NASA CONTRACTOR REPORT 166444 USAAVRADCOM TR 83-A-2

INTEGRATED TECHNOLOGY ROTOR/FLIGHT RESEARCH ROTOR (ITR/FRR) CONCEPT DEFINITION STUDY

Charles W. Hughes

Contract DAAK51-81-C-0028
March 1983

NASA

NASA CONTRACTOR REPORT 166444 USAAVRADCOM TR 83-A-2

INTEGRATED TECHNOLOGY ROTOR/FLIGHT RESEARCH ROTOR (ITR/FRR) CONCEPT DEFINITION STUDY

Charles W. Hughes
Hughes Helicopters, Inc.
Culver City, CA 90230

Prepared for
U.S. Army Research and Technology
Laboratory (AVRADCOM)
under Contract DAAK51-81-C-0028

[redacted]

Date for general release March 1985

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

United States Army
Aviation Research and
Development Command
Research and Technology
Laboratory
Moffett Field, California 94035

PREFACE

This report was prepared by Hughes Helicopters, Inc. for the Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM) under Contract DAAK51-81-C-0028. Program funding was also provided by the National Aeronautics and Space Administration.

Technical program guidance was provided by Messrs. P. Mirick and R. Powell of ATL, USARTL, Messrs. R. Ormiston and W. Bousman of AL, USARTL, and Messrs. J. Biggers and L. Haslim of Ames Research Center, NASA. Principal HHI personnel associated with the program were as follows:

Aeromechanics	D. Banerjee, R. Johnston
Design	S. Yao, S. Chu, J. Alexander, S. Das
Project Manager	C. Hughes
Stress	J. Crandell, D. Mancill

Other contributors to this program were:

Manufacturing of Composites	R. Lofland
Reliability	J. Jones
Rotor Hub Design	R. Head
Survivability/Vulnerability	R. Scheel

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT)

LIST OF TABLES

LIST OF TABLES (CONT)

INTRODUCTION

The Army, in conjunction with the National Aeronautics and Space Administration (NASA), is engaged in an advanced rotor program. This program, Integrated Technology Rotor/Flight Research Rotor (ITR/FRR) Project, will provide and validate the integrated rotor system technology required to substantially improve the performance, noise, vibration, reliability, maintainability, survivability, and cost of civil and military rotorcraft. The ITR/FRR Project objectives will be accomplished through system design studies, small and large scale ground tests, and ultimately flight tests of advanced technology rotors.

A major area for improving the main rotor is the hub and control system. The complexity of the controls, blade retention system, bearings, lag dampers, and droop stops contribute to the rotor's maintenance, operational, and acquisition costs. An improved hub and control system would also have lower drag, reduced weight, and increased reliability and maintainability compared to a conventional system.

A predesign study of advanced hubs including bearingless designs is the subject of this report. This work, ITR/FRR Concept Definition Study, is also part of the Army/NASA ITR/FRR Project. The main objectives of this study were to explore concepts and possible approaches for practical hub configurations that simultaneously provided rotor stability, reduced weight, low hub drag, simplicity and reliability, low flexbeam flapwise and torsional stiffness, high survivability, adequate strength, and acceptable fatigue life. Other program objectives included the identification and conceptual design of hub parametric variations (such as pitch-flap and pitch-lag couplings) and the compatibility of the advanced hubs with the Rotor Systems Research Aircraft (RSRA).

The first task under this study was to review the goals and specifications provided by the Army and NASA to guide the design of the advanced hubs and rotors. A discