192	8834	16716
4.0	-2.50	4.67	27.03	6751	5584	8761
5.0	-1.94	2.42	30.53	1448	3851	4115
6.0	-1.20	.85	32.11	-1517	3283	3617
7.0	-.65	-.04	32.47	-2612	3147	4090
8.0	-.31	-.51	32.16	-2533	3106	4008
9.0	-.05	-.68	31.54	-1968	3074	3650
10.0	.11	-.64	30.87	-1240	3048	3291
11.0	.18	-.48	30.31	-567	3013	3066
12.0	.18	-.29	29.92	-64	2998	2999
13.0	.15	-.13	29.71	238	2992	3001
14.0	.10	-.00	29.65	363	2984	3006
15.0	.05	.07	29.69	360	2975	2997
16.0	.01	.10	29.77	284	2967	2981
17.0	-.01	.09	29.87	183	2964	2970
18.0	-.03	.07	29.95	87	2961	2963
19.0	-.03	.04	30.01	14	2961	2961
20.0	-.02	.02	30.04	-30	2961	2961
21.0	-.01	.00	30.05	-50	2960	2961
22.0	-.01	-.01	30.04	-50	2959	2959
23.0	-.00	-.01	30.03	-40	2958	2958
24.0	.00	-.01	30.02	-26	2957	2957
25.0	.00	-.01	30.01	-13	2957	2957
26.0	.00	-.01	30.00	-2	2957	2957
27.0	.00	-.00	29.99	4	2957	2957
28.0	.00	-.00	29.99	7	2957	2957
29.0	.00	.00	29.99	7	2957	2957
30.0	.00	.00	30.00	6	2956	2956
31.0	-.00	.00	30.00	4	2956	2956
32.0	-.00	.00	30.00	2	2956	2956
33.0	-.00	.00	30.00	0	2956	2956
34.0	-.00	.00	30.00	0	2956	2956
35.0	-.00	.00	30.00	0	2956	2956
36.0	-.00	-.00	30.00	0	2956	2956
37.0	-.00	-.00	30.00	0	2956	2956
38.0	.00	-.00	30.00	0	2956	2956
39.0	.00	-.00	30.00	0	2956	2956
40.0	.00	-.00	30.00	0	2956	2956
41.0	.00	.00	30.00	0	2956	2956
42.0	.00	.00	30.00	0	2956	2956
43.0	.00	.00	30.00	0	2956	2956
44.0	.00	.00	30.00	0	2956	2956
45.0	.00	.00	30.00	0	2956	2956
46.0	.00	.00	30.00	0	2956	2956
47.0	.00	.00	30.00	0	2956	2956

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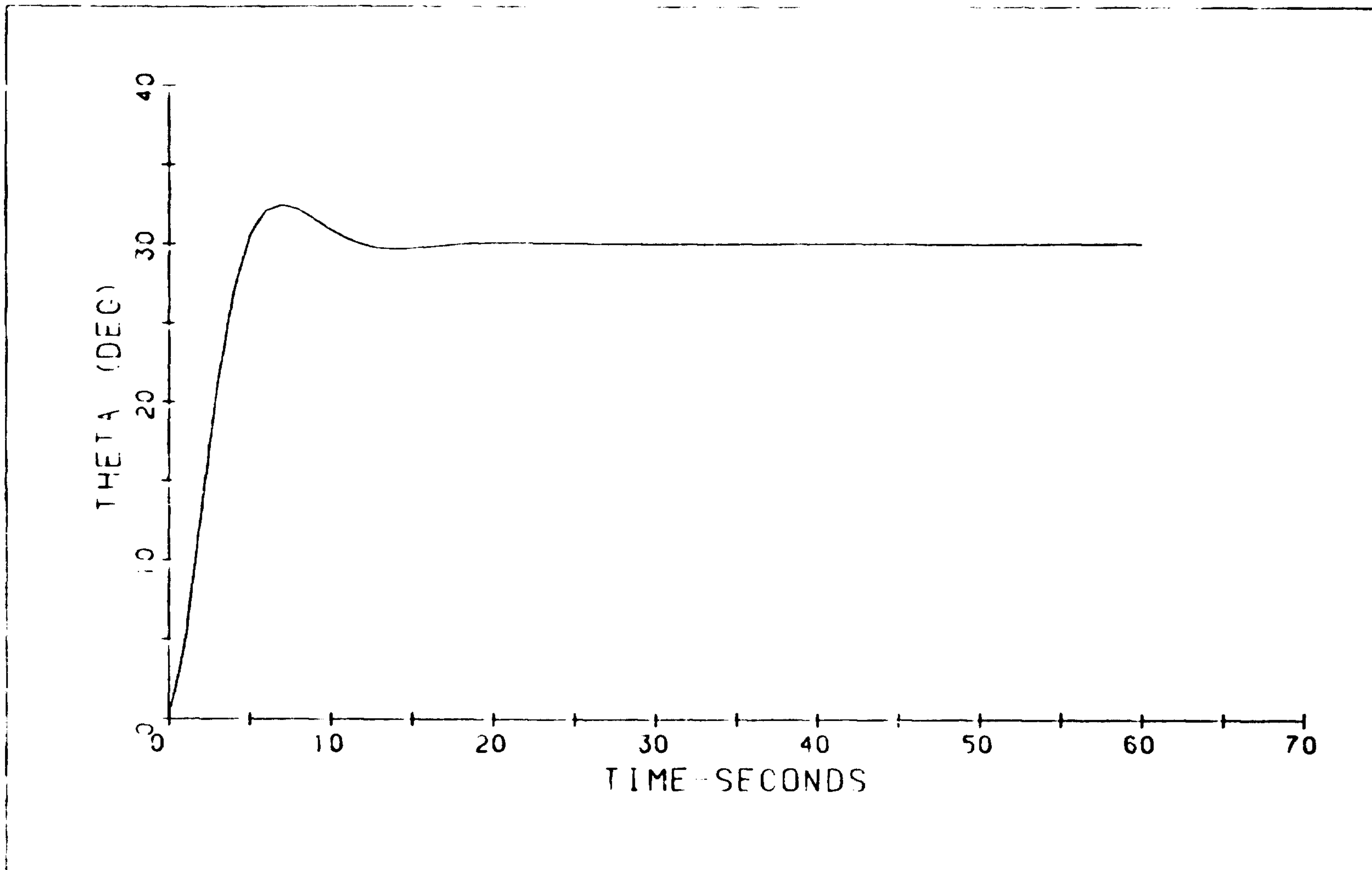
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
48.0	.00	.00	30.00	0	2956	2956
49.0	.00	.00	30.00	0	2956	2956
50.0	.00	.00	30.00	0	2956	2956
51.0	.00	.00	30.00	0	2956	2956
52.0	.00	.00	30.00	0	2956	2956
53.0	.00	.00	30.00	0	2956	2956
54.0	.00	.00	30.00	0	2956	2956
55.0	.00	.00	30.00	0	2956	2956
56.0	.00	.00	30.00	0	2956	2956
57.0	.00	.00	30.00	0	2956	2956
58.0	.00	.00	30.00	0	2956	2956
59.0	.00	.00	30.00	0	2956	2956
60.0	.00	.00	30.00	0	2956	2956

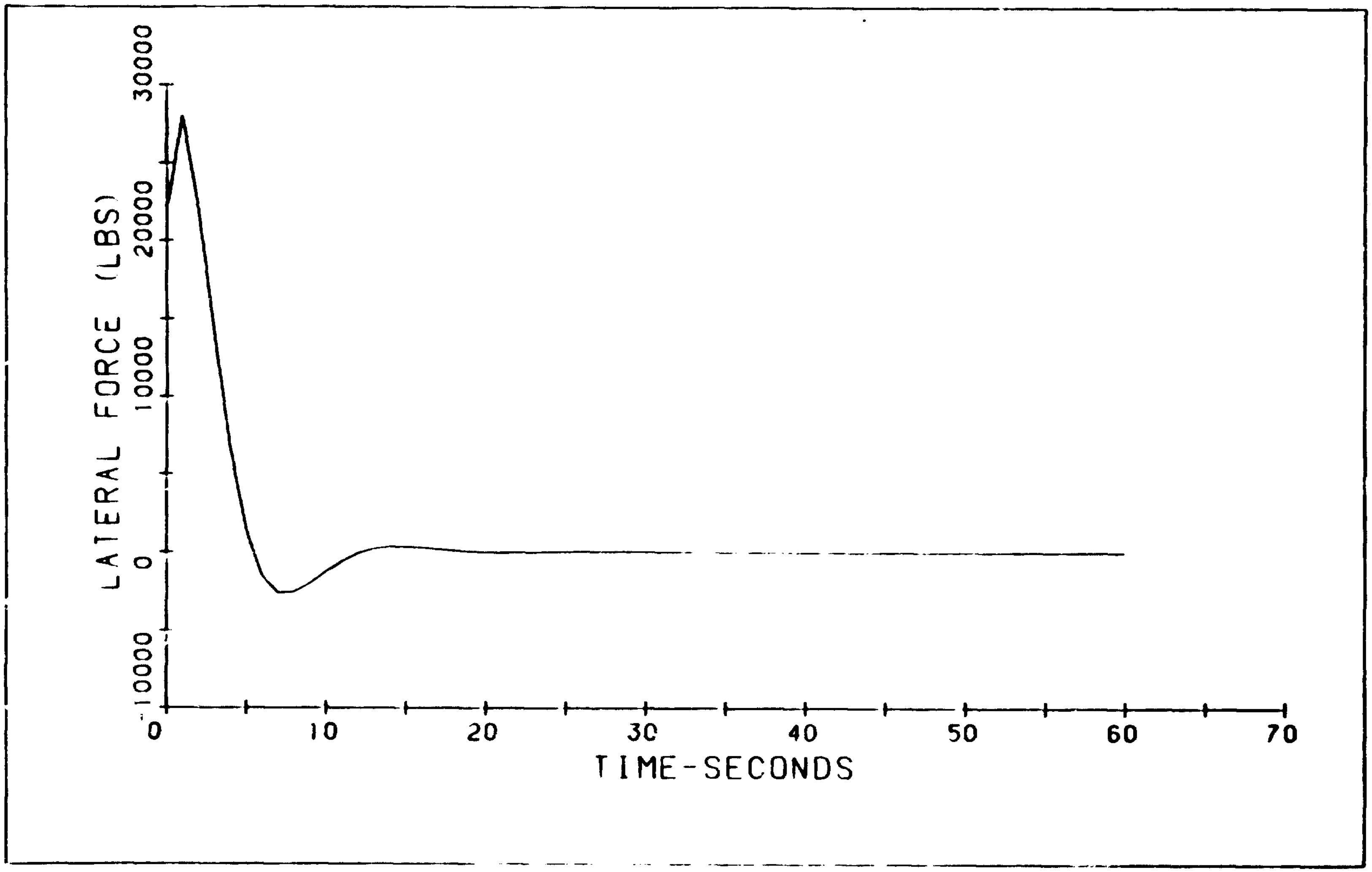
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 30°



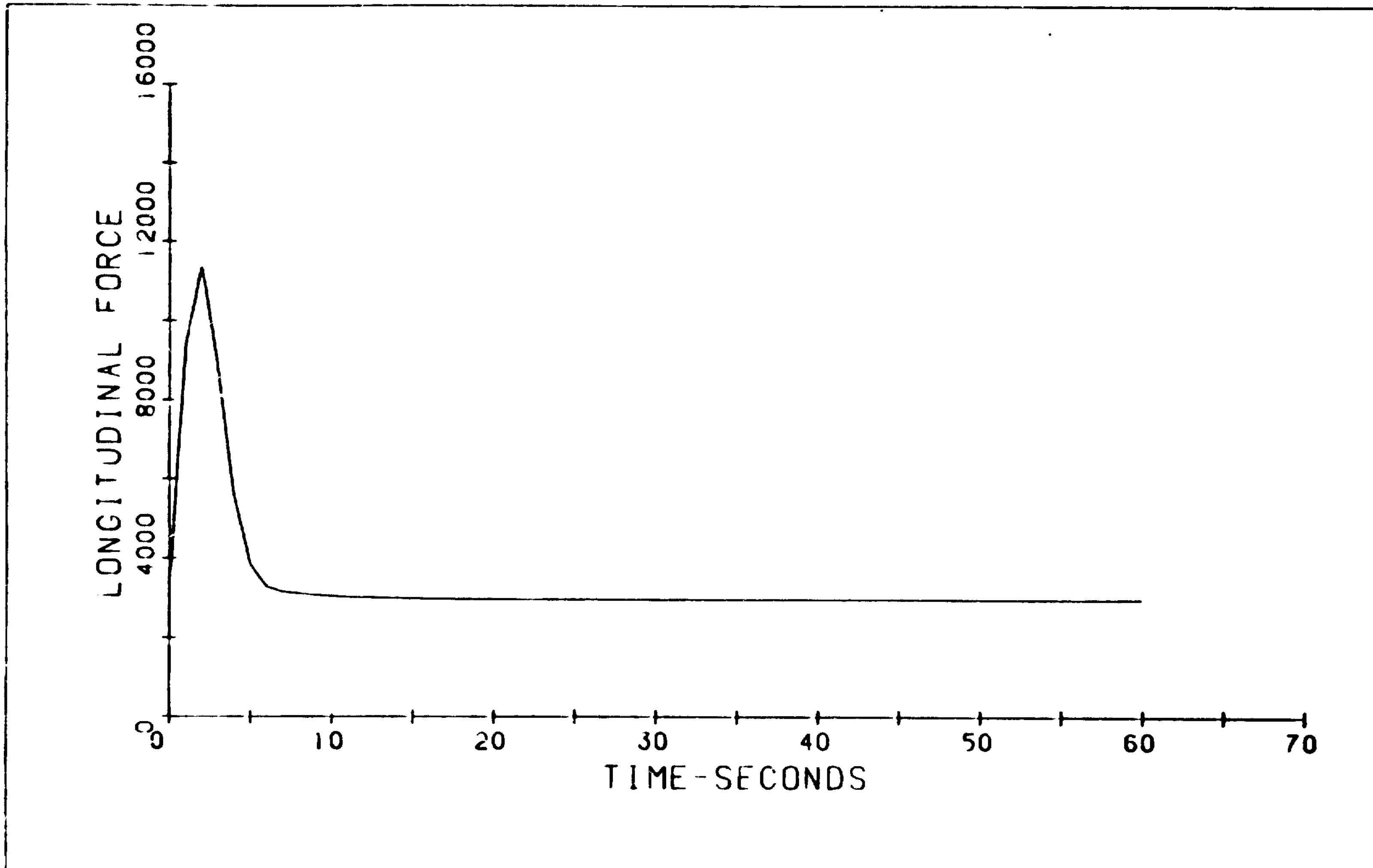
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 30°



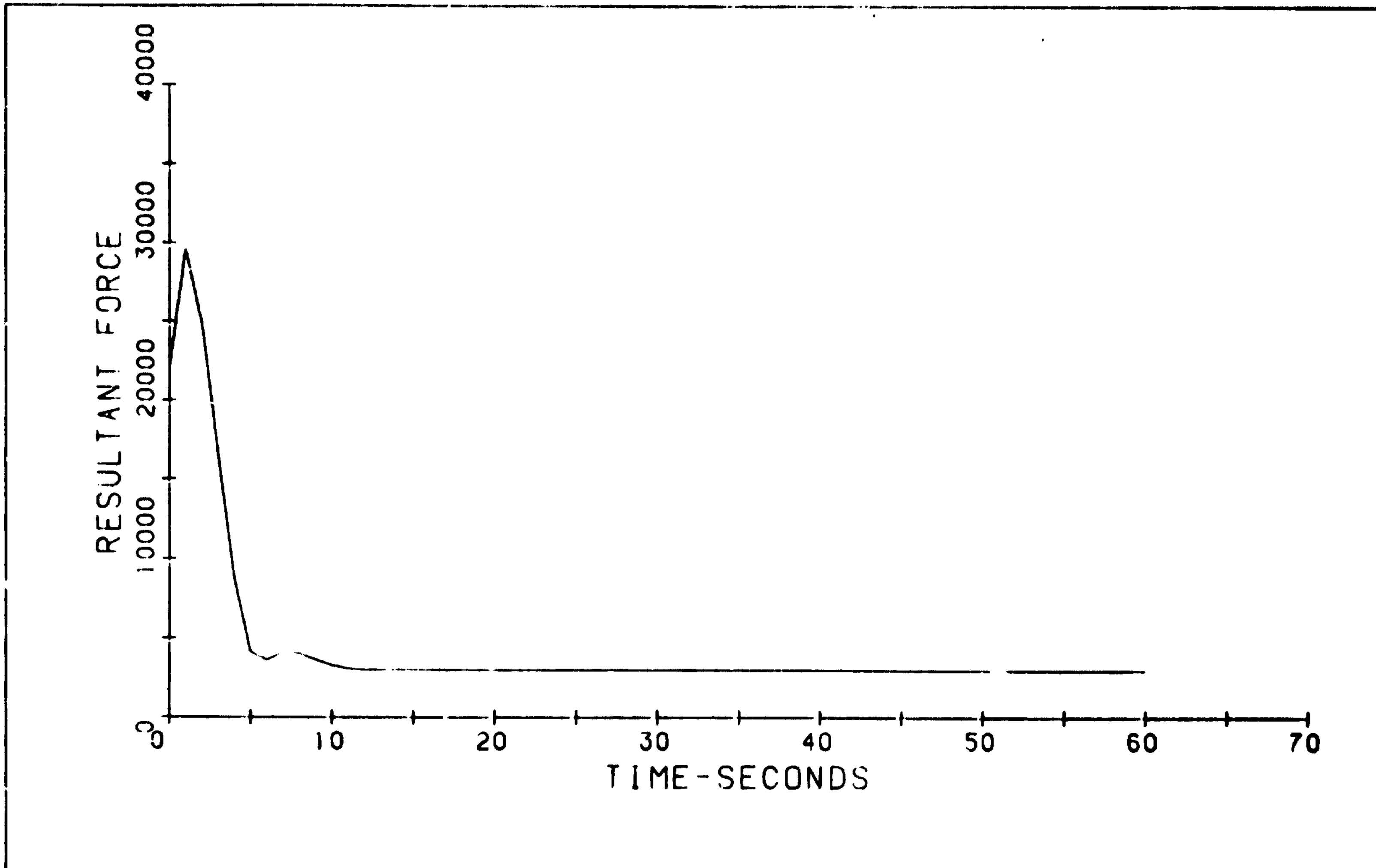
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 30°



** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 30°



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*                                      *
*    AIRSHIP MOORING LOADS ANALYSIS    *
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AIRSHIP CONFIGURATION DATA
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** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE.........:    143.6 FEET


MOORING STYLE
-------------

** BOW MOORED **
MAST LOCATION RELATIVE TO NOSE.......:       .0 FEET
HEIGHT OF MAST.......................:     50.0 FEET
MOMENT OF INERTIA ABOUT MAST.........: .597E 08 SLUG-FTSQ


INITIAL CONDITIONS
------------------

WIND SPEED...........................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     45.0 DEGREES
THETA (DISPLACEMENT ANGLE)...........:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY).........:       .0 DEG/SEC
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** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	F -TR LBS	FLONG LBS	FMAST LBS
.0	22.47	.00	.00	26685	-2803	26831
1.0	4.55	11.10	6.92	37764	14897	40596
2.0	-.55	12.73	19.24	31796	20430	37794
3.0	-3.32	10.58	31.13	21834	15413	26726
4.0	-3.68	6.93	39.92	11012	8496	13909
5.0	-2.84	3.62	45.12	3103	4706	5638
6.0	-1.77	1.32	47.50	-1350	3470	3723
7.0	-.88	.02	48.10	-3211	3202	4535
8.0	-.42	-.61	47.76	-3213	3155	4503
9.0	-.08	-.85	47.00	-2536	3119	4020
10.0	.13	-.81	46.16	-1628	3089	3492
11.0	.23	-.62	45.43	-772	3039	3136
12.0	.23	-.39	44.93	-121	3013	3015
13.0	.19	-.17	44.65	277	3002	3015
14.0	.13	-.01	44.57	449	2992	3025
15.0	.06	.08	44.60	456	2981	3015
16.0	.01	.12	44.71	366	2971	2993
17.0	-.02	.12	44.83	239	2967	2977
18.0	-.03	.09	44.93	117	2963	2966
19.0	-.03	.06	45.01	23	2962	2962
20.0	-.03	.03	45.05	-35	2962	2963
21.0	-.02	.00	45.06	-61	2961	2962
22.0	-.01	-.01	45.06	-64	2960	2960
23.0	-.00	-.02	45.04	-52	2958	2959
24.0	.00	-.02	45.03	-34	2958	2958
25.0	.00	-.01	45.01	-17	2957	2957
26.0	.00	-.01	45.00	-3	2957	2957
27.0	.00	-.00	44.99	4	2957	2957
28.0	.00	-.00	44.99	8	2957	2957
29.0	.00	.00	44.99	9	2957	2957
30.0	.00	.00	44.99	7	2957	2957
31.0	-.00	.00	45.00	5	2956	2956
32.0	-.00	.00	45.00	2	2956	2956
33.0	-.00	.00	45.00	0	2956	2956
34.0	-.00	.00	45.00	0	2956	2956
35.0	-.00	.00	45.00	0	2956	2956
36.0	-.00	-.00	45.00	-1	2956	2956
37.0	-.00	-.00	45.00	0	2956	2956
38.0	.00	-.00	45.00	0	2956	2956
39.0	.00	-.00	45.00	0	2956	2956
40.0	.00	-.00	45.00	0	2956	2956
41.0	.00	-.00	45.00	0	2956	2956
42.0	.00	.00	45.00	0	2956	2956
43.0	.00	.00	45.00	0	2956	2956
44.0	.00	.00	45.00	0	2956	2956
45.0	.00	.00	45.00	0	2956	2956
46.0	.00	.00	45.00	0	2956	2956
47.0	.00	.00	45.00	0	2956	2956

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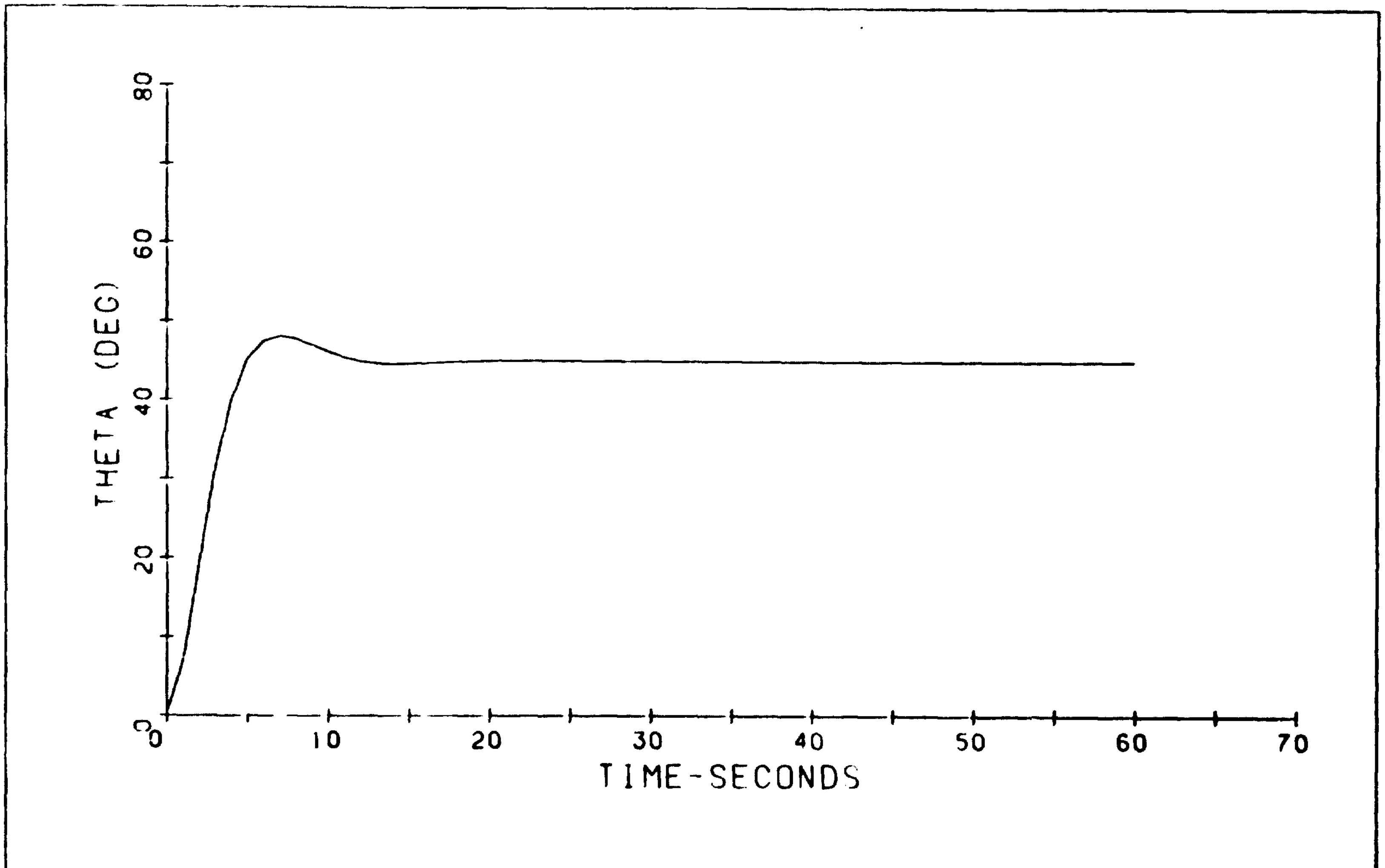
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
48.0	.00	.00	45.00	0	2956	2956
49.0	.00	.00	45.00	0	2956	2956
50.0	.00	.00	45.00	0	2956	2956
51.0	.00	.00	45.00	0	2956	2956
52.0	.00	.00	45.00	0	2956	2956
53.0	.00	.00	45.00	0	2956	2956
54.0	.00	.00	45.00	0	2956	2956
55.0	.00	.00	45.00	0	2956	2956
56.0	.00	.00	45.00	0	2956	2956
57.0	.00	.00	45.00	0	2956	2956
58.0	.00	.00	45.00	0	2956	2956
59.0	.00	.00	45.00	0	2956	2956
60.0	.00	.00	45.00	0	2956	2956

•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

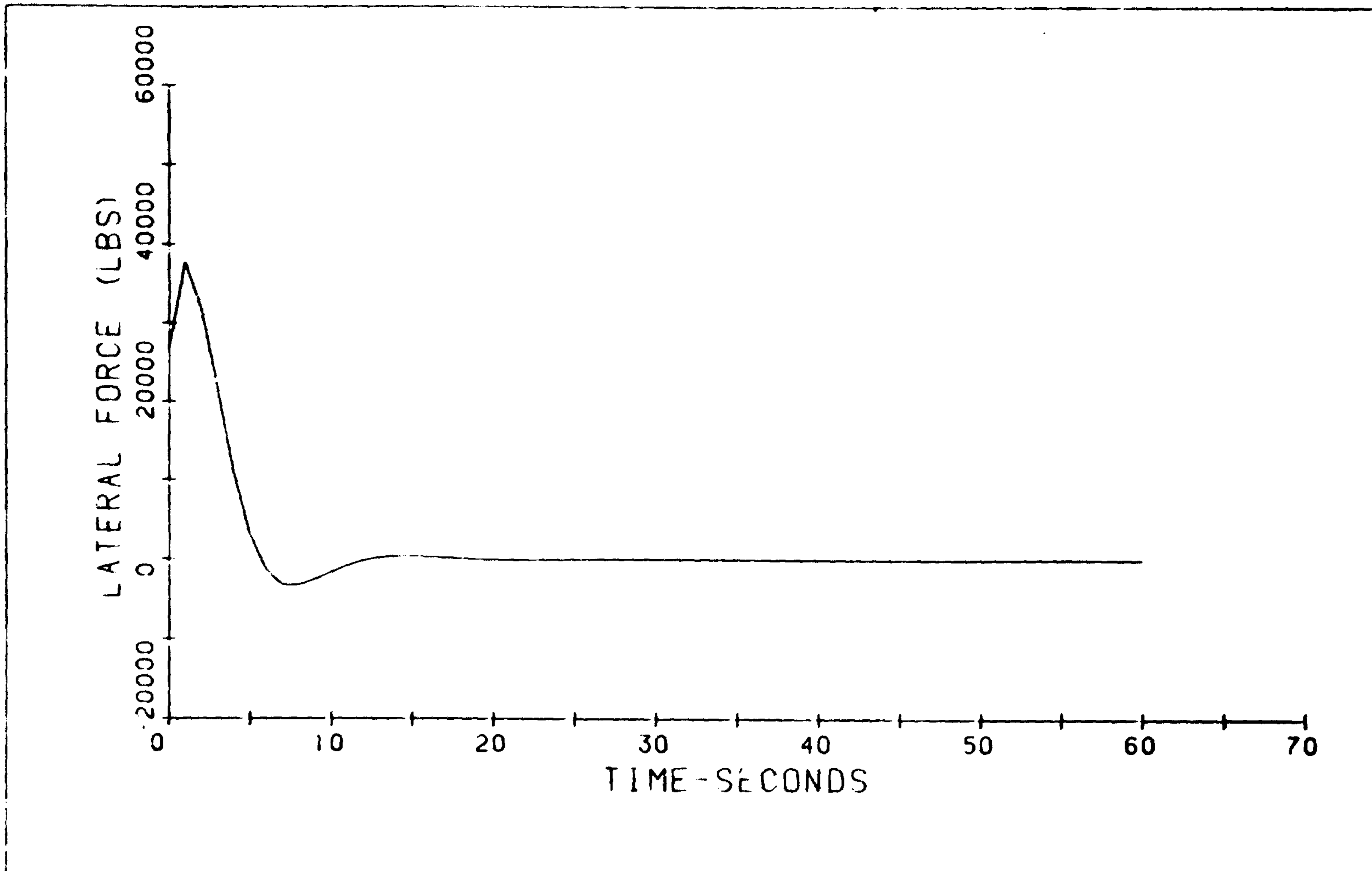
Wind = 60 Knots @ 45°



•• MARITIME PATROL AIRSHIP ••

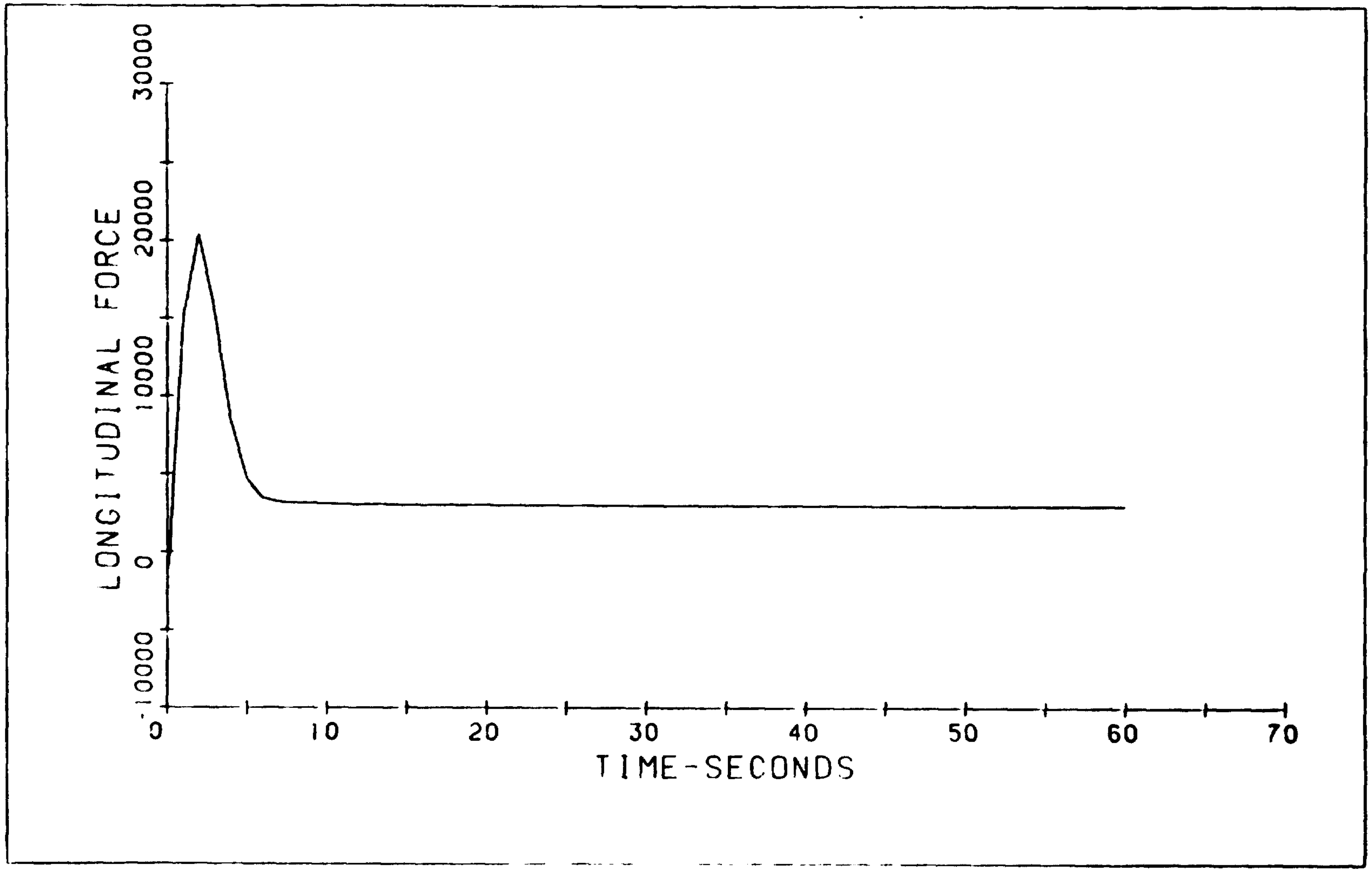
•• BOW MOORED ••

Wind = 60 Knots @ 45°



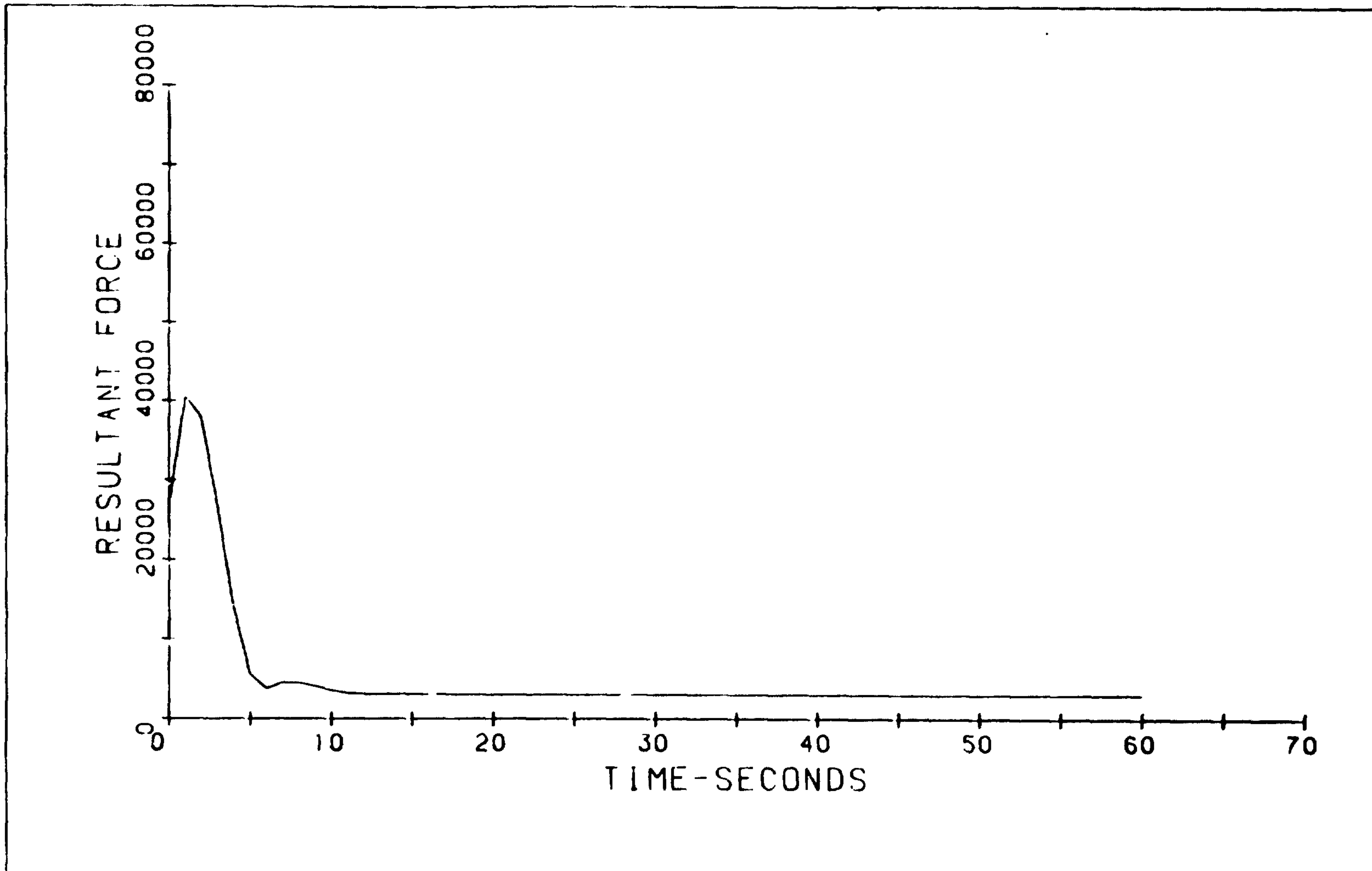
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 45°



** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 45°



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*                                       *
*    AIRSHIP MOORING LOADS ANALYSIS     *
*                                       *
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AIRSHIP CONFIGURATION DATA
--------------------------

** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET

MOORING STYLE
-------------

** BOW MOORED **
MAST LOCATION RELATIVE TO NOSE........:       .0 FEET
HEIGHT OF MAST........................:     50.0 FEET
MOMENT OF INERTIA ABOUT MAST..........: .597E 08 SLUG-FTSQ

INITIAL CONDITIONS
------------------

WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS...:     60.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
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OF POOR QUALITY

** MARITIME PATROL AIRSHIP **

** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
.0	26.04	.00	.00	30231	-9351	31644
1.0	6.33	13.48	8.28	45209	18811	48967
2.0	.03	16.34	23.70	39275	30300	49605
3.0	-3.83	14.21	39.29	30839	25000	39699
4.0	-4.76	9.68	51.31	17113	13482	21786
5.0	-3.82	5.32	58.73	6166	6387	8878
6.0	-2.47	2.17	62.36	-315	3863	3876
7.0	-1.30	.32	63.51	-3245	3275	4611
8.0	-.59	-.57	63.32	-3778	3196	4949
9.0	-.17	-.94	62.52	-3129	3160	4447
10.0	.11	-.96	61.55	-2115	3133	3780
11.0	.24	-.77	60.67	-1098	3072	3262
12.0	.27	-.51	60.03	-286	3027	3041
13.0	.23	-.25	59.65	239	3013	3023
14.0	.16	-.05	59.51	492	3000	3040
15.0	.09	.08	59.52	538	2988	3036
16.0	.03	.13	59.63	454	2975	3010
17.0	-.01	.14	59.77	314	2970	2987
18.0	-.03	.11	59.89	170	2965	2970
19.0	-.04	.08	59.99	53	2963	2963
20.0	-.03	.04	60.04	-23	2963	2963
21.0	-.02	.01	60.06	-61	2962	2963
22.0	-.01	-.01	60.06	-70	2961	2961
23.0	-.00	-.02	60.05	-59	2959	2959
24.0	.00	-.02	60.03	-42	2958	2958
25.0	.00	-.01	60.01	-22	2957	2957
26.0	.01	-.01	60.00	-6	2957	2957
27.0	.00	-.00	59.99	5	2957	2957
28.0	.00	-.00	59.99	11	2957	2957
29.0	.00	.00	59.99	12	2957	2957
30.0	.00	.00	59.99	11	2957	2957
31.0	-.00	.00	59.99	9	2957	2957
32.0	-.00	.00	59.99	6	2957	2957
33.0	-.00	.00	60.00	4	2956	2956
34.0	-.00	.00	60.00	2	2956	2956
35.0	-.00	.00	60.00	2	2956	2956
36.0	-.00	.00	60.00	2	2956	2956
37.0	-.00	.00	60.00	1	2956	2956
38.0	-.00	.00	60.00	1	2956	2956
39.0	-.00	.00	60.00	1	2956	2956
40.0	-.00	.00	60.00	1	2956	2956
41.0	-.00	.00	60.00	1	2956	2956
42.0	-.00	.00	60.00	1	2956	2956
43.0	-.00	.00	60.00	1	2956	2956
44.0	-.00	.00	60.00	1	2956	2956
45.0	-.00	.00	60.00	1	2956	2956
46.0	-.00	.00	60.00	1	2956	2956
47.0	-.00	.00	60.00	1	2956	2956

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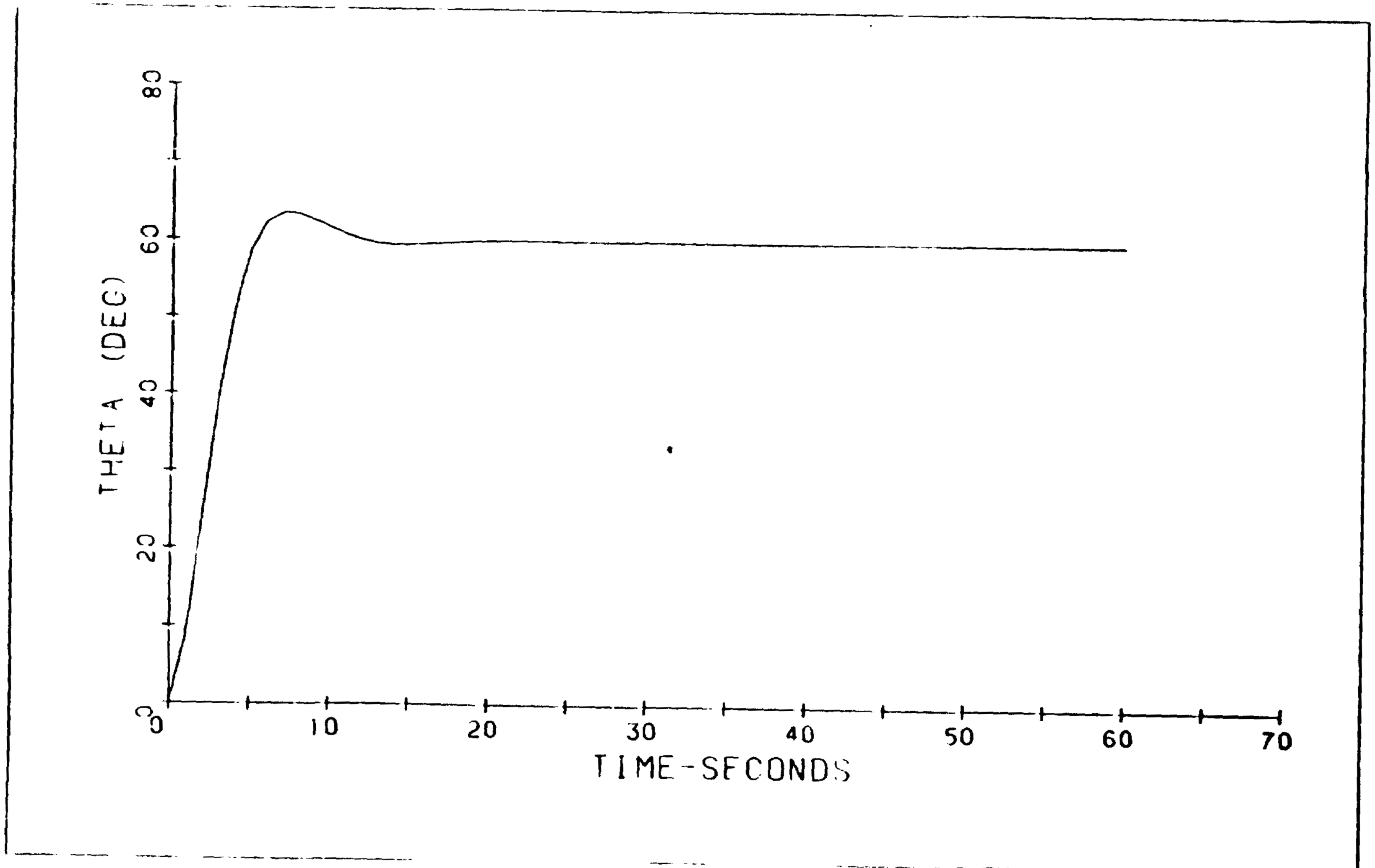
** MARITIME PATROL AIRSHIP **
** HOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLUNG LBS	FMAST LBS
48.0	-.00	.00	60.00	1	2956	2956
49.0	-.00	.00	60.00	1	2956	2956
50.0	-.00	.00	60.00	1	2956	2956
51.0	-.00	.00	60.00	1	2956	2956
52.0	-.00	.00	60.00	1	2956	2956
53.0	-.00	.00	60.00	1	2956	2956
54.0	-.00	.00	60.00	1	2956	2956
55.0	-.00	.00	60.00	1	2956	2956
56.0	.00	.00	60.00	1	2956	2956
57.0	.00	.00	60.00	1	2956	2956
58.0	.00	.00	60.00	1	2956	2956
59.0	.00	.00	60.00	1	2956	2956
60.0	-.00	.00	60.00	1	2956	2956

•• MARITIME PATROL AIRSHIP ••

•• BOW MOORED ••

Wind = 60 Knots @ 60°



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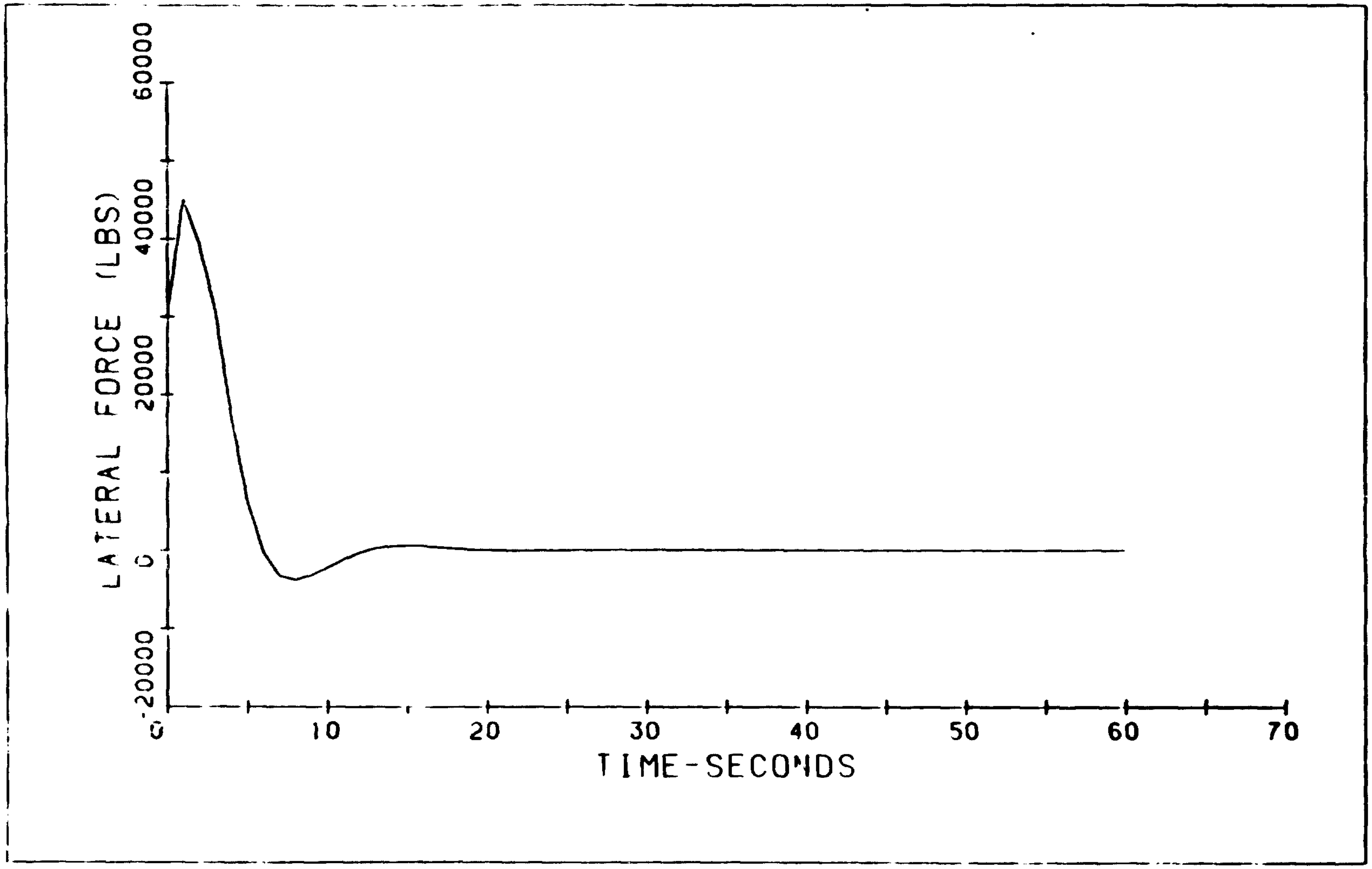
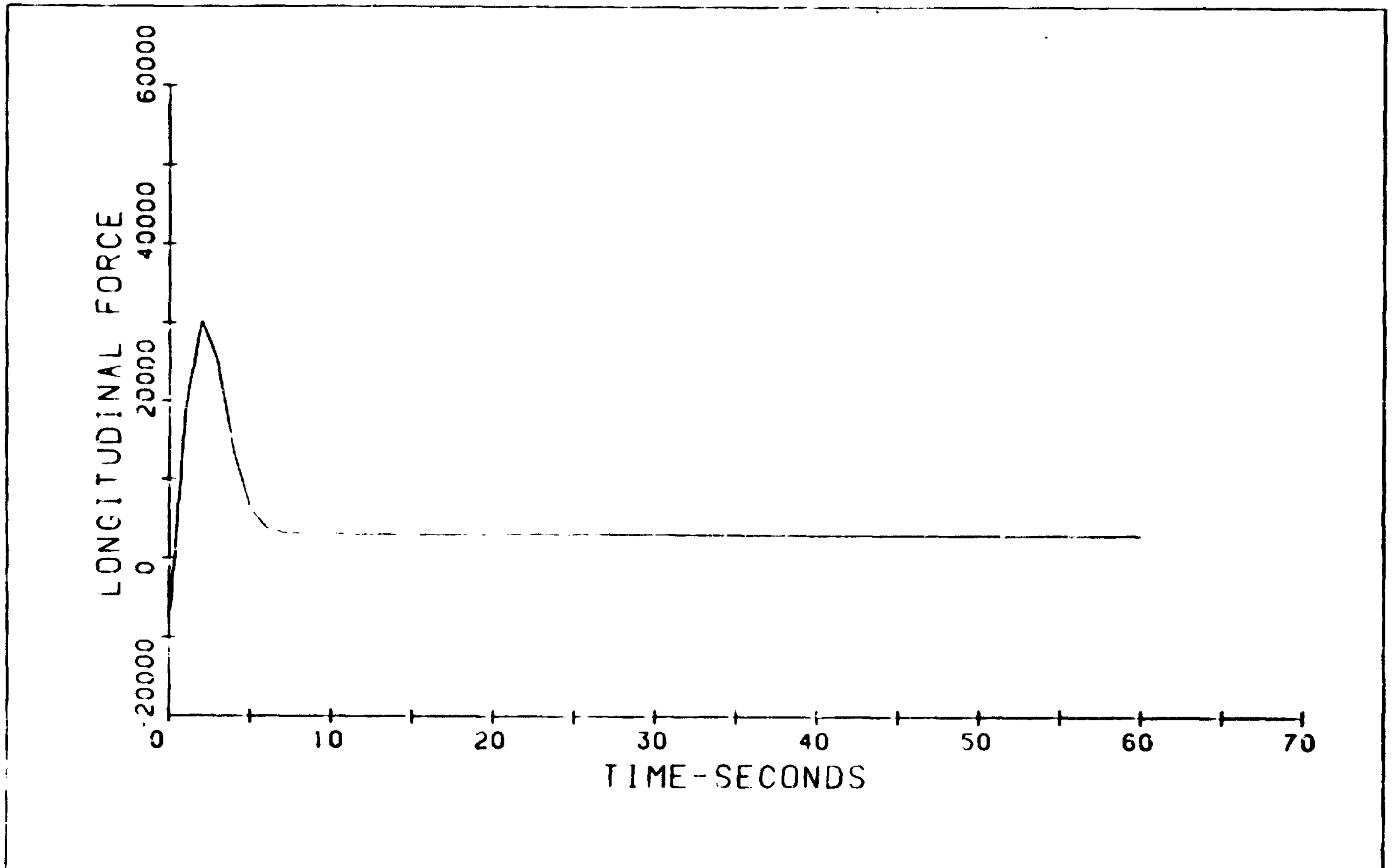
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 60°



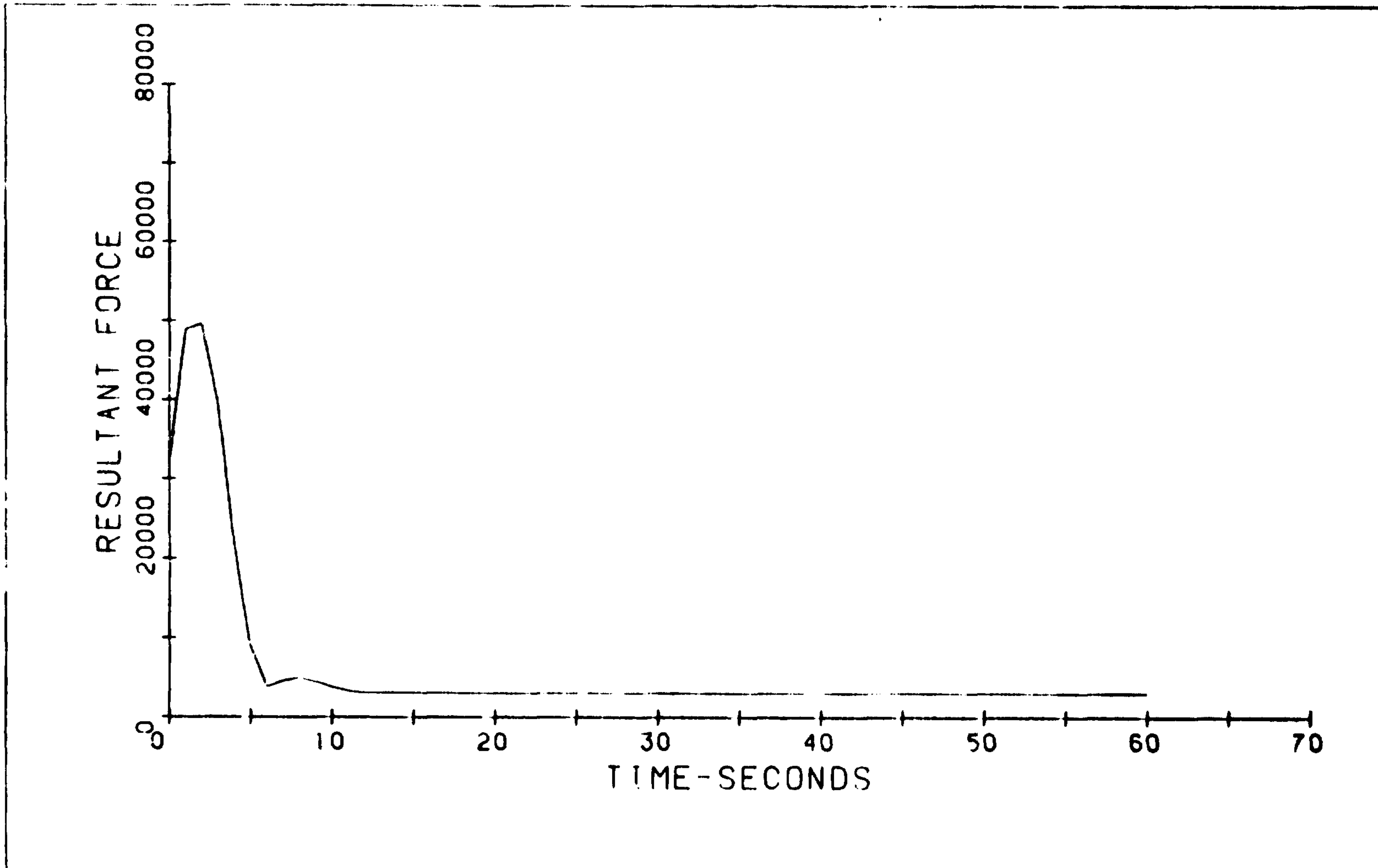
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 60°



** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 60°



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*****************************************
*                                       *
*    AIRSHIP MOORING LOADS ANALYSIS     *
*                                       *
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE.........:    143.6 FEET
```

MOORING STYLE

```
** BOW MOORED **
MAST LOCATION RELATIVE TO NOSE.......:       .0 FEET
HEIGHT OF MAST.......................:     50.0 FEET
MOMENT OF INERTIA ABOUT MAST.........: .597E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED...........................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     75.0 DEGREES
THETA (DISPLACEMENT ANGLE)...........:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY).........:       .0 DEG/SEC
```

ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
.0	29.07	.00	.00	24752	-14000	28437
1.0	7.44	14.59	8.89	43865	19388	47959
2.0	1.66	18.89	26.12	46164	37923	59743
3.0	-3.42	17.83	44.91	34	36582	53366
4.0	-5.58	13.04	60.52	555	21662	33501
5.0	-4.94	7.68	70.81	11334	9741	14945
6.0	-3.32	3.60	76.32	2116	4793	5240
7.0	-1.90	1.01	78.50	-2508	3443	4260
8.0	-.84	-.33	78.75	-4108	3231	5226
9.0	-.34	-.91	78.09	-3704	3199	4894
10.0	.02	-1.06	77.07	-2712	3170	4173
11.0	.22	-.92	76.06	-1587	3113	3494
12.0	.29	-.66	75.27	-613	3048	3109
13.0	.27	-.37	74.75	73	3024	3025
14.0	.21	-.13	74.51	453	3009	3043
15.0	.12	.04	74.47	579	2995	3051
16.0	.05	.13	74.55	533	2982	3029
17.0	.00	.15	74.69	398	2973	3000
18.0	-.03	.13	74.84	240	2968	2978
19.0	-.04	.10	74.95	101	2964	2966
20.0	-.04	.06	75.03	1	2964	2964
21.0	-.03	.02	75.06	-55	2963	2964
22.0	-.02	-.00	75.07	-75	2962	2963
23.0	-.01	-.01	75.06	-70	2960	2960
24.0	-.00	-.02	75.04	-53	2959	2959
25.0	.00	-.02	75.02	-31	2958	2958
26.0	.01	-.01	75.01	-12	2957	2957
27.0	.01	-.01	74.99	1	2957	2957
28.0	.00	-.00	74.99	10	2957	2957
29.0	.00	.00	74.99	13	2957	2957
30.0	.00	.00	74.99	12	2957	2957
31.0	.00	.00	74.99	11	2957	2957
32.0	-.00	.00	74.99	8	2957	2957
33.0	-.00	.00	75.00	6	2956	2956
34.0	-.00	.00	75.00	3	2956	2956
35.0	-.00	.00	75.00	2	2956	2956
36.0	-.00	.00	75.00	1	2956	2956
37.0	-.00	.00	75.00	1	2956	2956
38.0	-.00	.00	75.00	1	2956	2956
39.0	-.00	.00	75.00	1	2956	2956
40.0	-.00	.00	75.00	1	2956	2956
41.0	-.00	.00	75.00	1	2956	2956
42.0	-.00	.00	75.00	1	2956	2956
43.0	-.00	.00	75.00	1	2956	2956
44.0	-.00	.00	75.00	1	2956	2956
45.0	-.00	.00	75.00	1	2956	2956
46.0	-.00	.00	75.00	1	2956	2956
47.0	-.00	.00	75.00	1	2956	2956

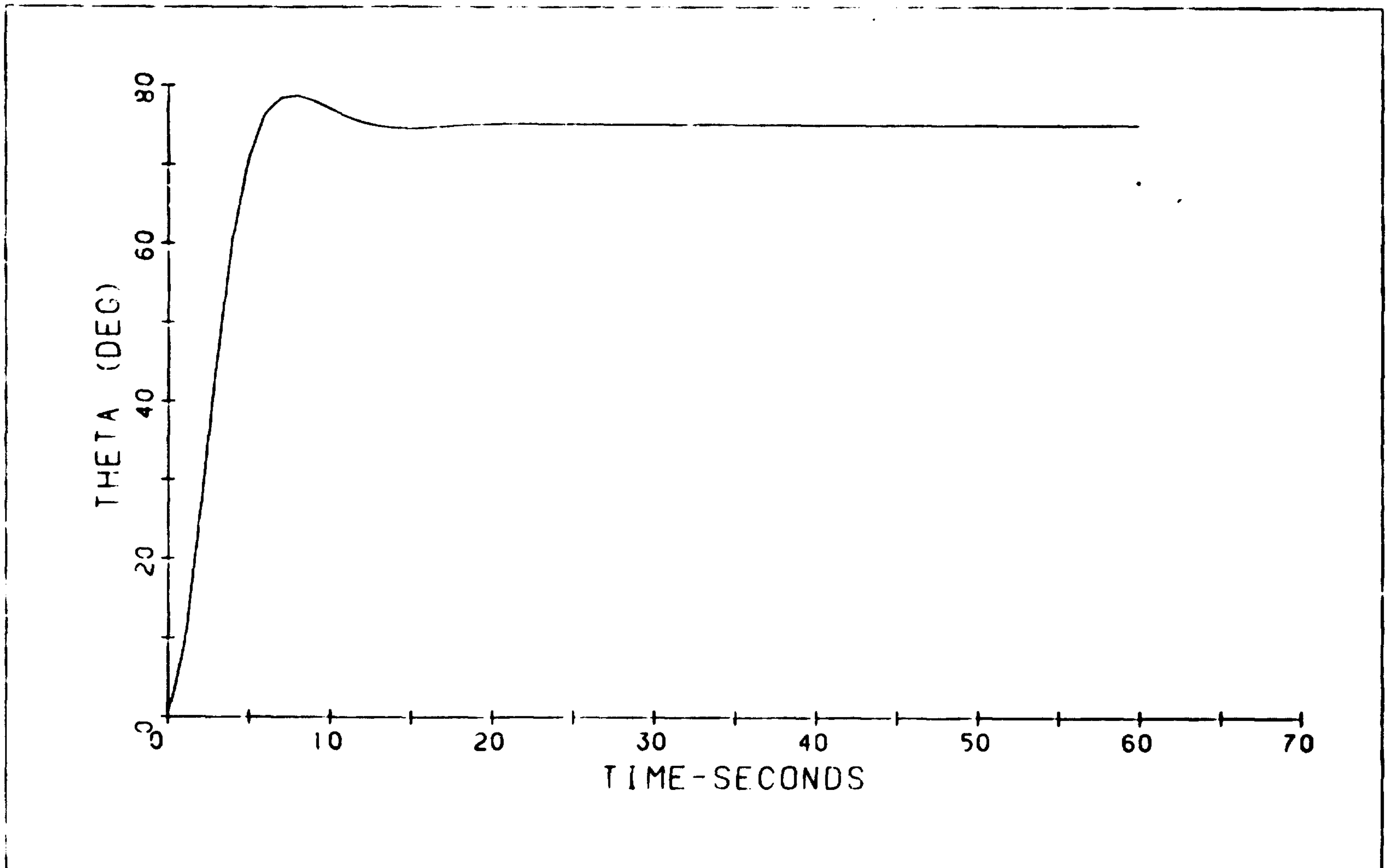
ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLUNG LBS	FMAST LBS
48.0	-.00	.00	75.00	1	2956	2956
49.0	-.00	.00	75.00	1	2956	2956
50.0	-.00	.00	75.00	1	2956	2956
51.0	-.00	.00	75.00	1	2956	2956
52.0	-.00	.00	75.00	1	2956	2956
53.0	-.00	.00	75.00	1	2956	2956
54.0	-.00	.00	75.00	1	2956	2956
55.0	-.00	.00	75.00	1	2956	2956
56.0	-.00	.00	75.00	1	2956	2956
57.0	-.00	.00	75.00	1	2956	2956
58.0	-.00	.00	75.00	1	2956	2956
59.0	-.00	.00	75.00	1	2956	2956
60.0	-.00	.00	75.00	1	2956	2956

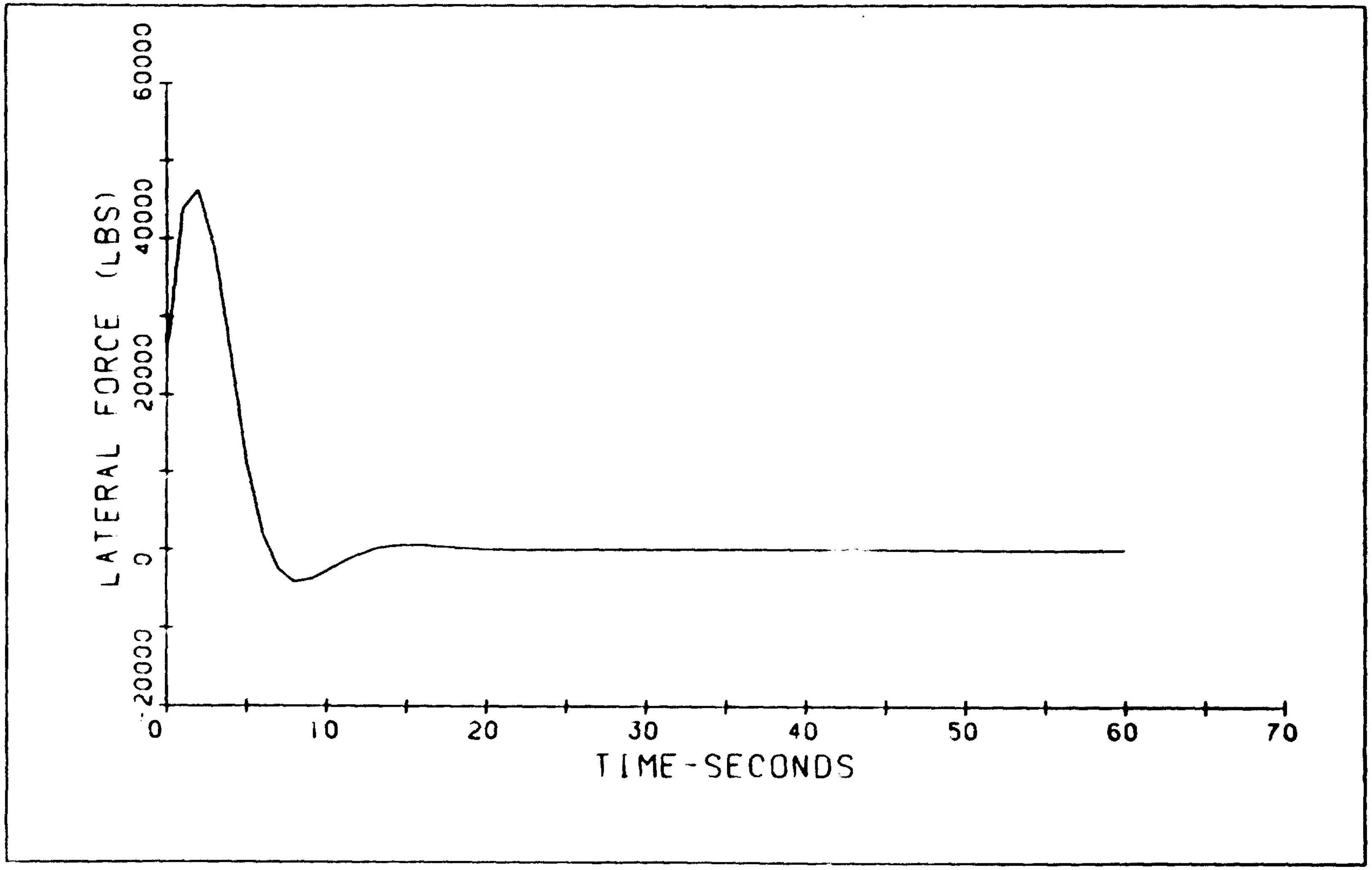
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

Wind = 60 Knots @ 75°



•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

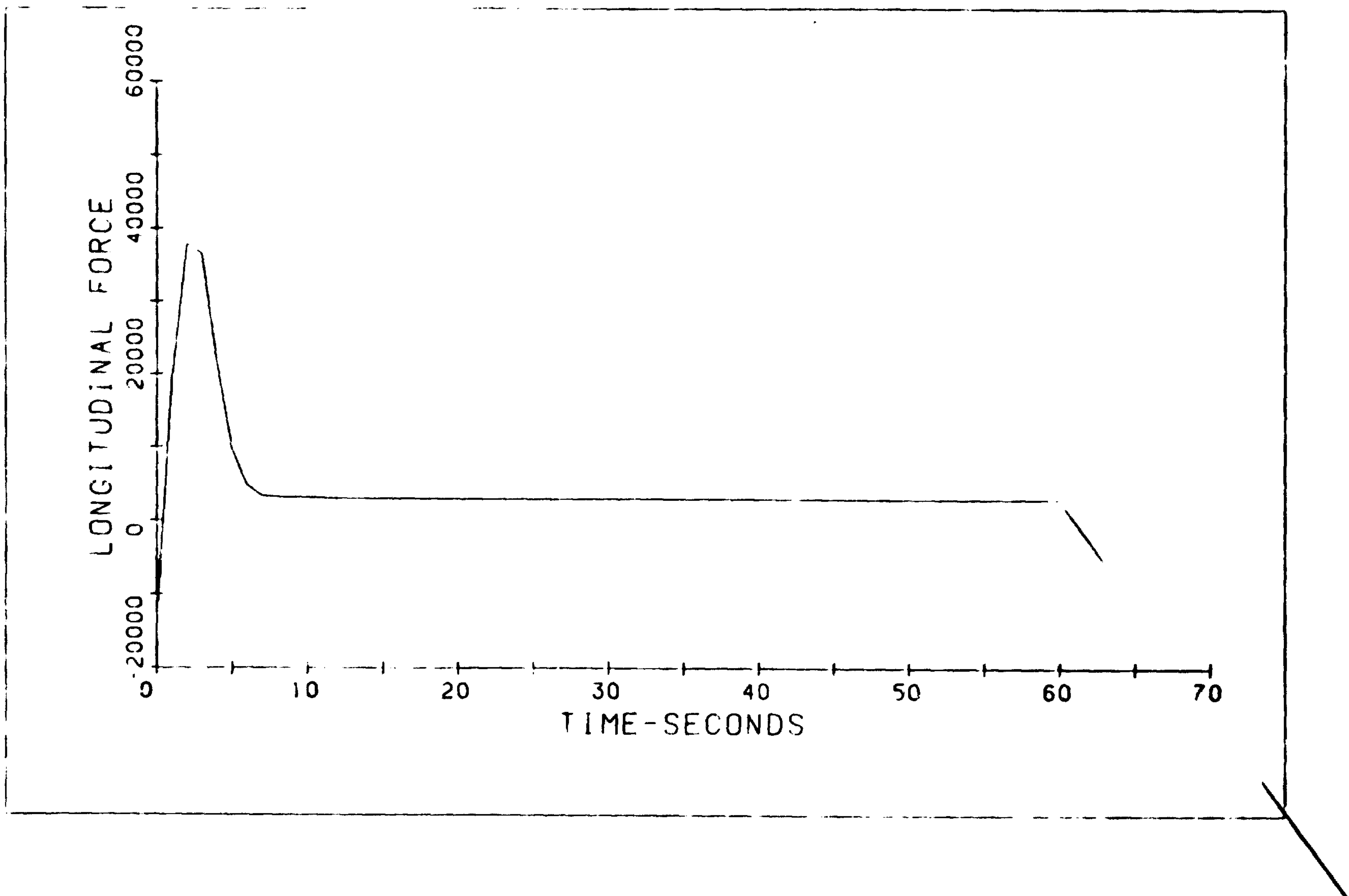
Wind = 60 Knots @ 75°



•• MARITIME PATROL AIRSHIP ••

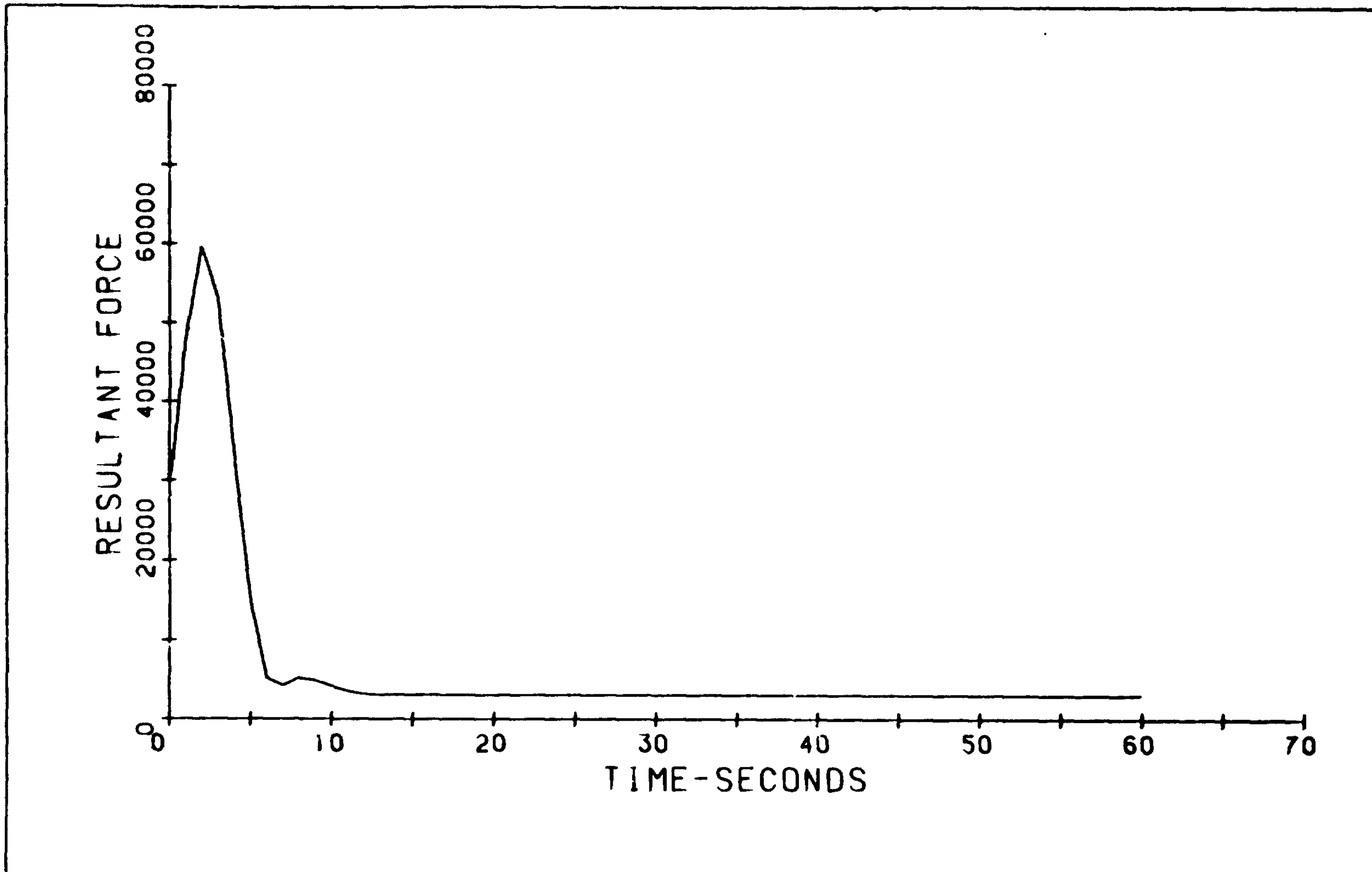
•• BOW MOORED ••

Wind = 60 Knots @ 75°



•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 75°



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*                                         *
*    AIRSHIP MOORING LOADS ANALYSIS       *
*                                         *
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET
```

MOORING STYLE

```
** BOW MOORED **
MAST LOCATION RELATIVE TO NOSE........:       .0 FEET
HEIGHT OF MAST........................:     50.0 FEET
MOMENT OF INERTIA ABOUT MAST..........: .597E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     90.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
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OF POOR QUALITY

** MARITIME PATROL AIRSHIP **

** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
.0	31.84	.00	.00	3769	-15382	15837
1.0	7.47	15.09	9.36	32954	19536	38310
2.0	3.00	20.23	27.38	45674	41269	61557
3.0	-2.05	20.87	48.35	45009	47496	65434
4.0	-5.71	16.74	67.47	35448	33241	48596
5.0	-5.87	10.70	81.20	18708	15757	24460
6.0	-4.27	5.58	89.20	6126	6749	9115
7.0	-2.66	2.13	92.92	-820	3886	3972
8.0	-1.34	.16	93.96	-3778	3287	5008
9.0	-.57	-.74	93.60	-4159	3225	5263
10.0	-.13	-1.08	92.66	-3336	3192	4617
11.0	.15	-1.05	91.57	-2179	3156	3835
12.0	.29	-.82	90.62	-1066	3082	3262
13.0	.30	-.52	89.95	-208	3036	3043
14.0	.25	-.24	89.57	328	3018	3036
15.0	.17	-.03	89.44	570	3003	3057
16.0	.09	.10	89.48	593	2989	3047
17.0	.02	.15	89.61	485	2976	3016
18.0	-.02	.15	89.76	324	2971	2989
19.0	-.04	.12	89.90	166	2966	2971
20.0	-.04	.08	90.00	43	2964	2964
21.0	-.04	.04	90.05	-35	2964	2964
22.0	-.02	.01	90.07	-72	2963	2964
23.0	-.01	-.01	90.07	-78	2961	2962
24.0	-.00	-.02	90.05	-64	2959	2959
25.0	.00	-.02	90.03	-43	2958	2958
26.0	.01	-.02	90.01	-21	2957	2957
27.0	.01	-.01	90.00	-4	2957	2957
28.0	.01	-.00	89.99	7	2957	2957
29.0	.00	-.00	89.99	12	2957	2957
30.0	.00	.00	89.99	14	2957	2957
31.0	.00	.00	89.99	12	2957	2957
32.0	-.00	.00	89.99	10	2957	2957
33.0	-.00	.00	89.99	7	2957	2957
34.0	-.00	.00	90.00	5	2956	2956
35.0	-.00	.00	90.00	2	2956	2956
36.0	-.00	.00	90.00	1	2956	2956
37.0	-.00	.00	90.00	1	2956	2956
38.0	-.00	.00	90.00	1	2956	2956
39.0	-.00	.00	90.00	1	2956	2956
40.0	-.00	.00	90.00	1	2956	2956
41.0	-.00	.00	90.00	1	2956	2956
42.0	-.00	.00	90.00	1	2956	2956
43.0	-.00	.00	90.00	1	2956	2956
44.0	-.00	.00	90.00	1	2956	2956
45.0	-.00	.00	90.00	1	2956	2956
46.0	-.00	.00	90.00	1	2956	2956
47.0	-.00	.00	90.00	1	2956	2956

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OF POOR QUALITY

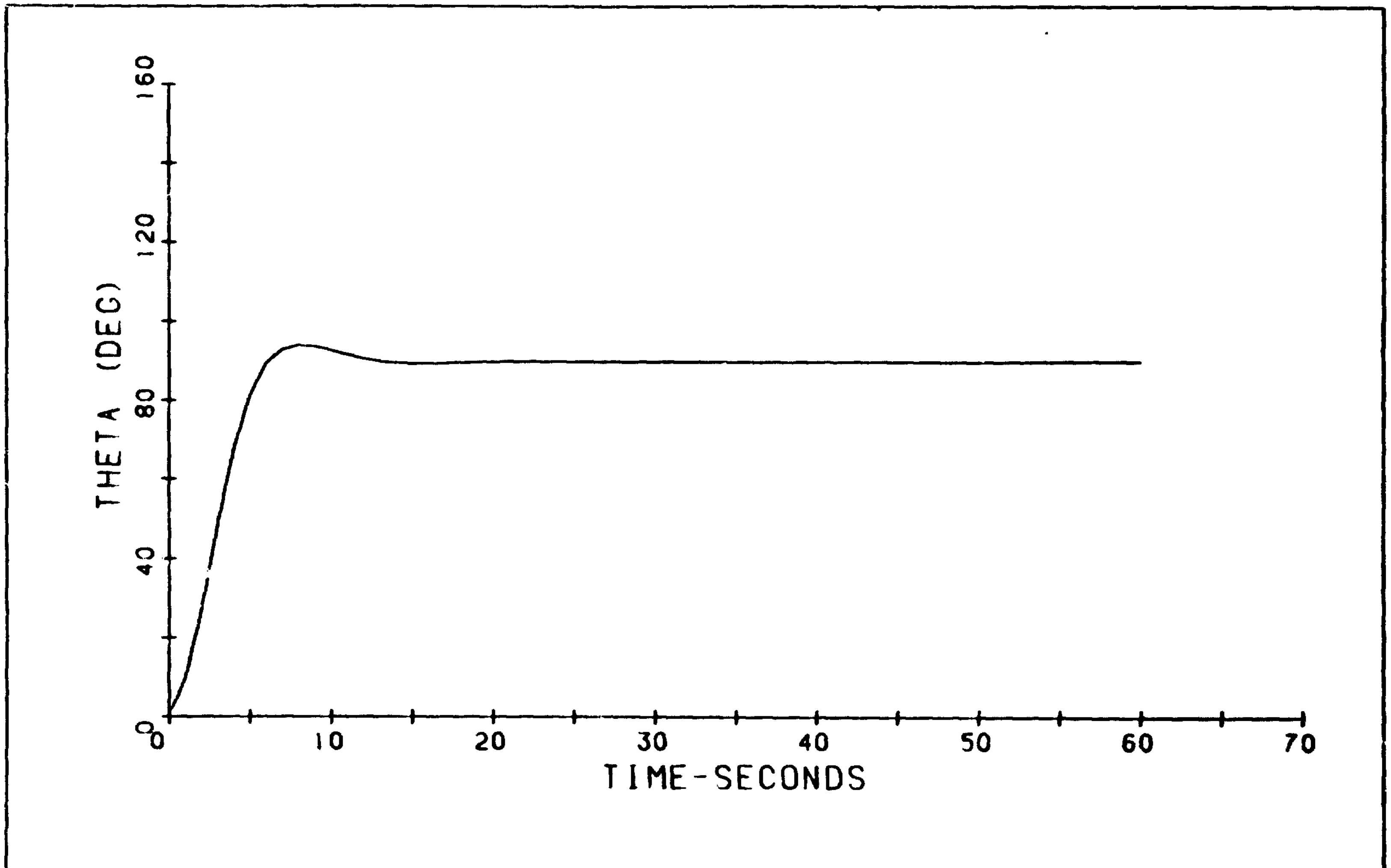
** MARITIME PATROL AIRSHIP **
** BOW MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS
48.0	-.00	.00	90.00	1	2956	2956
49.0	-.00	.00	90.00	1	2956	2956
50.0	-.00	.00	90.00	1	2956	2956
51.0	-.00	.00	90.00	1	2956	2956
52.0	-.00	.00	90.00	1	2956	2956
53.0	-.00	.00	90.00	1	2956	2956
54.0	-.00	.00	90.00	1	2956	2956
55.0	-.00	.00	90.00	1	2956	2956
56.0	-.00	.00	90.00	1	2956	2956
57.0	-.00	.00	90.00	1	2956	2956
58.0	-.00	.00	90.00	1	2956	2956
59.0	-.00	.00	90.00	1	2956	2956
60.0	-.00	.00	90.00	1	2956	2956

EXIT

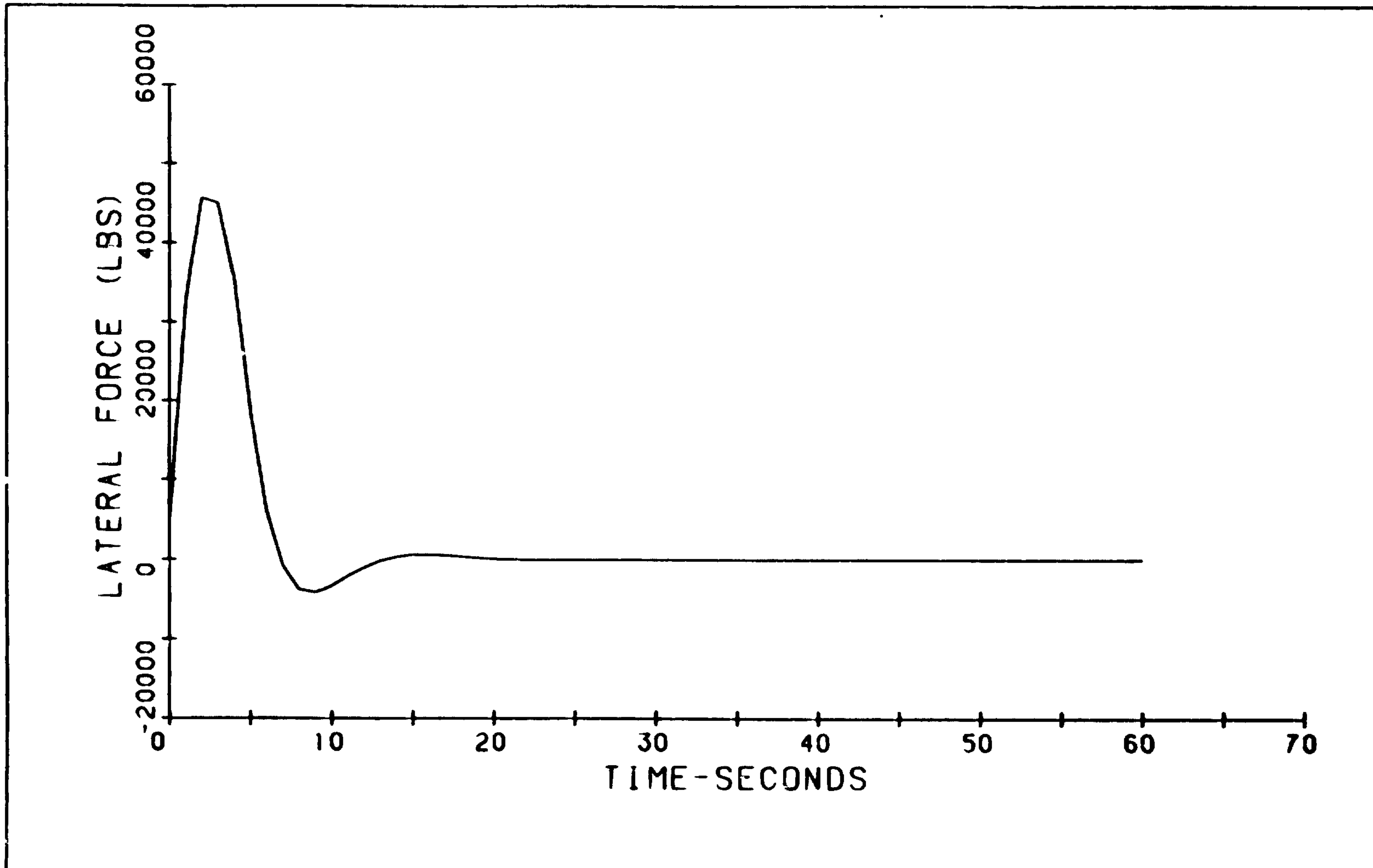
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 90°



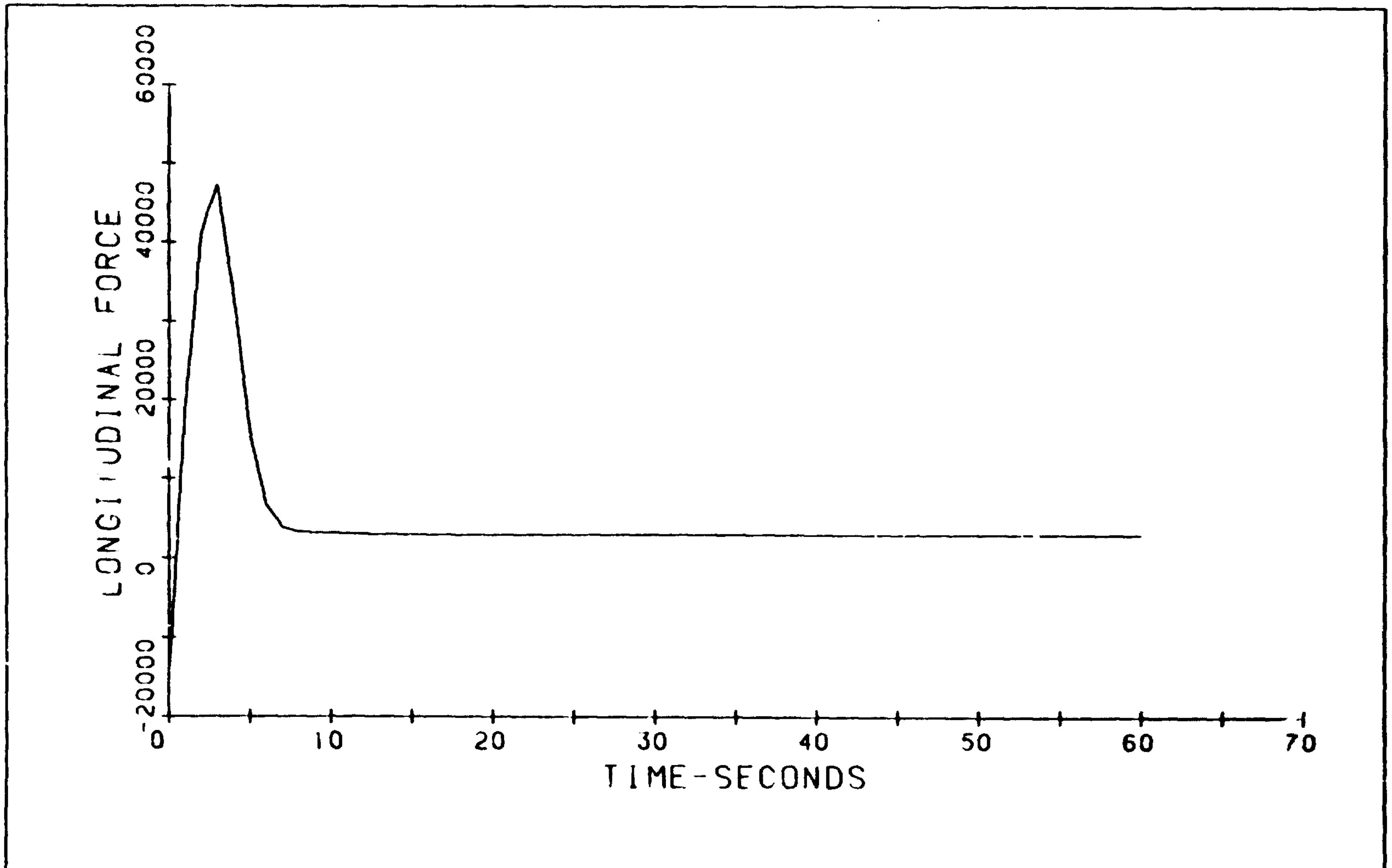
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 90°



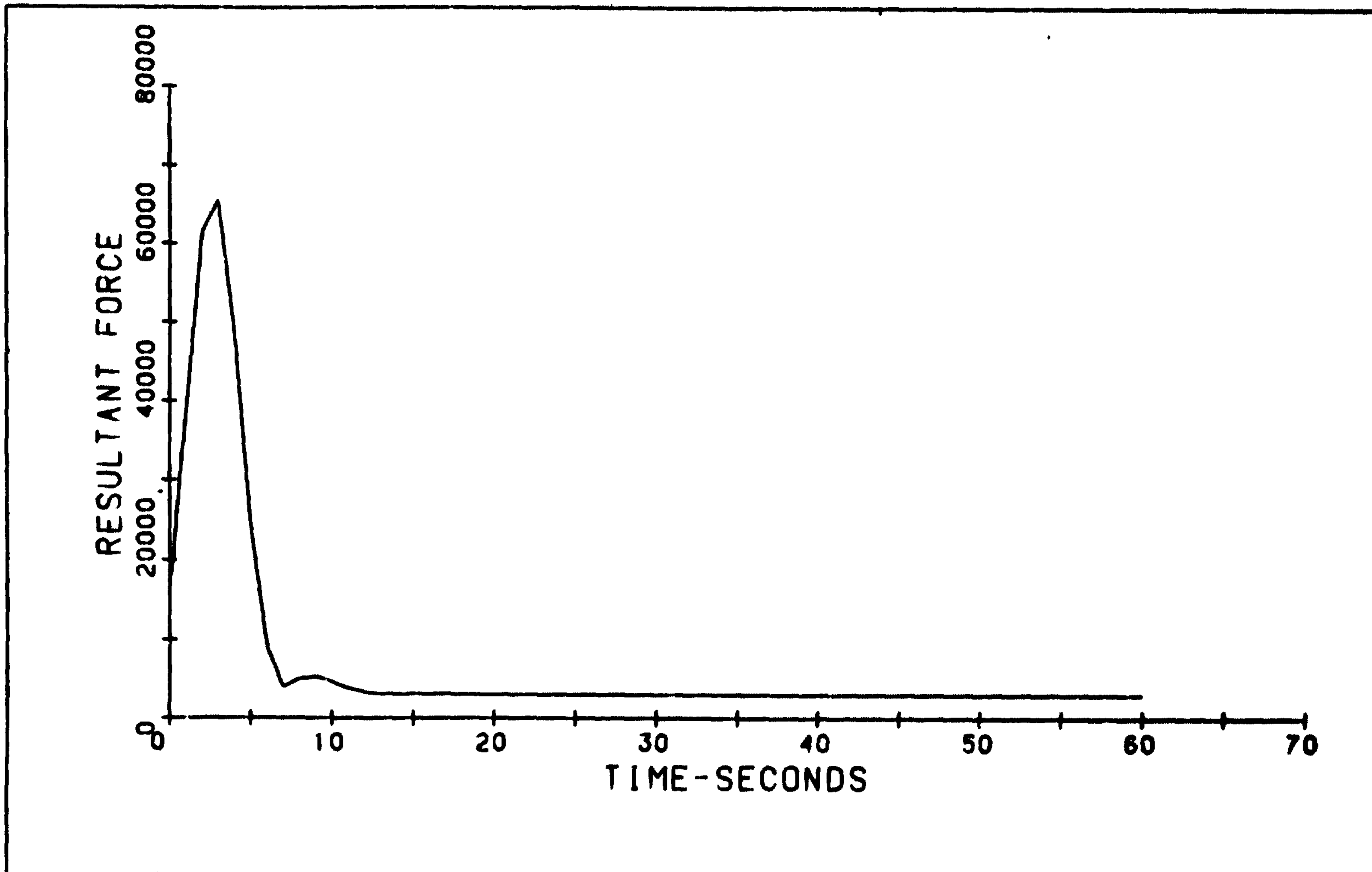
•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 90°



•• MARITIME PATROL AIRSHIP ••
•• BOW MOORED ••

Wind = 60 Knots @ 90°



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*                                       *
*    AIRSHIP MOORING LOADS ANALYSIS     *
*                                       *
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET
```

MOORING STYLE

```
** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE.......:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     15.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
```

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
.0	5.39	.00	.00	27697	4140	28005	325	16245	0
1.0	1.26	2.99	1.84	30581	4501	30910	353	17922	0
2.0	-.24	3.39	5.15	25414	4425	25796	347	15029	0
3.0	-.65	2.86	8.31	18351	3968	18775	311	11005	0
4.0	-.66	2.20	10.84	12117	3562	12629	279	7453	0
5.0	-.59	1.57	12.72	7274	3292	7984	258	4702	0
6.0	-.48	1.04	14.01	3766	3125	4894	245	2715	0
7.0	-.36	.62	14.83	1410	3029	3341	237	1384	0
8.0	-.25	.32	15.30	-35	2998	2998	235	573	612
9.0	-.16	.12	15.51	-809	3001	3109	235	142	1044
10.0	-.09	-.00	15.56	-1126	3000	3205	235	0	1220
11.0	-.04	-.07	15.52	-1157	2995	3211	235	0	1236
12.0	-.01	-.10	15.43	-1030	2988	3161	234	16	1164
13.0	.01	-.10	15.33	-833	2980	3094	234	124	1053
14.0	.02	-.09	15.24	-624	2973	3037	233	239	935
15.0	.02	-.07	15.16	-433	2967	2998	233	344	828
16.0	.02	-.05	15.09	-277	2962	2975	232	431	740
17.0	.02	-.04	15.05	-158	2960	2964	232	497	673
18.0	.01	-.02	15.02	-74	2958	2959	232	543	626
19.0	.01	-.01	15.00	-19	2957	2957	232	573	595
20.0	.01	-.01	14.99	12	2957	2957	232	591	577
21.0	.00	-.00	14.98	28	2958	2958	232	600	569
22.0	.00	.00	14.98	33	2957	2958	232	603	566
23.0	.00	.00	14.99	31	2957	2957	232	602	566
24.0	.00	.00	14.99	27	2957	2957	232	599	569
25.0	-.00	.00	14.99	21	2957	2957	232	596	572
26.0	-.00	.00	14.99	15	2957	2957	232	593	575
27.0	-.00	.00	15.00	10	2956	2956	232	590	578
28.0	-.00	.00	15.00	6	2956	2956	232	588	580
29.0	-.00	.00	15.00	3	2956	2956	232	586	582
30.0	-.00	.00	15.00	2	2956	2956	232	585	583
31.0	-.00	.00	15.00	0	2956	2956	232	584	584
32.0	-.00	.00	15.00	0	2956	2956	232	584	584
33.0	-.00	.00	15.00	0	2956	2956	232	584	584
34.0	-.00	.00	15.00	0	2956	2956	232	584	584
35.0	-.00	-.00	15.00	0	2956	2956	232	584	584
36.0	.00	-.00	15.00	0	2956	2956	232	584	584
37.0	.00	-.00	15.00	0	2956	2956	232	584	584
38.0	.00	.00	15.00	0	2956	2956	232	584	584
39.0	.00	.00	15.00	0	2956	2956	232	584	584
40.0	.00	.00	15.00	0	2956	2956	232	584	584
41.0	.00	.00	15.00	0	2956	2956	232	584	584
42.0	.00	.00	15.00	0	2956	2956	232	584	584
43.0	.00	.00	15.00	0	2956	2956	232	584	584
44.0	.00	.00	15.00	0	2956	2956	232	584	584
45.0	.00	.00	15.00	0	2956	2956	232	584	584
46.0	.00	.00	15.00	0	2956	2956	232	584	584
47.0	-.00	.00	15.00	0	2956	2956	232	584	584

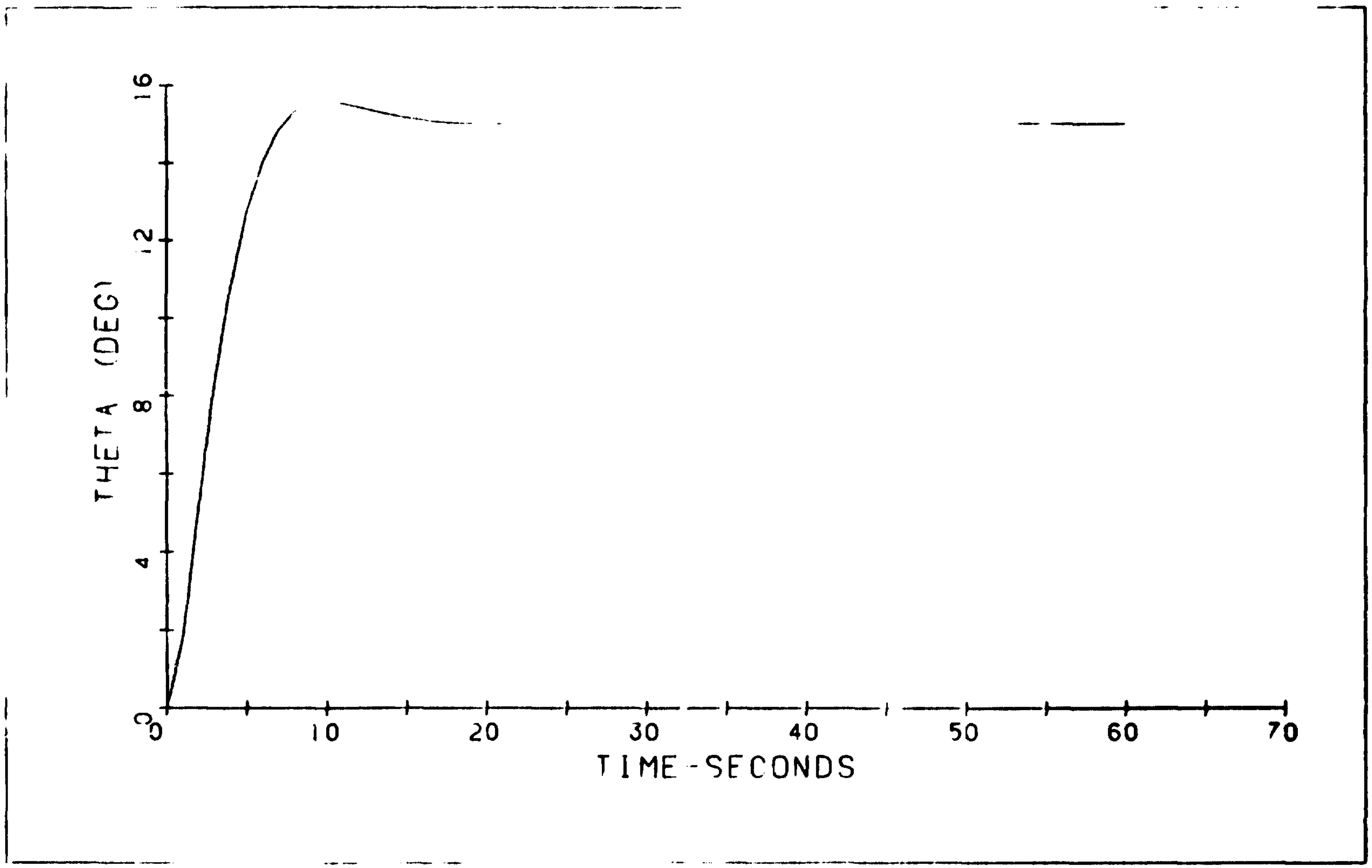
ORIGINAL PAGE IS
OF POOR QUALITY

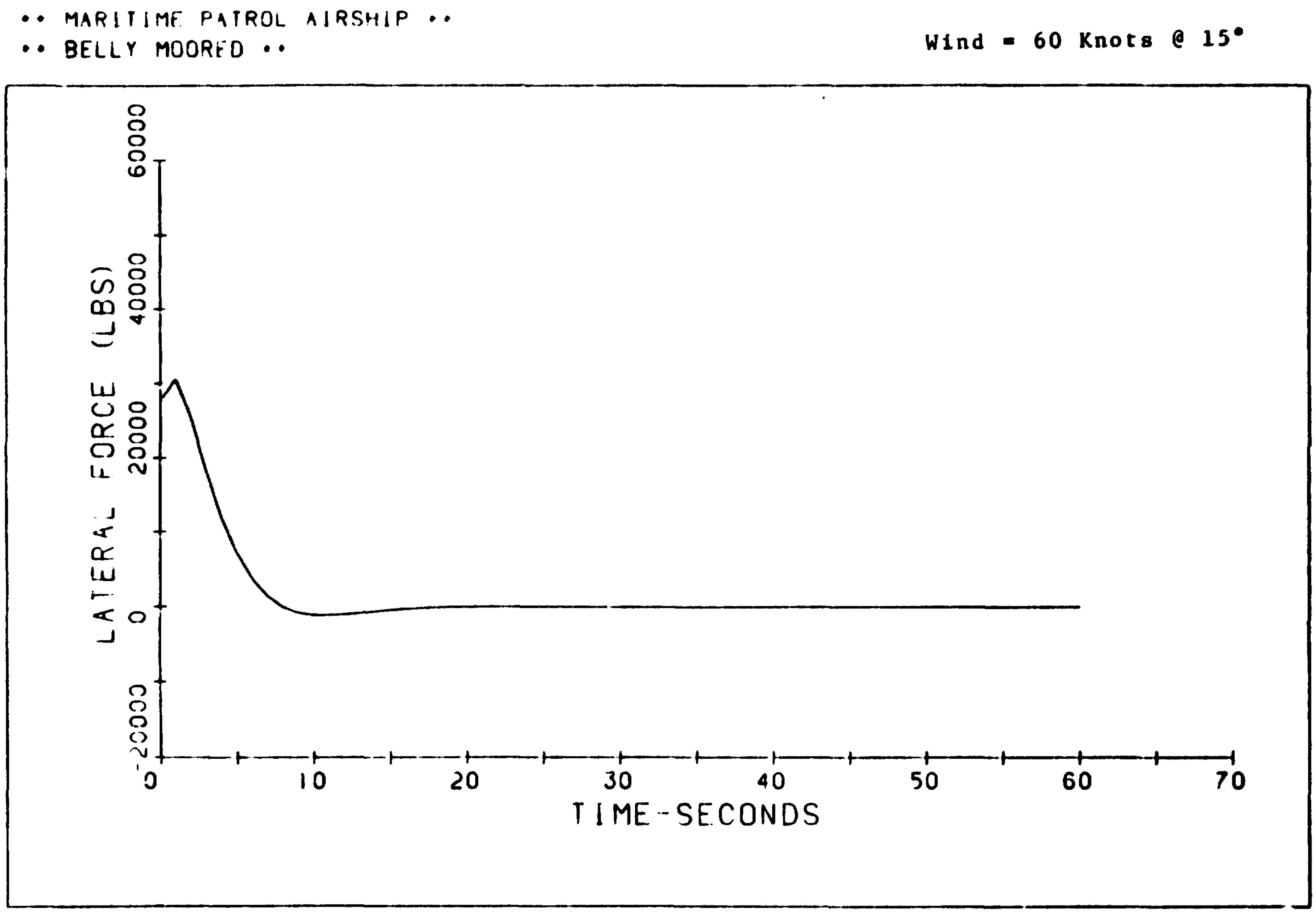
** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	-.00	.00	15.00	0	2956	2956	232	584	584
49.0	-.00	.00	15.00	0	2956	2956	232	584	584
50.0	-.00	.00	15.00	0	2956	2956	232	584	584
51.0	-.00	.00	15.00	0	2956	2956	232	584	584
52.0	-.00	.00	15.00	0	2956	2956	232	584	584
53.0	-.00	.00	15.00	0	2956	2956	232	584	584
54.0	-.00	.00	15.00	0	2956	2956	232	584	584
55.0	-.00	.00	15.00	0	2956	2956	232	584	584
56.0	-.00	.00	15.00	0	2956	2956	232	584	584
57.0	-.00	.00	15.00	0	2956	2956	232	584	584
58.0	-.00	.00	15.00	0	2956	2956	232	584	584
59.0	-.00	.00	15.00	0	2956	2956	232	584	584
60.0	-.00	.00	15.00	0	2956	2956	232	584	584

•• MARITIME PAT OL AIRSHIP ••
•• BELLY MOORED ••

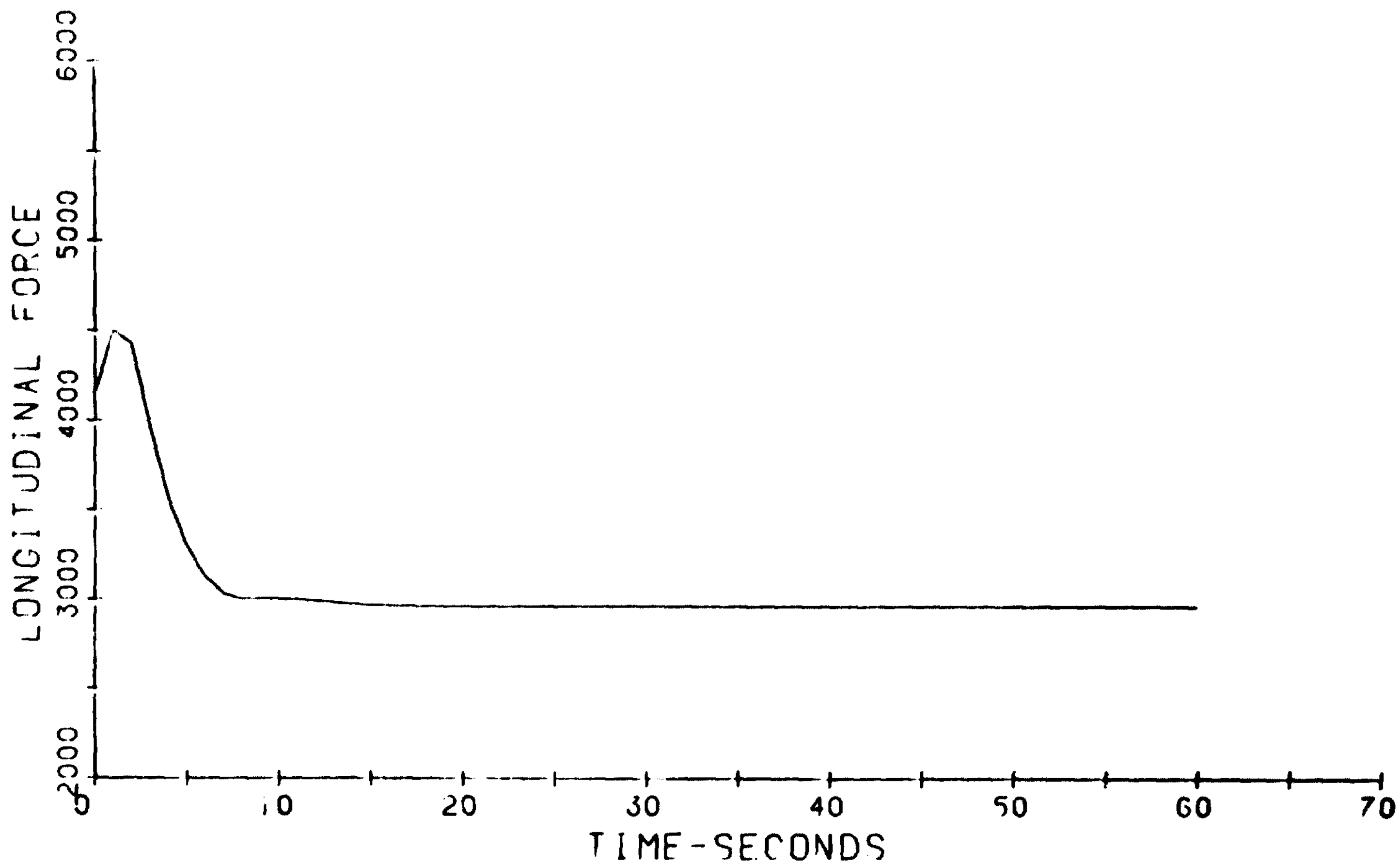
Wind = 60 Knots @ 15°




** MARITIME PATROL AIRSHIP **
** BELLY MOORED **
Wind = 60 Knots @ 15°
LATERAL FORCE (LBS)
60000
40000
20000
0
-20000
0
10
20
30
40
50
60
70
TIME-SECONDS

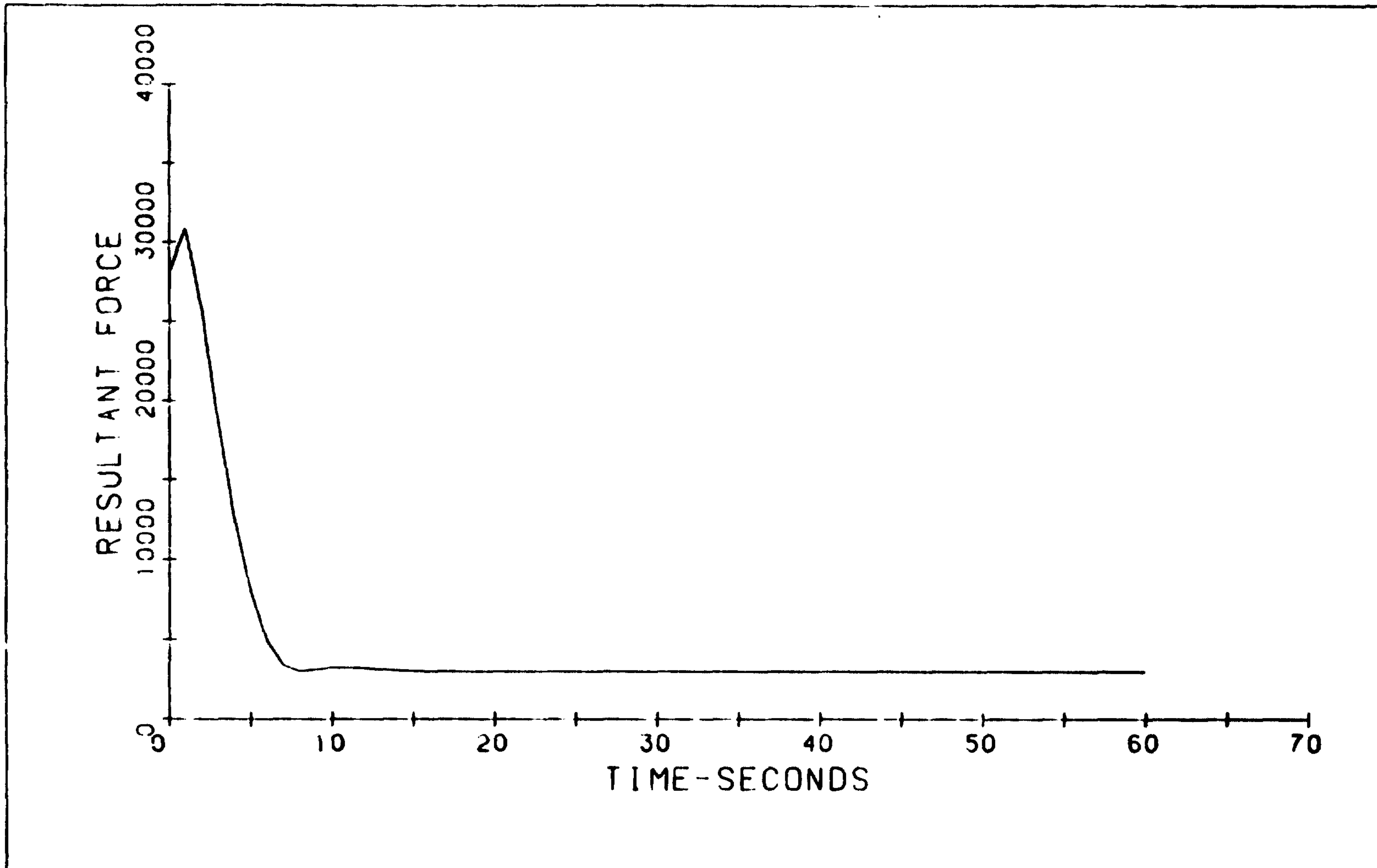
** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

Wind = 60 Knots @ 15°



•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 15°



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OF POOR QUALITY

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*****************************************
*                                       *
*    AIRSHIP MOORING LOADS ANALYSIS     *
*                                       *
*****************************************

AIRSHIP CONFIGURATION DATA
--------------------------

** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET

MOORING STYLE
-------------

** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE........:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ

INITIAL CONDITIONS
------------------

WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     30.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
```

ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
.0	14.23	.00	.00	50683	3160	50781	248	28853	0
1.0	2.44	7.16	4.52	59601	7057	60017	554	34590	0
2.0	-1.15	7.44	12.12	48696	7826	49320	614	28669	0
3.0	-1.73	5.79	18.77	32778	6041	33330	474	19450	0
4.0	-1.52	4.16	23.72	19784	4621	20317	362	11933	0
5.0	-1.24	2.78	27.17	10454	3759	11109	295	6565	0
6.0	-.94	1.69	29.38	4160	3285	5301	258	2967	0
7.0	-.66	.89	30.64	259	3094	3105	243	756	467
8.0	-.43	.35	31.25	-1874	3075	3602	241	0	1652
9.0	-.25	.02	31.42	-2791	3069	4148	241	0	2161
10.0	-.12	-.16	31.33	-2939	3058	4241	240	0	2241
11.0	-.04	-.24	31.12	-2653	3041	4036	238	0	2079
12.0	.01	-.25	30.87	-2170	3021	3720	237	0	1806
13.0	.04	-.23	30.62	-1640	3002	3421	235	0	1507
14.0	.05	-.19	30.42	-1150	2985	3200	234	0	1231
15.0	.04	-.14	30.25	-744	2974	3065	233	173	1002
16.0	.04	-.10	30.13	-432	2967	2998	233	345	827
17.0	.03	-.06	30.05	-210	2962	2969	232	468	702
18.0	.02	-.04	30.00	-64	2959	2960	232	549	620
19.0	.02	-.02	29.97	22	2959	2959	232	597	572
20.0	.01	-.01	29.96	66	2959	2960	232	622	548
21.0	.01	.00	29.96	82	2959	2960	232	630	539
22.0	.00	.01	29.96	80	2959	2960	232	629	540
23.0	.00	.01	29.97	69	2958	2959	232	623	546
24.0	-.00	.01	29.98	55	2958	2958	232	615	554
25.0	-.00	.01	29.98	40	2957	2958	232	607	561
26.0	-.00	.00	29.99	28	2957	2957	232	600	568
27.0	-.00	.00	29.99	17	2957	2957	232	594	574
28.0	-.00	.00	30.00	10	2956	2956	232	590	578
29.0	-.00	.00	30.00	5	2956	2956	232	587	581
30.0	-.00	.00	30.00	1	2956	2956	232	585	583
31.0	-.00	.00	30.00	0	2956	2956	232	584	584
32.0	-.00	.00	30.00	-1	2956	2956	232	583	585
33.0	-.00	-.00	30.00	-1	2956	2956	232	583	585
34.0	-.00	-.00	30.00	-1	2956	2956	232	583	585
35.0	-.00	-.00	30.00	-1	2956	2956	232	583	585
36.0	.00	-.00	30.00	0	2956	2956	232	584	585
37.0	.00	-.00	30.00	0	2956	2956	232	584	584
38.0	.00	-.00	30.00	0	2956	2956	232	584	584
39.0	.00	-.00	30.00	0	2956	2956	232	584	584
40.0	.00	-.00	30.00	0	2956	2956	232	584	584
41.0	.00	.00	30.00	0	2956	2956	232	584	584
42.0	.00	.00	30.00	0	2956	2956	232	584	584
43.0	.00	.00	30.00	0	2956	2956	232	584	584
44.0	.00	.00	30.00	0	2956	2956	232	584	584
45.0	.00	.00	30.00	0	2956	2956	232	584	584
46.0	.00	.00	30.00	0	2956	2956	232	584	584
47.0	.00	.00	30.00	0	2956	2956	232	584	584

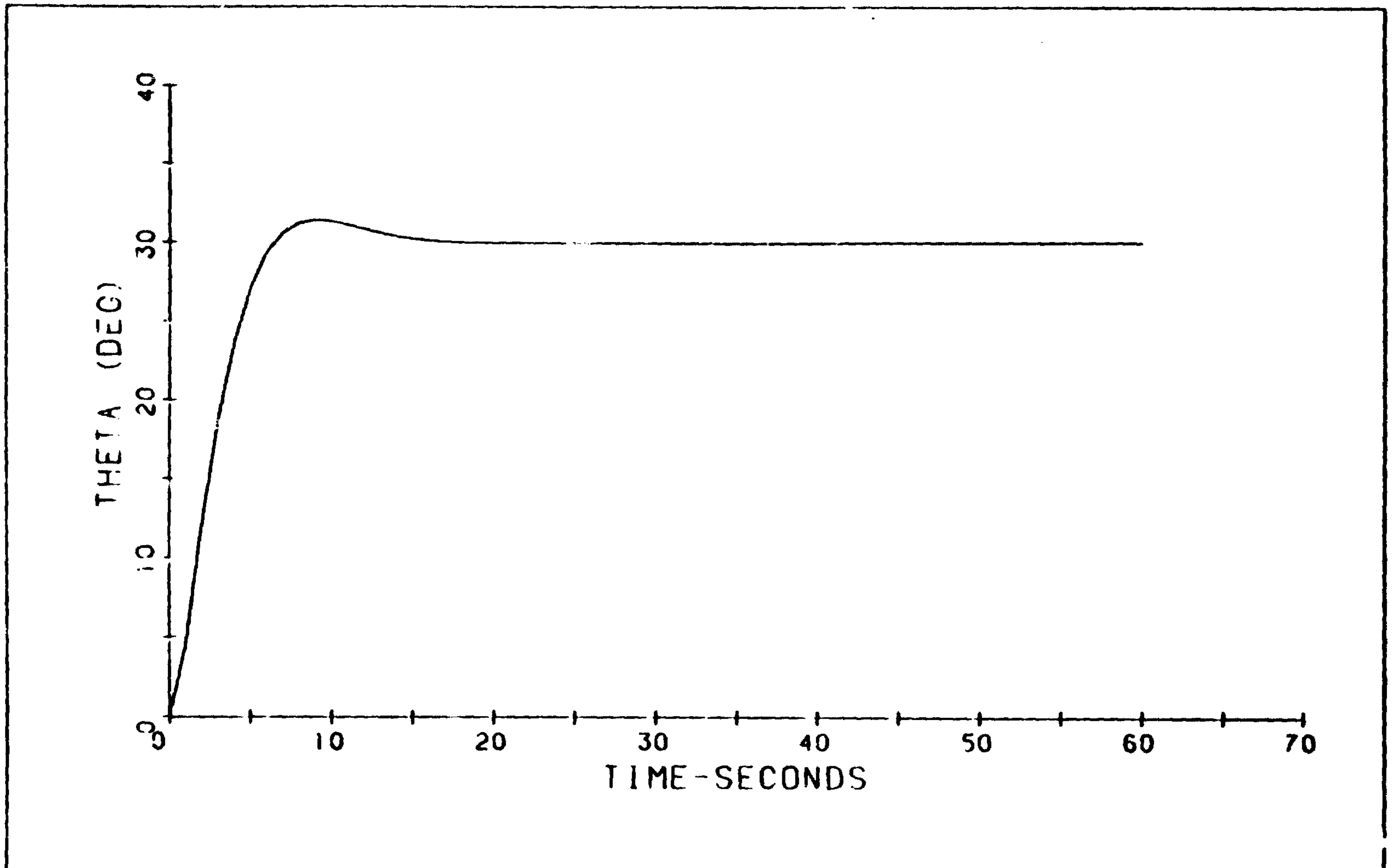
ORIGINAL PAGE IS
OF POOR QUALITY

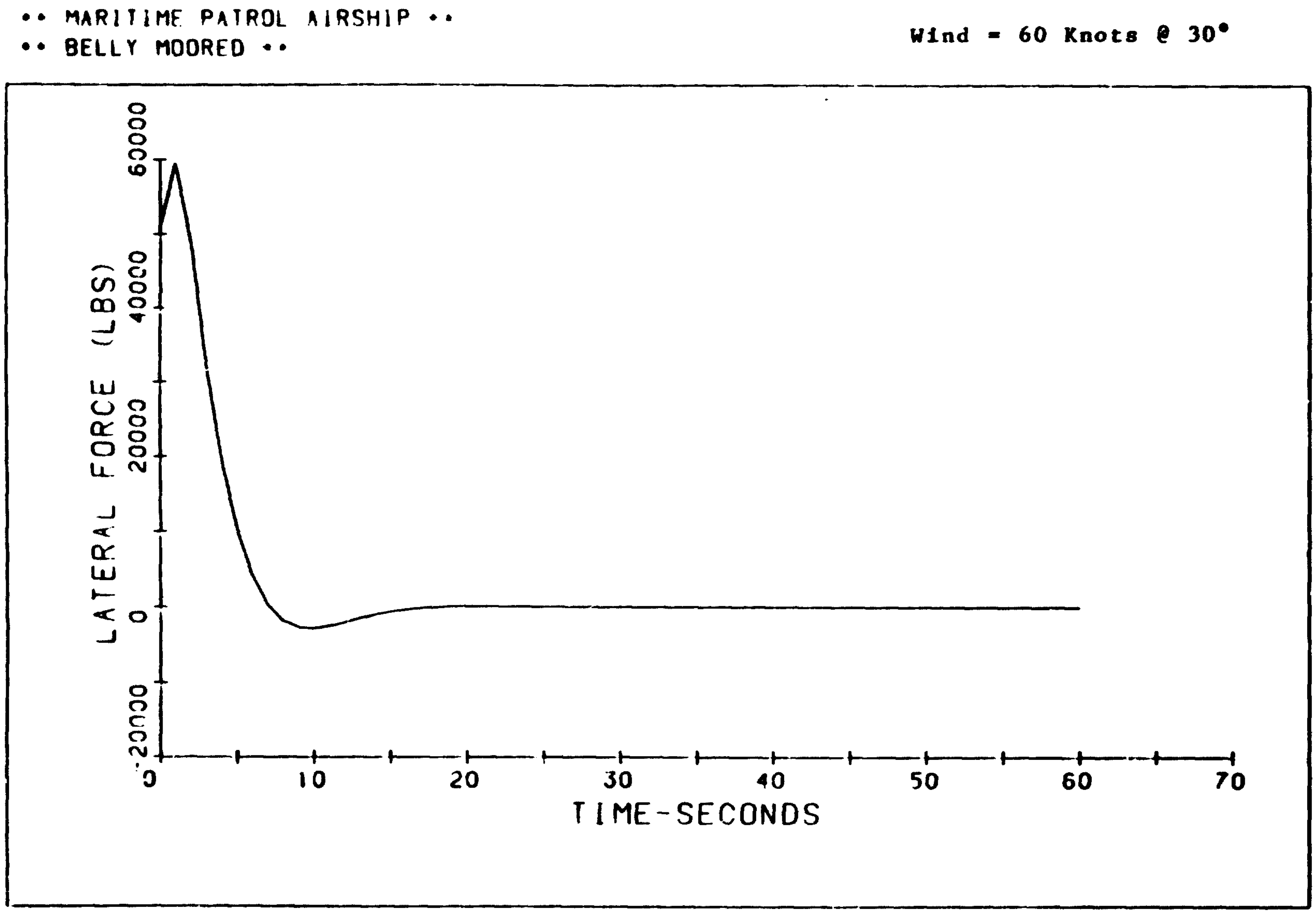
** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	.00	.00	30.00	0	2956	2956	232	584	584
49.0	.00	.00	30.00	0	2956	2956	232	584	584
50.0	.00	.00	30.00	0	2956	2956	232	584	584
51.0	.00	.00	30.00	0	2956	2956	232	584	584
52.0	.00	.00	30.00	0	2956	2956	232	584	584
53.0	.00	.00	30.00	0	2956	2956	232	584	584
54.0	.00	.00	30.00	0	2956	2956	232	584	584
55.0	.00	.00	30.00	0	2956	2956	232	584	584
56.0	.00	.00	30.00	0	2956	2956	232	584	584
57.0	.00	.00	30.00	0	2956	2956	232	584	584
58.0	.00	.00	30.00	0	2956	2956	232	584	584
59.0	.00	.00	30.00	0	2956	2956	232	584	584
60.0	.00	.00	30.00	0	2956	2956	232	584	584

•• MARITIMC PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 30°

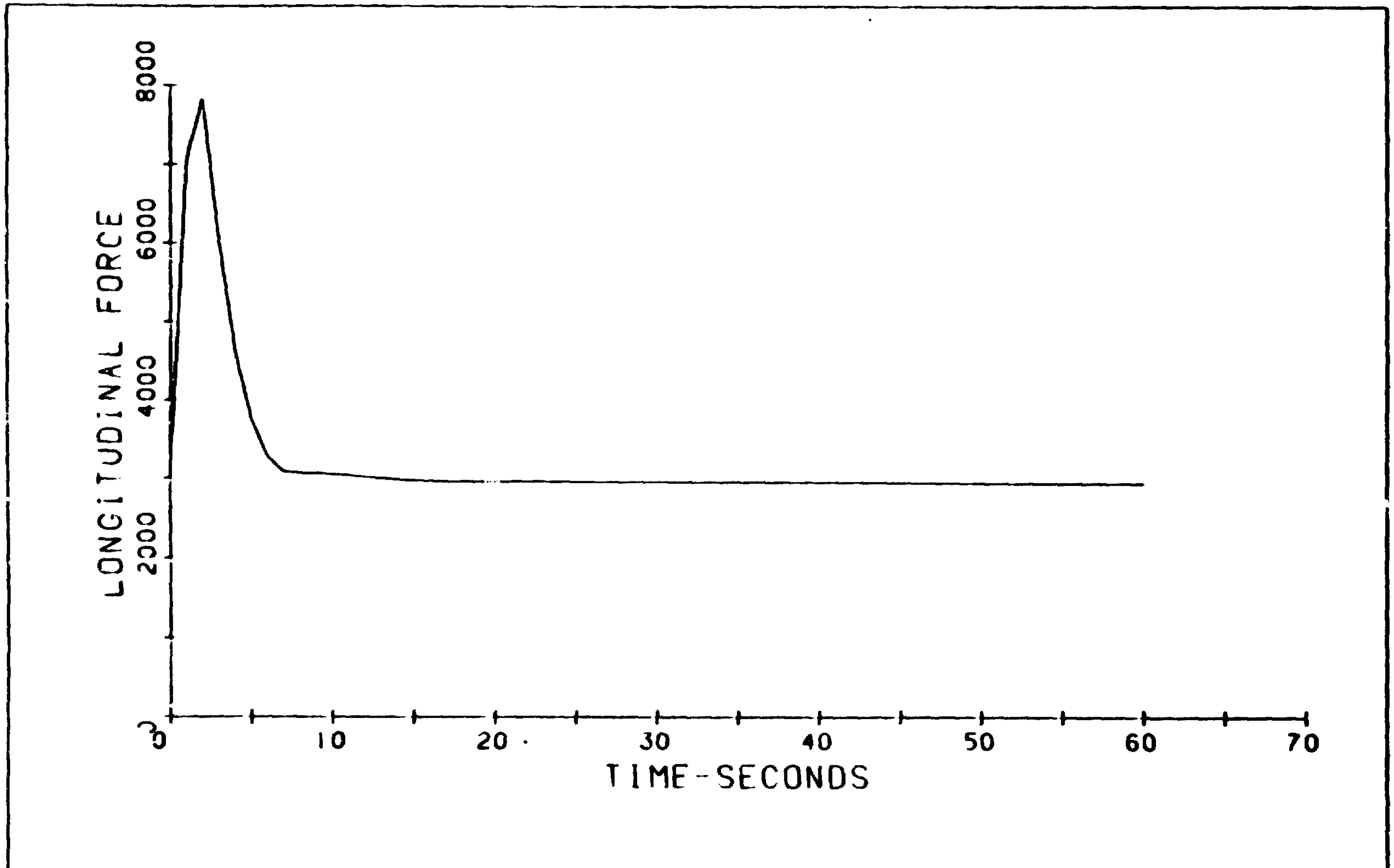




•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••
Wind = 60 Knots @ 30°
LATERAL FORCE (LBS)
60000
40000
20000
0
-20000
0
10
20
30
40
50
60
70
TIME-SECONDS

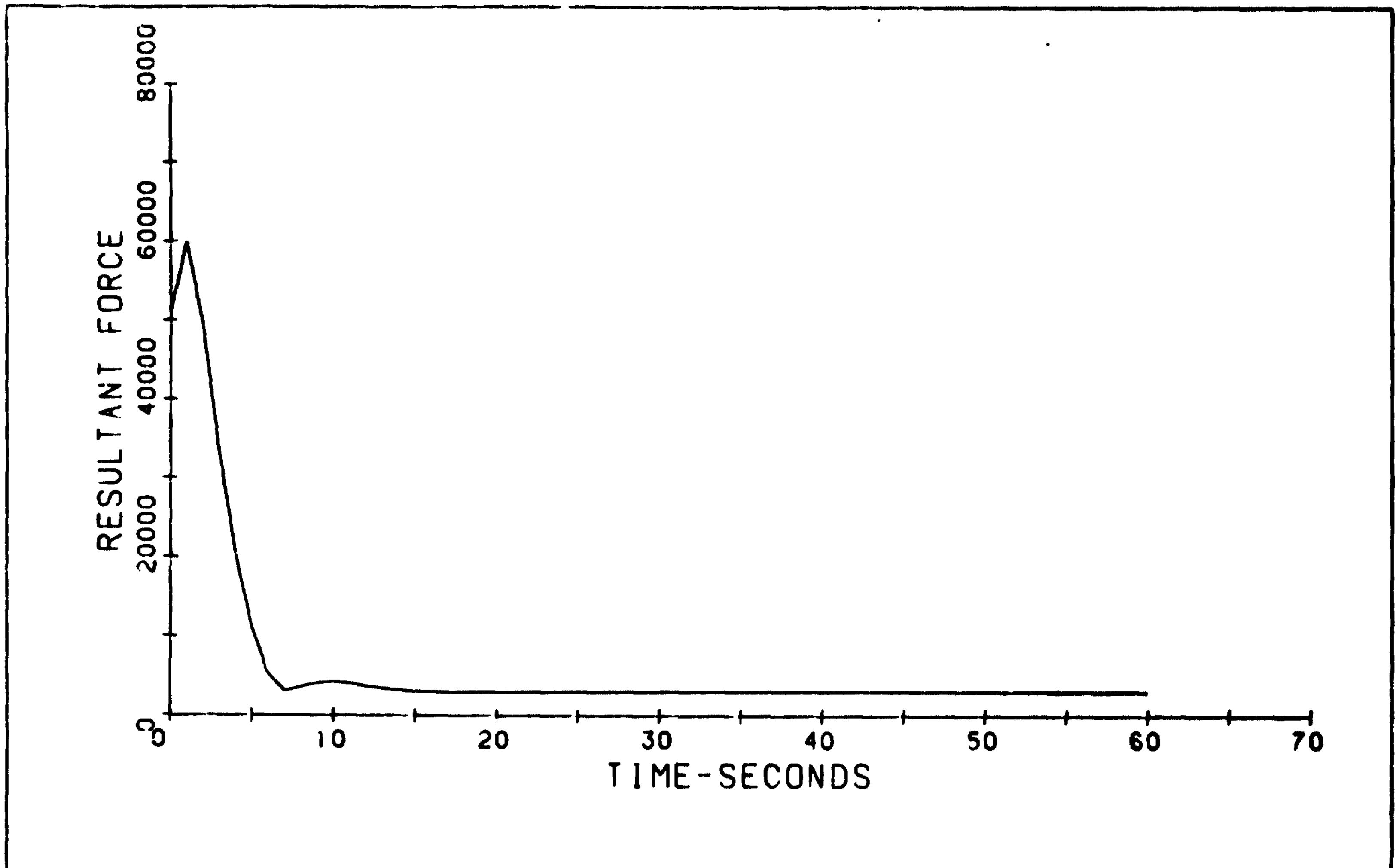
** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

Wind = 60 Knots @ 30°



•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 30°



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*                                      *
*    AIRSHIP MOORING LOADS ANALYSIS    *
*                                      *
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET
```

MOORING STYLE

```
** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE........:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     45.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
```

**ORIGINAL PAGE IS
OF POOR QUALITY**

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
.0	22.93	.00	.00	66817	-2803	66876	0	36660	0
1.0	3.92	10.80	6.88	86892	9753	87437	765	50324	0
2.0	-1.64	11.51	18.50	69832	12442	70932	977	41354	0
3.0	-2.91	8.98	28.85	48442	9588	49381	753	28876	0
4.0	-2.46	6.28	36.44	28165	6400	28883	502	16952	0
5.0	-2.00	4.06	41.57	13966	4491	14670	352	8666	0
6.0	-1.49	2.31	44.72	4684	3504	5850	275	3302	0
7.0	-.95	1.10	46.37	-795	3190	3288	250	187	1073
8.0	-.57	.36	47.07	-3506	3141	4707	246	0	2574
9.0	-.32	-.08	47.19	-4498	3126	5478	245	0	3123
10.0	-.14	-.31	46.98	-4470	3109	5448	244	0	3106
11.0	-.03	-.39	46.62	-3905	3082	4975	242	0	2784
12.0	.03	-.39	46.23	-3114	3051	4360	239	0	2337
13.0	.06	-.34	45.86	-2301	3021	3798	237	0	1879
14.0	.07	-.27	45.56	-1577	2997	3387	235	0	1471
15.0	.07	-.20	45.33	-991	2980	3141	234	37	1141
16.0	.06	-.14	45.16	-551	2970	3021	233	279	894
17.0	.04	-.09	45.05	-246	2963	2974	232	448	723
18.0	.03	-.05	44.98	-51	2960	2960	232	556	613
19.0	.02	-.02	44.95	60	2961	2961	232	619	551
20.0	.01	-.00	44.94	113	2961	2963	232	648	522
21.0	.01	.01	44.94	128	2961	2964	232	656	514
22.0	.00	.01	44.95	120	2960	2962	232	652	518
23.0	.00	.01	44.96	101	2959	2961	232	641	528
24.0	-.00	.01	44.97	78	2958	2959	232	628	541
25.0	-.00	.01	44.98	56	2958	2958	232	616	553
26.0	-.00	.01	44.99	37	2957	2957	232	605	563
27.0	-.00	.00	44.99	23	2957	2957	232	597	571
28.0	-.00	.00	45.00	12	2957	2957	232	591	577
29.0	-.00	.00	45.00	5	2956	2956	232	587	581
30.0	-.00	.00	45.00	1	2956	2956	232	585	583
31.0	-.00	.00	45.00	-1	2956	2956	232	583	585
32.0	-.00	.00	45.00	-2	2956	2956	232	583	585
33.0	-.00	-.00	45.00	-2	2956	2956	232	583	586
34.0	-.00	-.00	45.00	-2	2956	2956	232	583	585
35.0	.00	-.00	45.00	-1	2956	2956	232	583	585
36.0	.00	-.00	45.00	-1	2956	2956	232	583	585
37.0	.00	-.00	45.00	0	2956	2956	232	584	584
38.0	.00	-.00	45.00	0	2956	2956	232	584	584
39.0	.00	-.00	45.00	0	2956	2956	232	584	584
40.0	.00	-.00	45.00	0	2956	2956	232	584	584
41.0	.00	.00	45.00	0	2956	2956	232	584	584
42.0	.00	.00	45.00	0	2956	2956	232	584	584
43.0	.00	.00	45.00	0	2956	2956	232	584	584
44.0	.00	.00	45.00	0	2956	2956	232	584	584
45.0	.00	.00	45.00	0	2956	2956	232	584	584
46.0	.00	.00	45.00	0	2956	2956	232	584	584
47.0	.00	.00	45.00	0	2956	2956	232	584	584

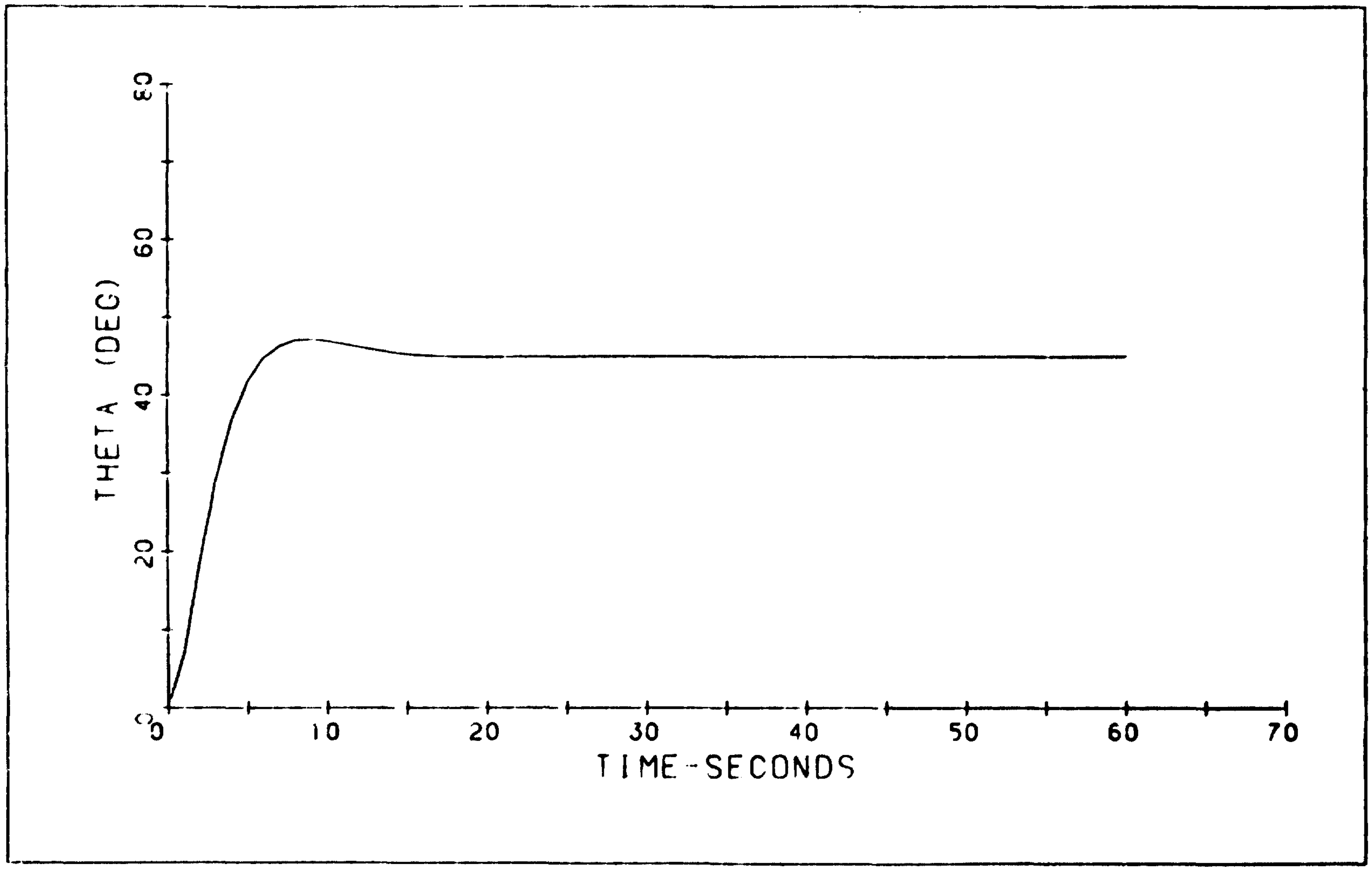
ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	.00	.00	45.00	0	2956	2956	232	584	584
49.0	.00	.00	45.00	0	2956	2956	232	584	584
50.0	.00	.00	45.00	0	2956	2956	232	584	584
51.0	.00	.00	45.00	0	2956	2956	232	584	584
52.0	-.00	.00	45.00	0	2956	2956	232	584	584
53.0	-.00	.00	45.00	0	2956	2956	232	584	584
54.0	-.00	.00	45.00	0	2956	2956	232	584	584
55.0	-.00	.00	45.00	0	2956	2956	232	584	584
56.0	-.00	.00	45.00	0	2956	2956	232	584	584
57.0	-.00	.00	45.00	0	2956	2956	232	584	584
58.0	-.00	.00	45.00	0	2956	2956	232	584	584
59.0	-.00	.00	45.00	0	2956	2956	232	584	584
60.0	-.00	.00	45.00	0	2956	2956	232	584	584

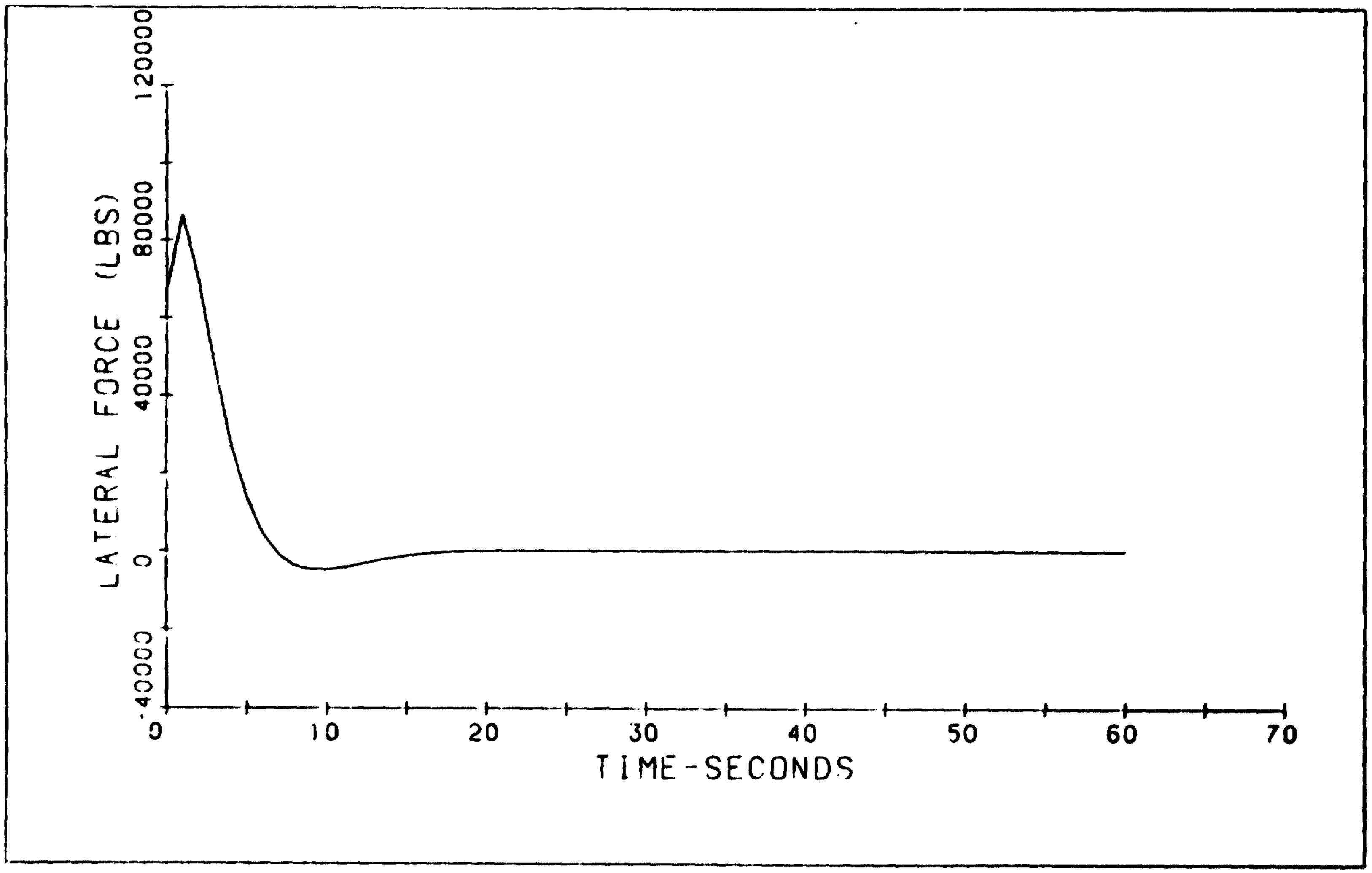
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 45°



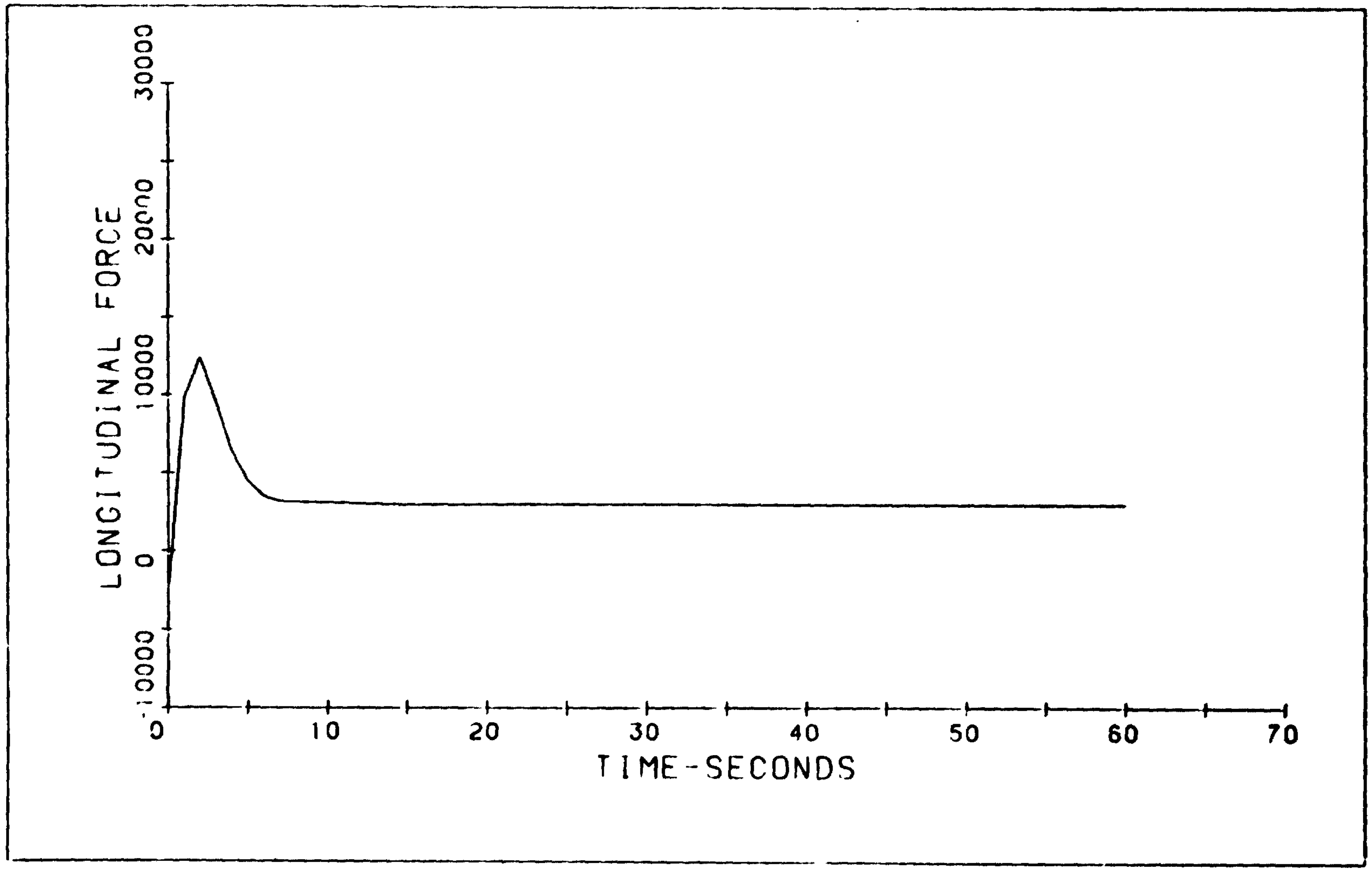
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 45°



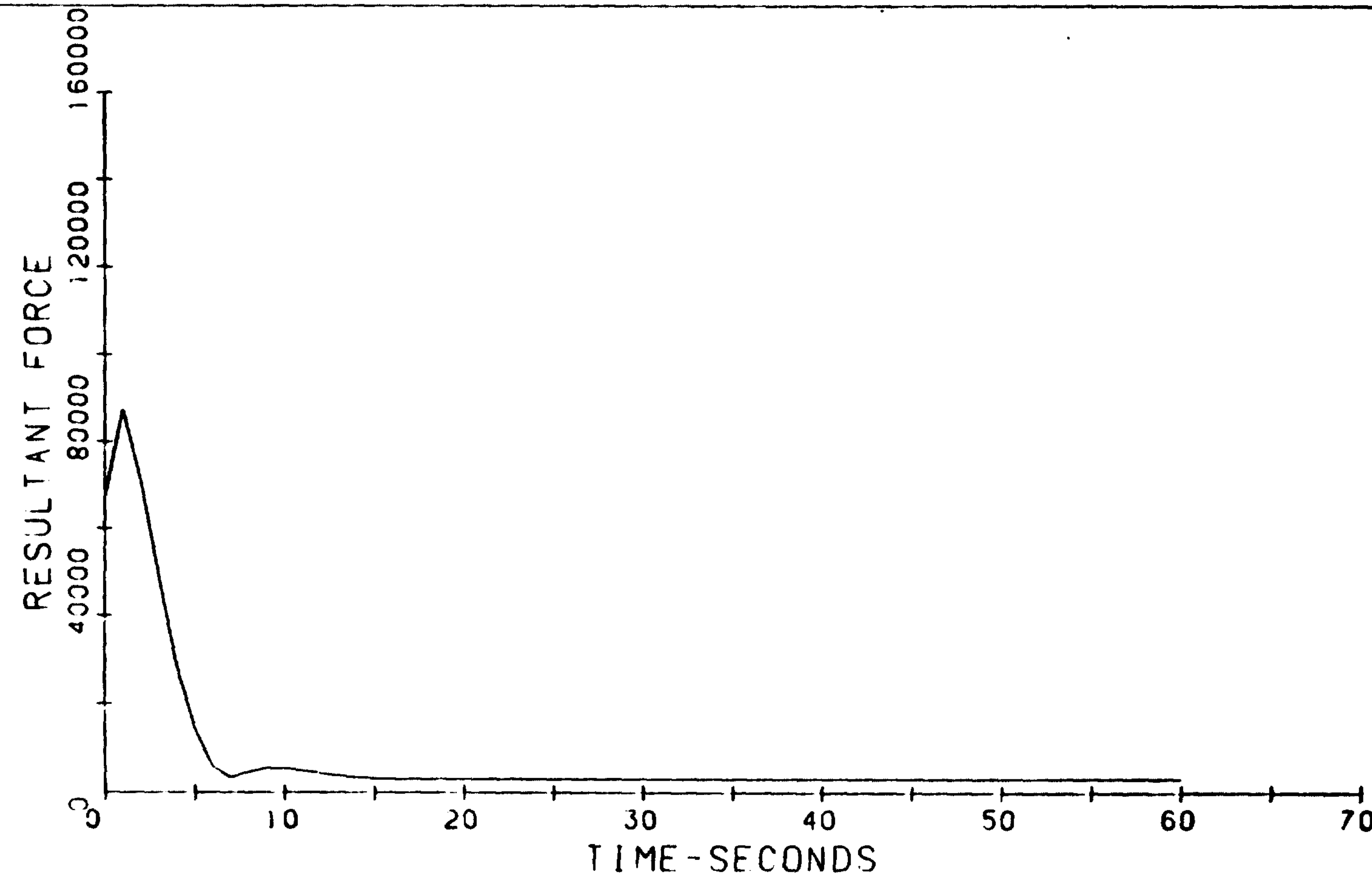
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 45°



•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 45°



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******************************************
*                                        *
*     AIRSHIP MOORING LOADS ANALYSIS     *
*                                        *
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET
```

MOORING STYLE

```
** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE........:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS...:     60.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
```

ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
.0	26.67	.00	.00	76296	-9351	76866	0	40645	0
1.0	5.25	13.52	8.45	104610	11112	105197	872	60461	0
2.0	-1.13	15.10	23.28	93876	17680	95526	1388	55781	0
3.0	-3.58	12.36	37.21	65256	14271	66798	1120	39166	0
4.0	-3.40	8.75	47.75	40255	9314	41319	731	24262	0
5.0	-2.86	5.62	54.89	20283	5716	21073	448	12426	0
6.0	-2.08	3.13	59.20	7346	3894	8315	305	4861	0
7.0	-1.30	1.45	61.43	-137	3273	3276	257	570	724
8.0	-.71	.47	62.34	-3824	3173	4969	249	0	2757
9.0	-.39	-.06	62.51	-5116	3153	6009	247	0	3472
10.0	-.18	-.34	62.30	-5160	3134	6037	246	0	3493
11.0	-.05	-.44	61.89	-4541	3105	5501	243	0	3143
12.0	.03	-.45	61.44	-3643	3069	4764	241	0	2636
13.0	.07	-.39	61.02	-2705	3035	4066	238	0	2107
14.0	.08	-.31	60.66	-1862	3005	3536	236	0	1631
15.0	.08	-.23	60.39	-1174	2985	3208	234	0	1244
16.0	.07	-.16	60.19	-656	2973	3045	233	222	953
17.0	.05	-.10	60.06	-294	2965	2979	232	422	749
18.0	.04	-.06	59.98	-60	2960	2961	232	551	619
19.0	.03	-.02	59.94	73	2962	2963	232	626	544
20.0	.02	-.00	59.93	138	2962	2965	232	662	508
21.0	.01	.01	59.93	157	2962	2966	232	673	498
22.0	.00	.01	59.94	149	2961	2965	232	668	502
23.0	.00	.01	59.95	127	2960	2963	232	656	514
24.0	-.00	.01	59.96	99	2959	2961	232	640	529
25.0	-.00	.01	59.97	74	2958	2959	232	626	543
26.0	-.00	.01	59.98	52	2957	2958	232	614	555
27.0	-.00	.01	59.99	35	2957	2957	232	604	564
28.0	-.00	.00	59.99	23	2957	2957	232	597	571
29.0	-.00	.00	60.00	15	2957	2957	232	593	576
30.0	-.00	.00	60.00	8	2956	2956	232	589	579
31.0	-.00	.00	60.00	7	2956	2956	232	588	580
32.0	-.00	.00	60.00	6	2956	2956	232	588	580
33.0	-.00	.00	60.00	6	2956	2956	232	588	580
34.0	-.00	.00	60.00	6	2956	2956	232	588	581
35.0	-.00	.00	60.00	6	2956	2956	232	588	581
36.0	-.00	.00	60.00	6	2956	2956	232	587	581
37.0	-.00	.00	60.00	6	2956	2956	232	587	581
38.0	-.00	.00	60.00	6	2956	2956	232	587	581
39.0	-.00	.00	60.00	6	2956	2956	232	587	581
40.0	-.00	.00	60.00	6	2956	2956	232	587	581
41.0	-.00	.00	60.00	6	2956	2956	232	587	581
42.0	-.00	.00	60.00	6	2956	2956	232	587	581
43.0	-.00	.00	60.00	6	2956	2956	232	587	581
44.0	-.00	.00	60.00	6	2956	2956	232	587	581
45.0	-.00	.00	60.00	6	2956	2956	232	587	581
46.0	-.00	.00	60.00	6	2956	2956	232	587	581
47.0	-.00	.00	60.00	6	2956	2956	232	587	581

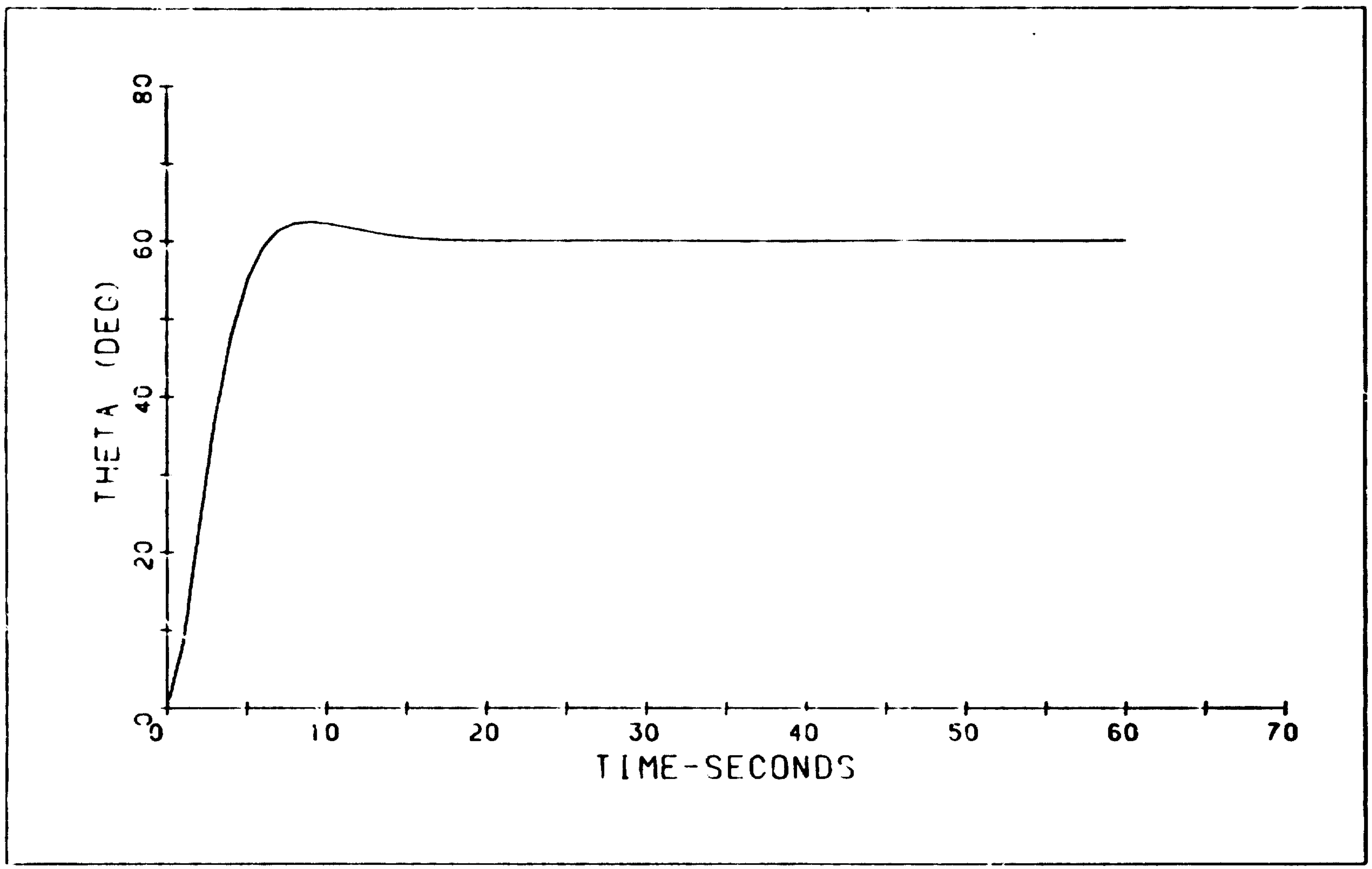
ORIGINAL PAGE IS
OF POOR QUALITY

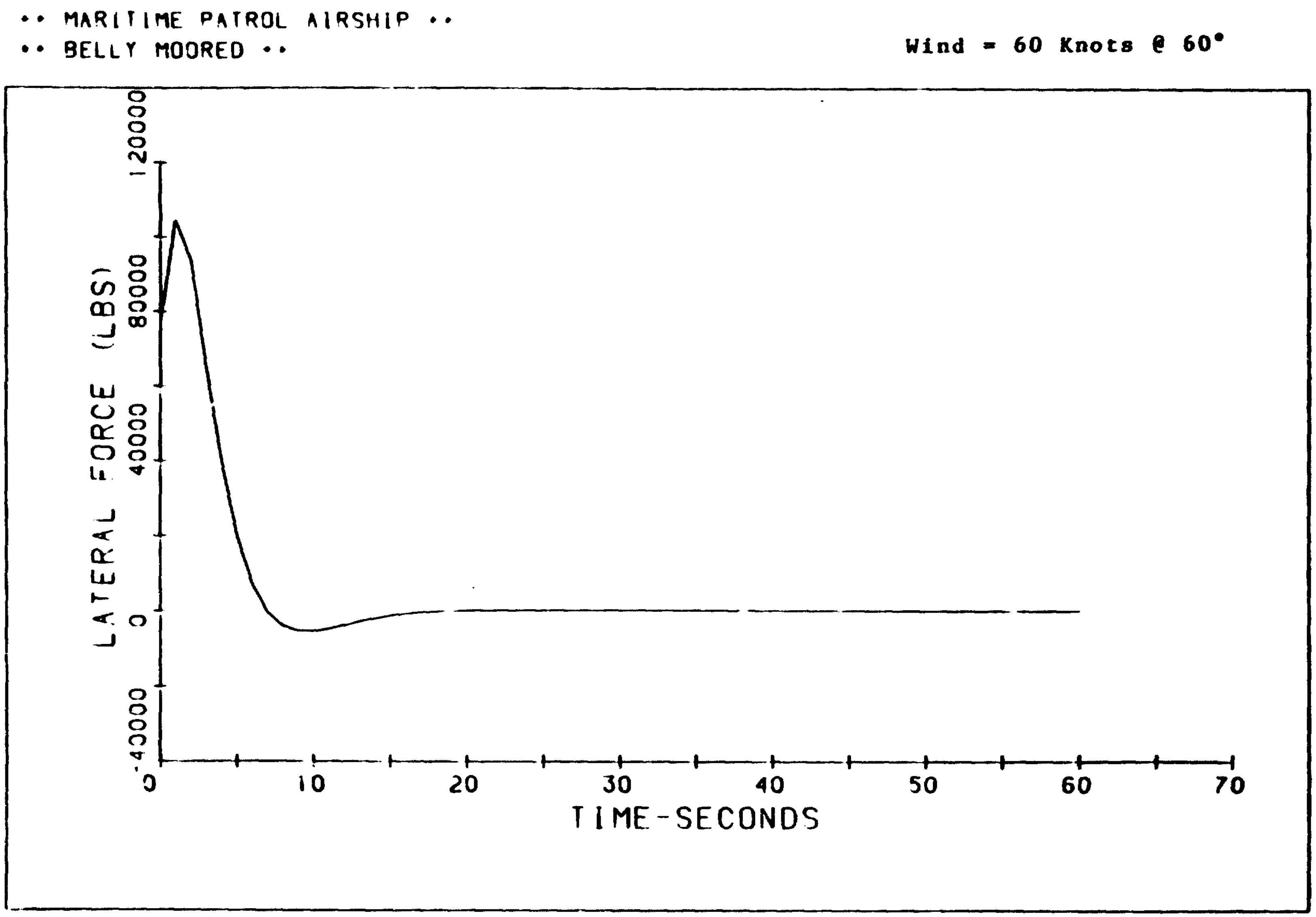
** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	-.00	.00	60.00	6	2956	2956	232	587	581
49.0	-.00	.00	60.00	6	2956	2956	232	587	581
50.0	-.00	.00	60.00	6	2956	2956	232	587	581
51.0	-.00	.00	60.00	6	2956	2956	232	587	581
52.0	-.00	.00	60.00	6	2956	2956	232	587	581
53.0	-.00	.00	60.00	6	2956	2956	232	587	581
54.0	-.00	.00	60.00	6	2956	2956	232	587	581
55.0	-.00	.00	60.00	6	2956	2956	232	587	581
56.0	-.00	.00	60.00	6	2956	2956	232	587	581
57.0	-.00	.00	60.00	6	2956	2956	232	587	581
58.0	-.00	.00	60.00	6	2956	2956	232	587	581
59.0	-.00	.00	60.00	6	2956	2956	232	587	581
60.0	-.00	.00	60.00	6	2956	2956	232	587	581

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

Wind = 60 Knots @ 60°

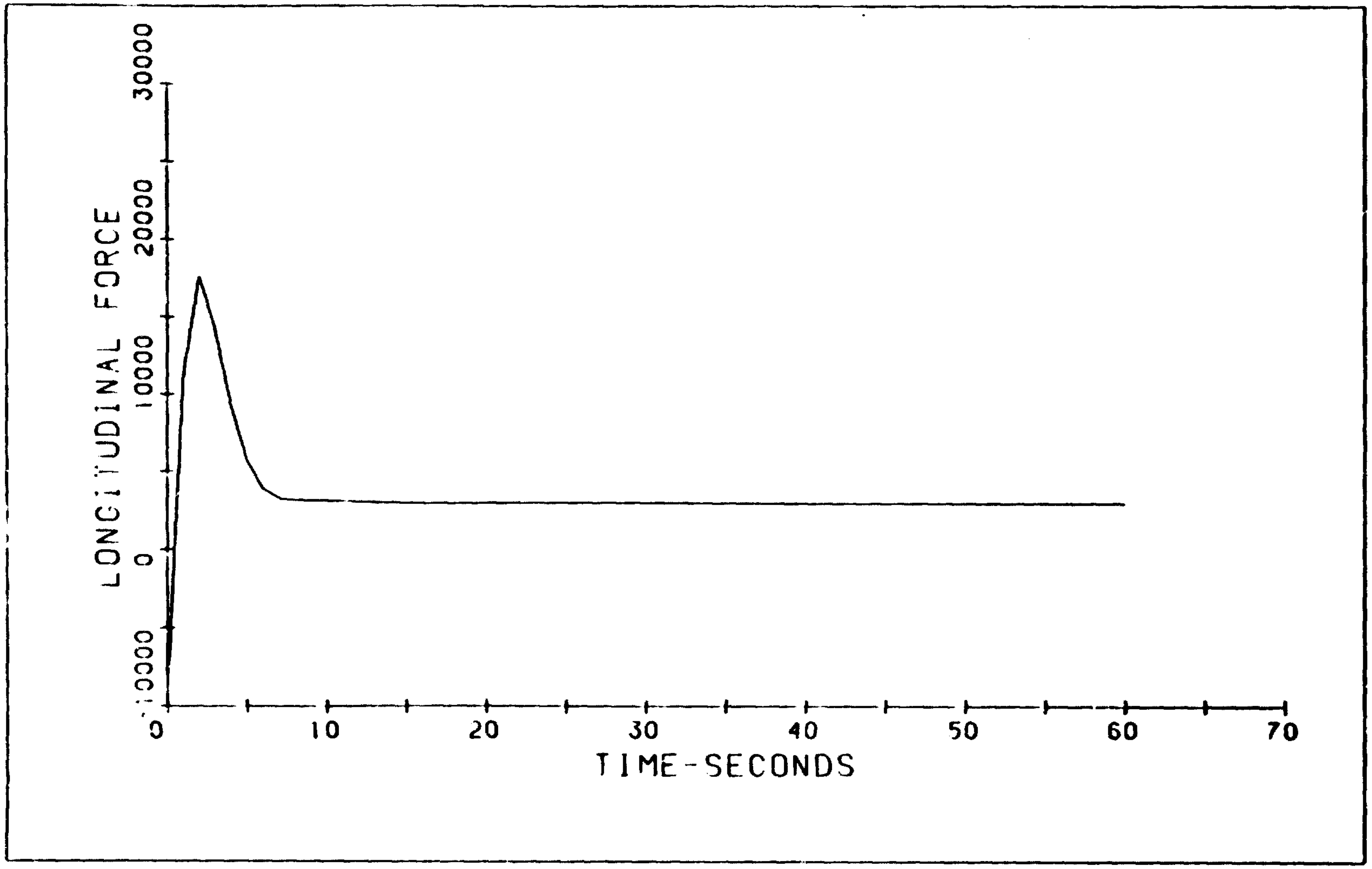




** MARITIME PATROL AIRSHIP **
** BELLY MOORED **
Wind = 60 Knots @ 60°
LATERAL FORCE (LBS)
120000
80000
40000
0
-40000
0
10
20
30
40
50
60
70
TIME-SECONDS

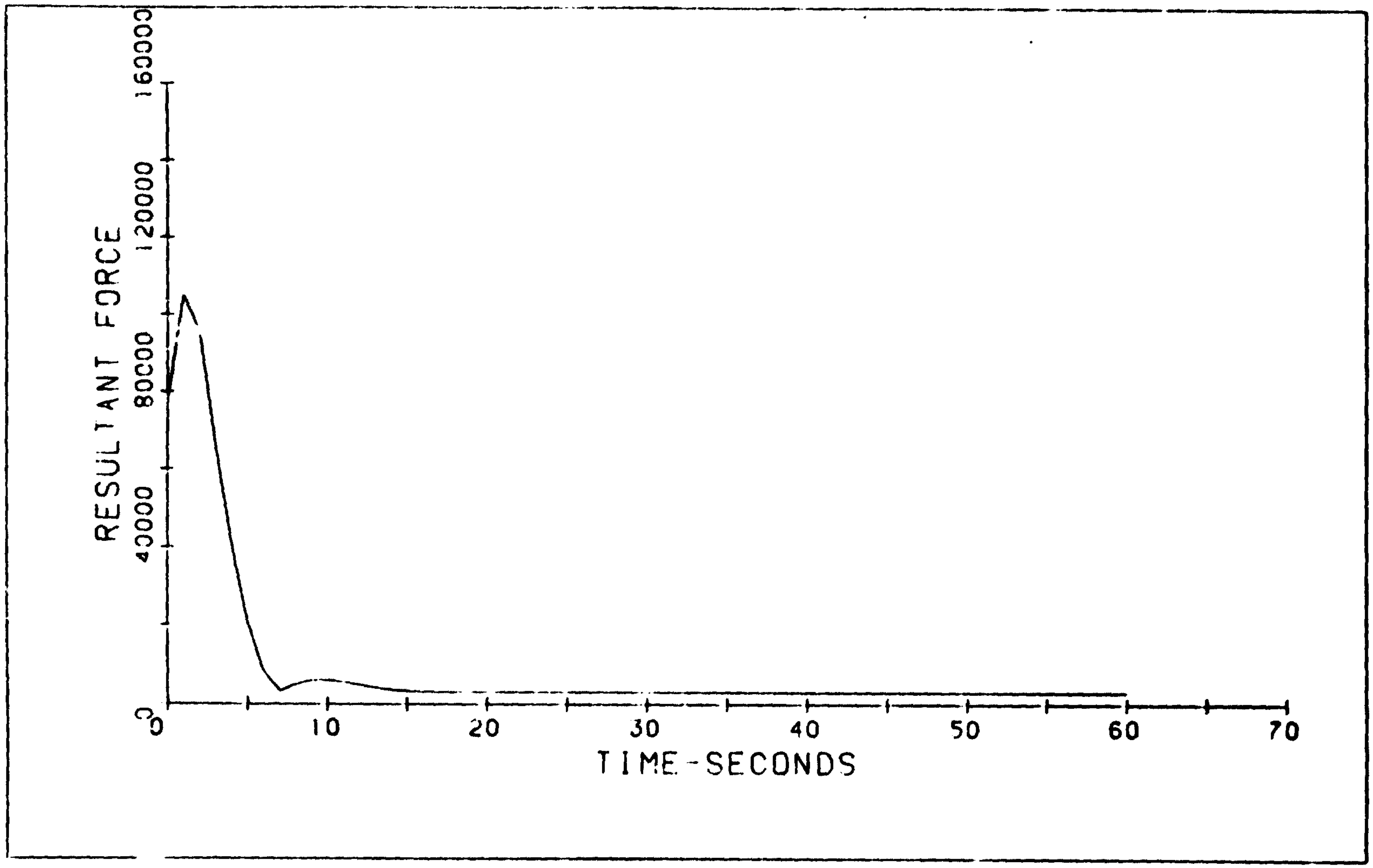
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 60°



** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

Wind = 60 Knots @ 60°



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OF POOR QUALITY

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*******************************************
*                                         *
*     AIRSHIP MOORING LOADS ANALYSIS      *
*                                         *
*******************************************
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AIRSHIP CONFIGURATION DATA

```
** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS)..:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET
```

MOORING STYLE

```
** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE........:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ
```

INITIAL CONDITIONS

```
WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS...:     75.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
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ORIGINAL PAGE IS
OF POOR QUALITY

** MARITIME PATROL AIRSHIP **

** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
.0	31.14	.00	.00	70543	-14000	71919	0	36522	0
1.0	6.79	15.13	9.44	110022	10870	110559	853	63428	0
2.0	-.22	18.00	26.58	112106	22141	114270	1738	66816	0
3.0	-3.81	15.73	43.74	86206	19908	88475	1563	51949	0
4.0	-4.22	11.58	57.43	55192	13431	56802	1054	33395	0
5.0	-3.68	7.60	66.97	29831	7796	30833	612	18156	0
6.0	-2.75	4.36	72.87	12308	4664	13162	366	7777	0
7.0	-1.77	2.11	76.01	1974	3443	3969	270	1780	0
8.0	-.99	.75	77.38	-3295	3212	4601	252	0	2470
9.0	-.49	.05	77.73	-5366	3174	6234	249	0	3616
10.0	-.24	-.31	77.58	-5678	3156	6496	247	0	3786
11.0	-.08	-.47	77.17	-5139	3127	6016	245	0	3480
12.0	.02	-.49	76.69	-4209	3090	5222	242	0	2955
13.0	.07	-.44	76.21	-3185	3052	4411	239	0	2377
14.0	.09	-.36	75.81	-2236	3018	3756	237	0	1842
15.0	.09	-.27	75.49	-1445	2993	3323	235	0	1396
16.0	.08	-.19	75.25	-837	2978	3093	233	122	1055
17.0	.06	-.12	75.10	-404	2968	2995	233	361	811
18.0	.04	-.07	75.00	-119	2961	2964	232	519	651
19.0	.03	-.03	74.95	50	2962	2962	232	613	557
20.0	.02	-.01	74.92	136	2963	2966	232	661	509
21.0	.01	.00	74.92	167	2962	2967	232	679	492
22.0	.00	.01	74.93	164	2962	2966	232	677	493
23.0	.00	.01	74.94	143	2960	2964	232	665	505
24.0	-.00	.01	74.95	117	2959	2962	232	650	519
25.0	-.00	.01	74.97	88	2958	2960	232	634	535
26.0	-.00	.01	74.98	63	2958	2958	232	620	549
27.0	-.00	.01	74.98	43	2957	2958	232	609	560
28.0	-.00	.01	74.99	28	2957	2957	232	600	568
29.0	-.00	.00	74.99	17	2957	2957	232	594	574
30.0	-.00	.00	75.00	11	2956	2956	232	590	578
31.0	-.00	.00	75.00	7	2956	2956	232	588	580
32.0	-.00	.00	75.00	6	2956	2956	232	588	580
33.0	-.00	.00	75.00	6	2956	2956	232	587	581
34.0	-.00	.00	75.00	5	2956	2956	232	587	581
35.0	-.00	.00	75.00	5	2956	2956	232	587	581
36.0	-.00	.00	75.00	5	2956	2956	232	587	581
37.0	-.00	.00	75.00	5	2956	2956	232	587	581
38.0	-.00	.00	75.00	5	2956	2956	232	587	581
39.0	-.00	.00	75.00	5	2956	2956	232	587	581
40.0	-.00	.00	75.00	5	2956	2956	232	587	581
41.0	-.00	.00	75.00	5	2956	2956	232	587	581
42.0	.00	.00	75.00	5	2956	2956	232	587	581
43.0	.00	.00	75.00	5	2956	2956	232	587	581
44.0	.00	.00	75.00	5	2956	2956	232	587	581
45.0	.00	.00	75.00	5	2956	2956	232	587	581
46.0	-.00	.00	75.00	5	2956	2956	232	587	581
47.0	.00	.00	75.00	5	2956	2956	232	587	581

ORIGINAL PAGE IS
OF POOR QUALITY

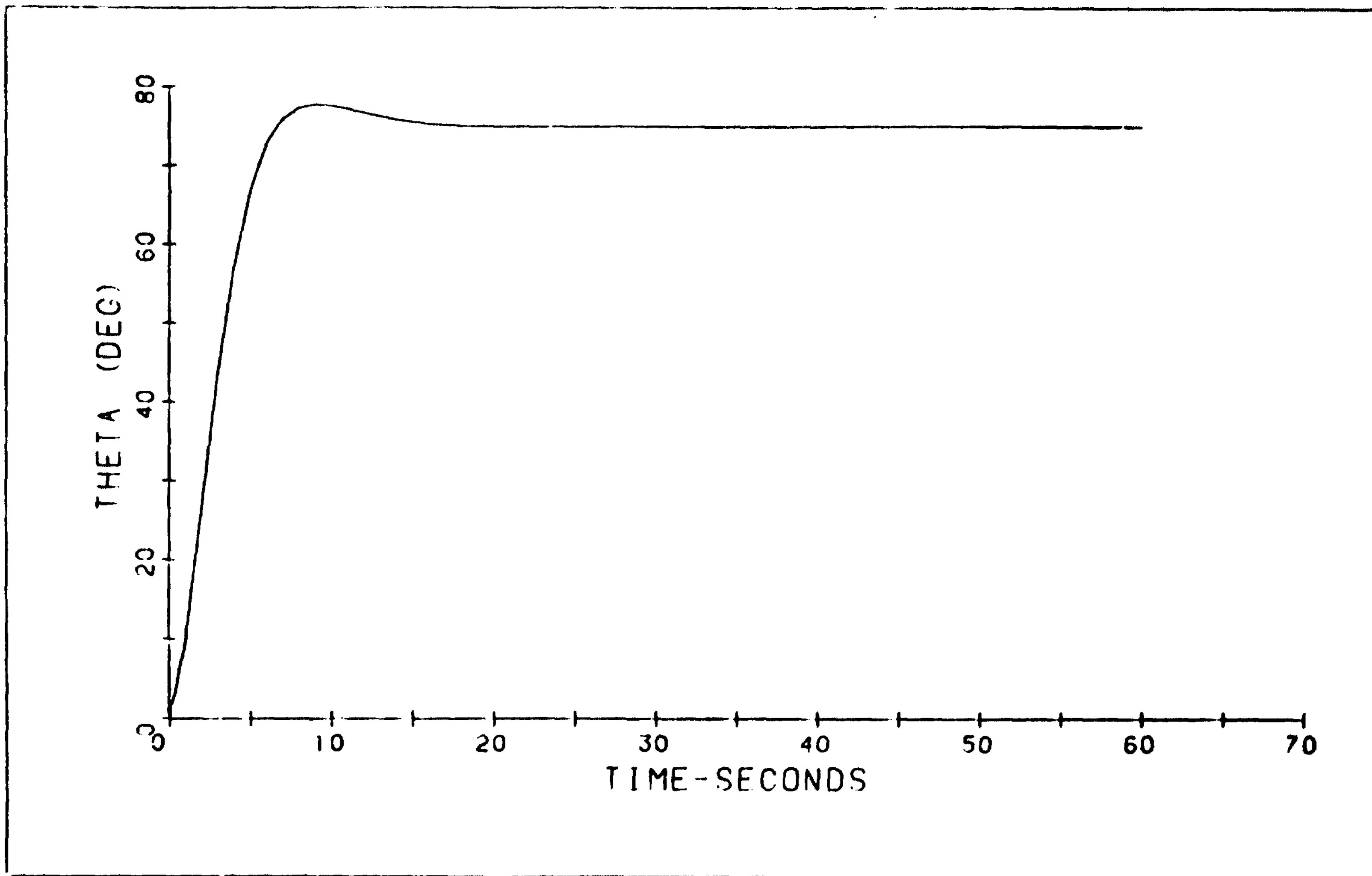
** MARITIME PATROL AIRSHIP **

** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	.00	.00	75.00	5	2956	2956	232	587	581
49.0	.00	.00	75.00	5	2956	2956	232	587	581
50.0	.00	.00	75.00	5	2956	2956	232	587	581
51.0	.00	.00	75.00	5	2956	2956	232	587	581
52.0	.00	.00	75.00	5	2956	2956	232	587	581
53.0	-.00	.00	75.00	5	2956	2956	232	587	581
54.0	.00	.00	75.00	5	2956	2956	232	587	581
55.0	.00	.00	75.00	5	2956	2956	232	587	581
56.0	.00	.00	75.00	5	2956	2956	232	587	581
57.0	.00	.00	75.00	5	2956	2956	232	587	581
58.0	.00	.00	75.00	5	2956	2956	232	587	581
59.0	.00	.00	75.00	5	2956	2956	232	587	581
60.0	.00	.00	75.00	5	2956	2956	232	587	581

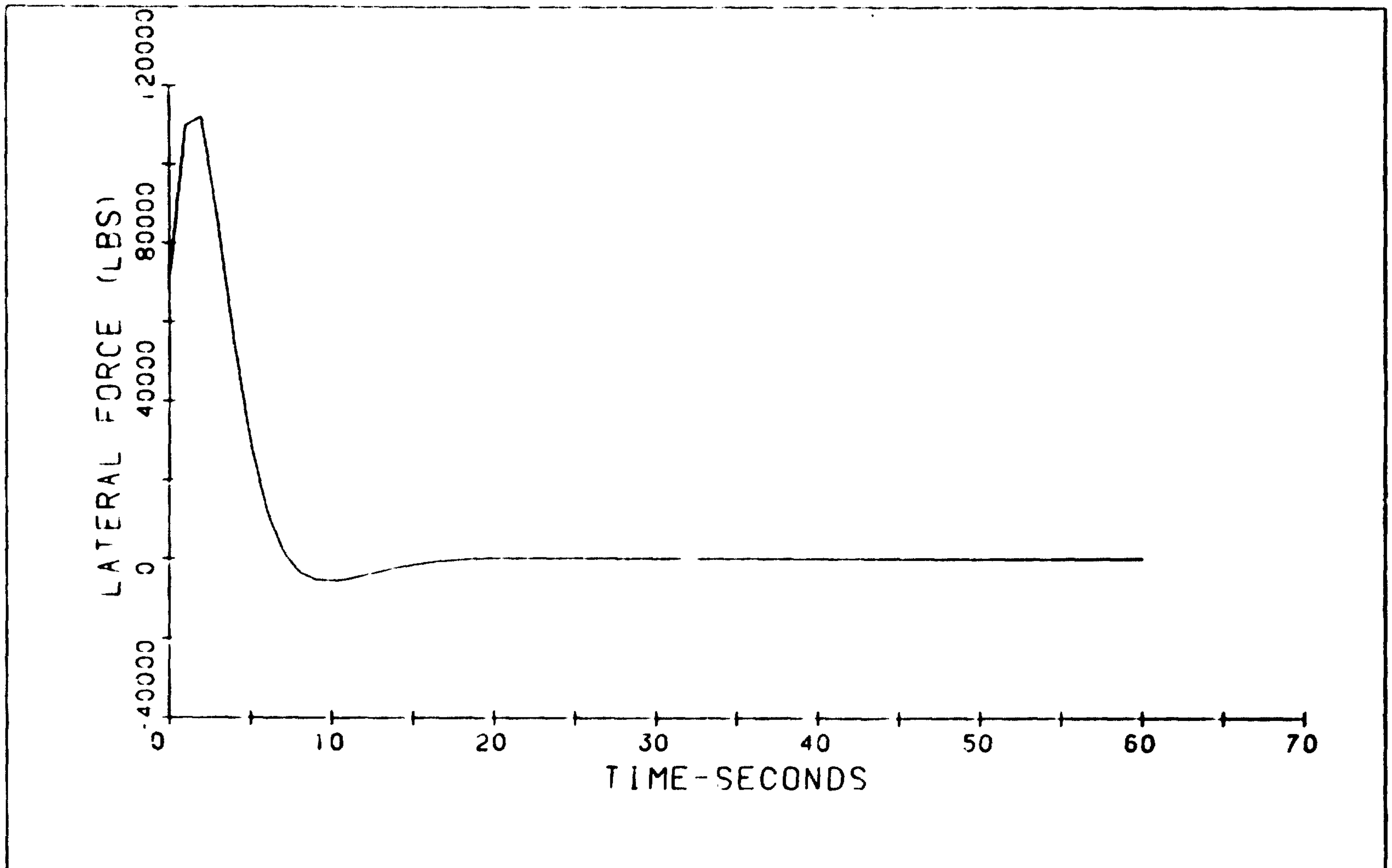
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 75°



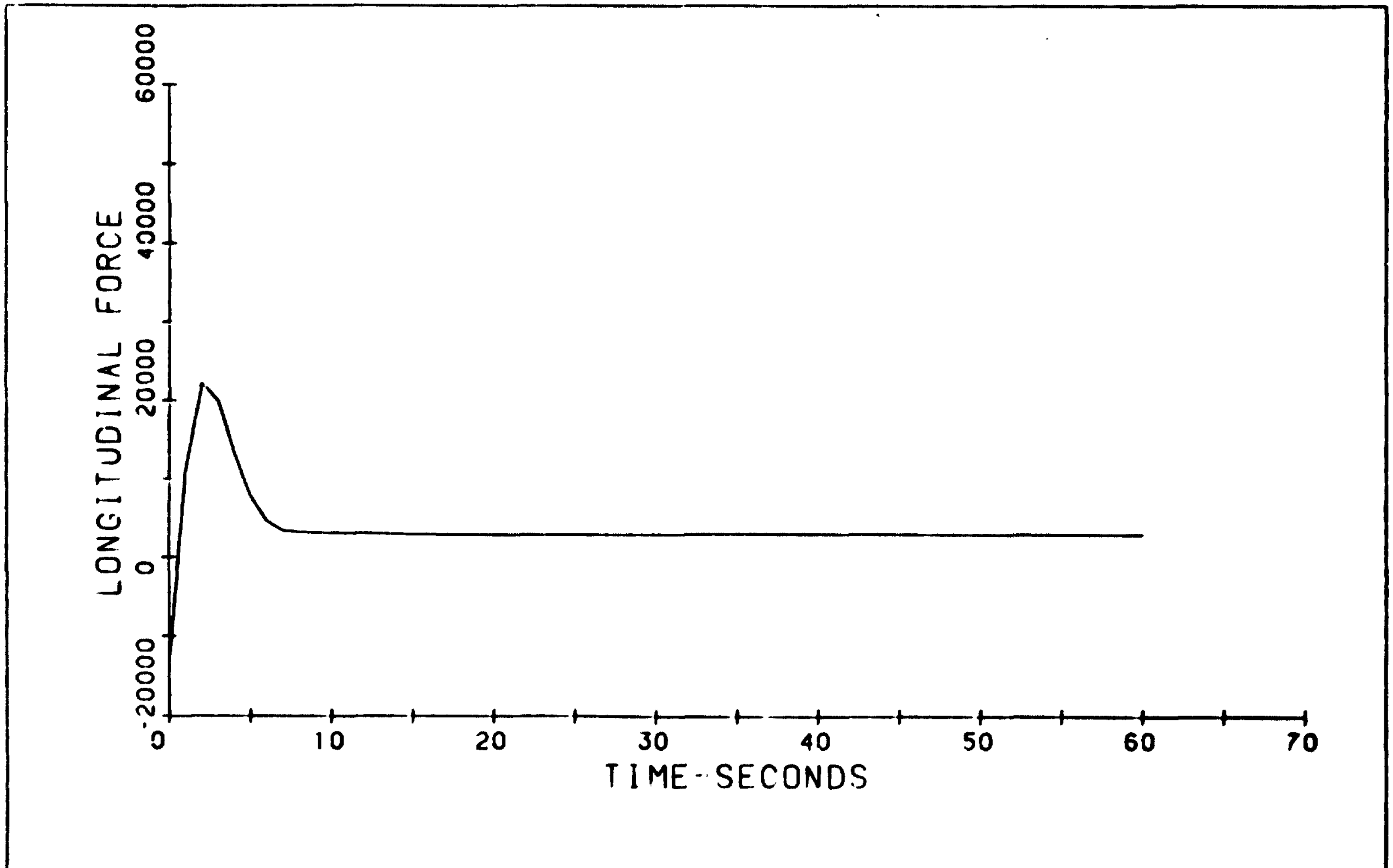
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 75°



** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

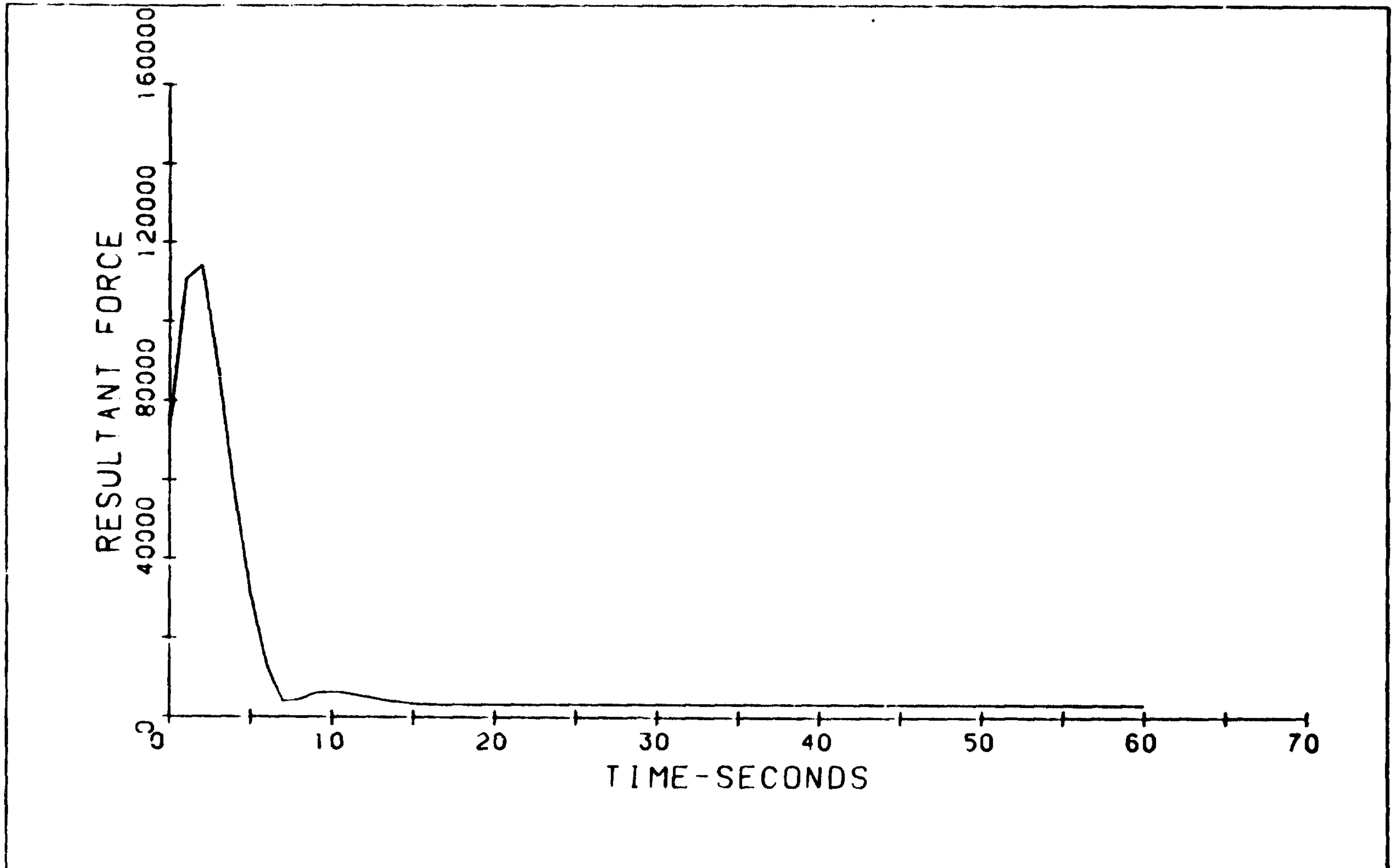
Wind = 60 Knots @ 75°



** MARITIME PATROL AIRSHIP **

** BELLY MOORED **

Wind = 60 Knots @ 75°



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*                                        *
*     AIRSHIP MOORING LOADS ANALYSIS     *
*                                        *
******************************************

AIRSHIP CONFIGURATION DATA
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** MARITIME PATROL AIRSHIP **
MOMENT OF INERTIA ABOUT CG............: .190E 08 SLUG-FTSQ
AIRSHIP MASS (INCLUDES VIRTUAL MASS).:   1976.0 SLUGS
HEIGHT OF CENTER LINE.................:     50.0 FEET
CG LOCATION RELATIVE TO NOSE..........:    143.6 FEET

MOORING STYLE
-------------

** BELLY MOORED **
MAST LOCATION RELATIVE TO NOSE........:     75.0 FEET
HEIGHT OF MAST........................:     16.6 FEET
MOMENT OF INERTIA ABOUT MAST..........: .283E 08 SLUG-FTSQ

INITIAL CONDITIONS
------------------

WIND SPEED............................:     60.0 KNOTS
WIND ANGLE RELATIVE TO AIRSHIP AXIS..:     90.0 DEGREES
THETA (DISPLACEMENT ANGLE)............:       .0 DEGREES
THETA-DOT (ANGULAR VELOCITY)..........:       .0 DEG/SEC
```

** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGA2 LBS
.0	37.65	.00	.00	39294	-15382	42198	0	18844	0
1.0	7.10	17.66	11.17	91963	15646	93284	1228	54313	0
2.0	.09	20.62	30.89	119925	27170	122964	2133	72165	0
3.0	-3.80	18.65	50.85	105224	25662	108308	2015	63679	0
4.0	-4.73	14.14	67.31	67927	17670	70188	1387	41326	0
5.0	-4.44	9.47	79.09	39240	10281	40565	807	23888	0
6.0	-3.37	5.54	86.50	17251	5613	18141	440	10718	0
7.0	-2.21	2.75	90.55	4169	3701	5575	290	3054	0
8.0	-1.26	1.05	92.36	-2652	3260	4203	256	0	2122
9.0	-.60	.14	92.90	-5509	3192	6367	250	0	3699
10.0	-.29	-.29	92.80	-6082	3173	6860	249	0	4015
11.0	-.11	-.48	92.40	-5616	3146	6437	247	0	3750
12.0	.01	-.53	91.88	-4667	3107	5607	244	0	3213
13.0	.07	-.48	91.37	-3575	3065	4710	240	0	2597
14.0	.09	-.40	90.93	-2541	3028	3953	237	0	2014
15.0	.09	-.31	90.57	-1666	2999	3431	235	0	1521
16.0	.08	-.22	90.31	-986	2981	3140	234	40	1138
17.0	.07	-.14	90.12	-495	2970	3011	233	311	863
18.0	.05	-.08	90.01	-168	2963	2967	232	492	679
19.0	.03	-.04	89.95	30	2962	2962	232	602	568
20.0	.02	-.01	89.92	135	2963	2966	232	661	510
21.0	.01	.00	89.91	175	2963	2968	232	683	487
22.0	.01	.01	89.92	177	2962	2967	232	684	486
23.0	.00	.02	89.93	157	2961	2965	232	675	497
24.0	-.00	.02	89.95	127	2960	2962	232	656	514
25.0	-.00	.01	89.96	97	2959	2960	232	639	530
26.0	-.00	.01	89.97	69	2958	2959	232	625	546
27.0	-.00	.01	89.98	47	2957	2958	232	611	558
28.0	-.00	.01	89.99	30	2957	2957	232	601	567
29.0	-.00	.00	89.99	18	2957	2957	232	595	574
30.0	-.00	.00	90.00	12	2957	2957	232	591	577
31.0	-.00	.00	90.00	7	2956	2956	232	588	580
32.0	-.00	.00	90.00	6	2956	2956	232	588	581
33.0	-.00	.00	90.00	5	2956	2956	232	587	581
34.0	-.00	.00	90.00	5	2956	2956	232	587	581
35.0	-.00	.00	90.00	5	2956	2956	232	587	581
36.0	-.00	.00	90.00	5	2956	2956	232	587	581
37.0	-.00	.00	90.00	5	2956	2956	232	587	581
38.0	-.00	.00	90.00	5	2956	2956	232	587	581
39.0	-.00	.00	90.00	5	2956	2956	232	587	581
40.0	-.00	.00	90.00	5	2956	2956	232	587	581
41.0	-.00	.00	90.00	5	2956	2956	232	587	581
42.0	-.00	.00	90.00	5	2956	2956	232	587	581
43.0	-.00	.00	90.00	5	2956	2956	232	587	581
44.0	-.00	.00	90.00	5	2956	2956	232	587	581
45.0	-.00	.00	90.00	5	2956	2956	232	587	581
46.0	-.00	.00	90.00	5	2956	2956	232	587	581
47.0	-.00	.00	90.00	5	2956	2956	232	587	581

**ORIGINAL PAGE IS
OF POOR QUALITY**

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** MARITIME PATROL AIRSHIP **
** BELLY MOORED **
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TIME SEC	THEDD D/S/S	THD D/S	TH DEG	FLATR LBS	FLONG LBS	FMAST LBS	FLGA1 LBS	FLGB1 LBS	FLGB2 LBS
48.0	-.00	.00	90.00	5	2956	2956	232	587	581
49.0	-.00	.00	90.00	5	2956	2956	232	587	581
50.0	-.00	.00	90.00	5	2956	2956	232	587	581
51.0	-.00	.00	90.00	5	2956	2956	232	587	581
52.0	-.00	.00	90.00	5	2956	2956	232	587	581
53.0	-.00	.00	90.00	5	2956	2956	232	587	581
54.0	.00	.00	90.00	5	2956	2956	232	587	581
55.0	-.00	.00	90.00	5	2956	2956	232	587	581
56.0	-.00	.00	90.00	5	2956	2956	232	587	581
57.0	-.00	.00	90.00	5	2956	2956	232	587	581
58.0	.00	.00	90.00	5	2956	2956	232	587	581
59.0	-.00	.00	90.00	5	2956	2956	232	587	581
60.0	-.00	.00	90.00	5	2956	2956	232	587	581

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*EXIT*

   5100 YOU STILL HAVE THIS FILE OPEN IN THROUGH ANOTHER DCB.
  AT 1ECB7
  ON DCB F16

USER'S PROGRAM STATUS DOUBLE WORD.
        10E1ECB7  00000000

USER'S GENERAL REGISTERS.
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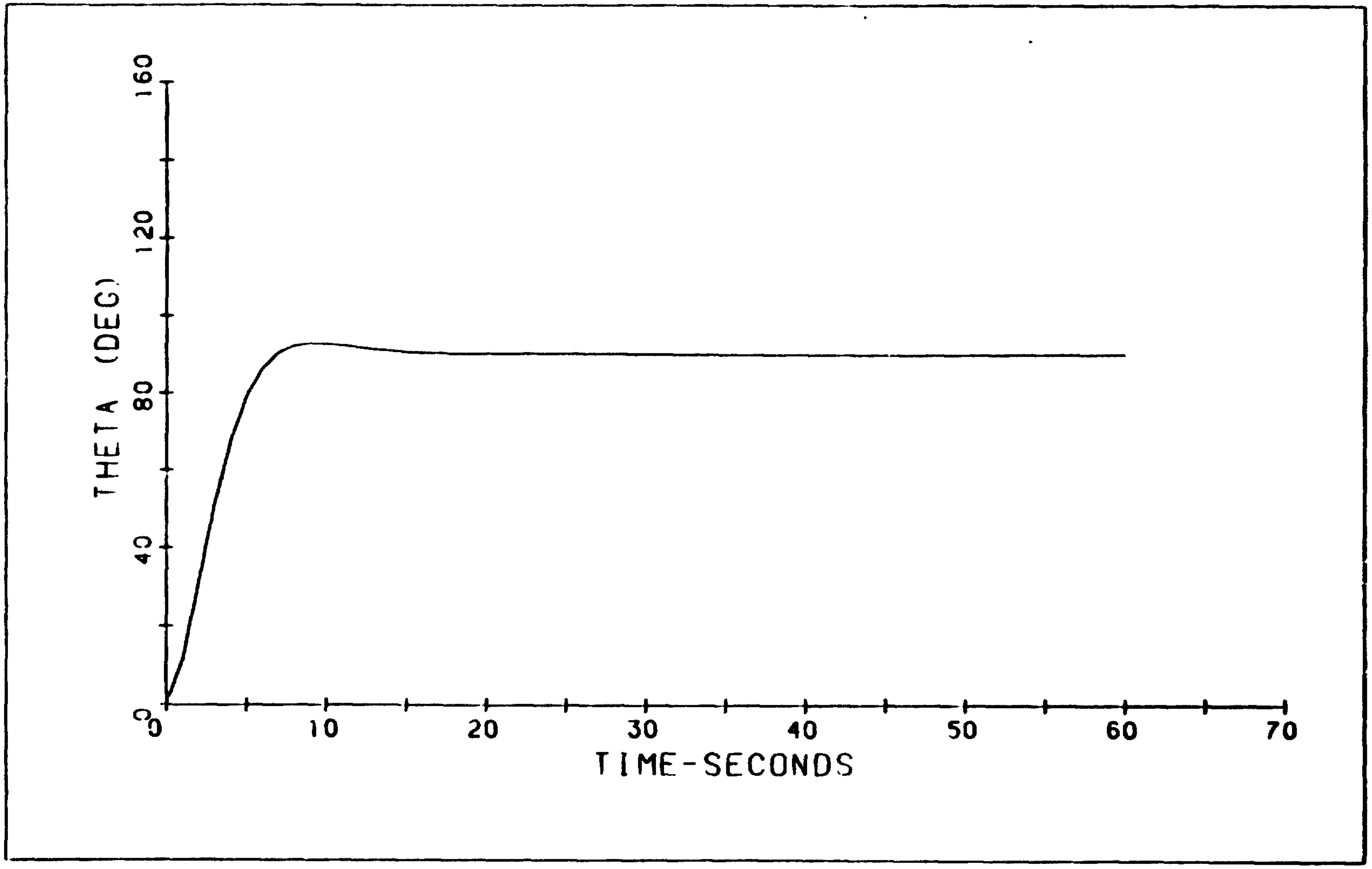
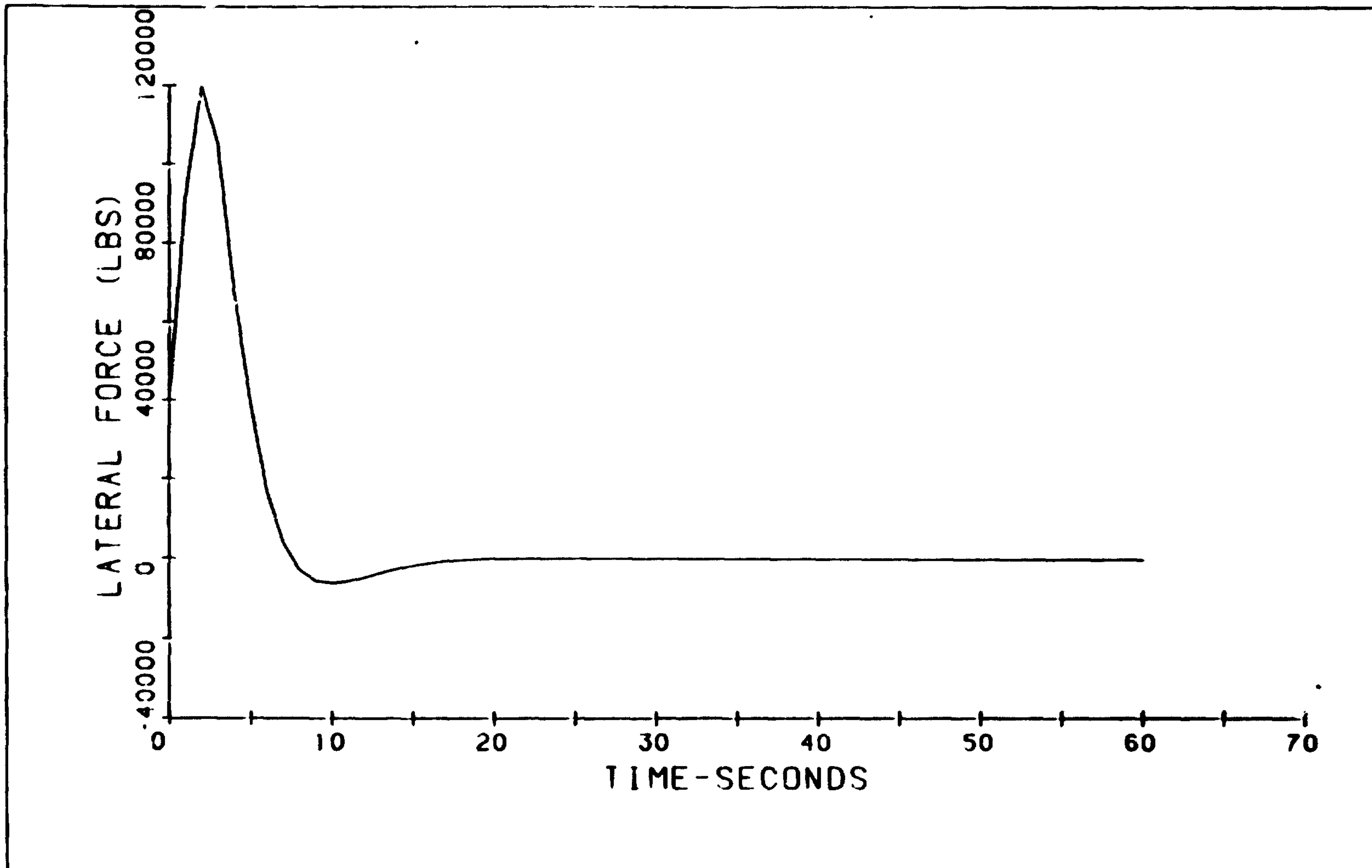
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 90°



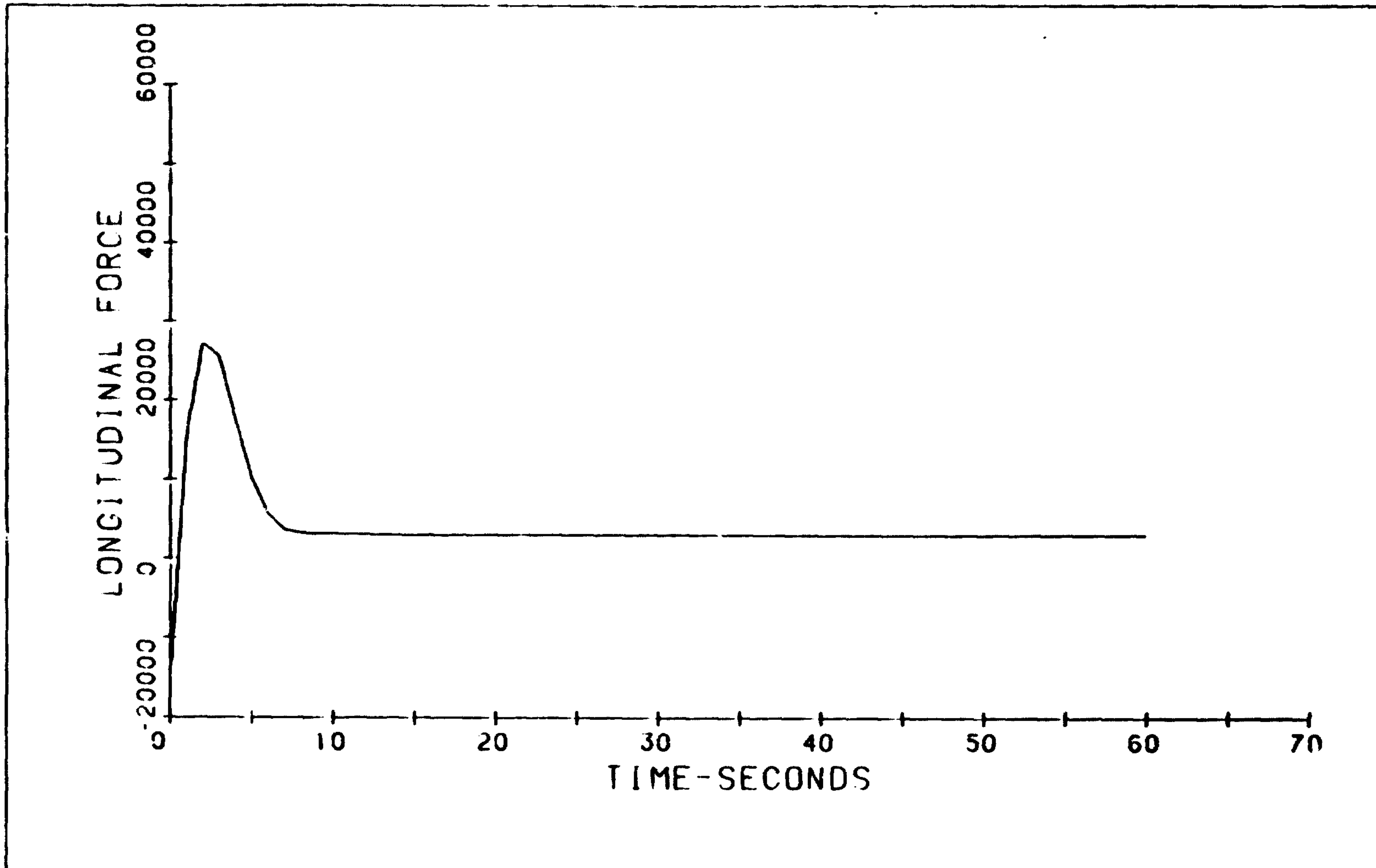
•• MARITIME PATROL AIRSHIP ••
•• BELLY MOORED ••

Wind = 60 Knots @ 90°



** MARITIME PATROL AIRSHIP **
** BELLY MOORED **

Wind = 60 Knots @ 90°



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Wind = 60 Knots @ 90°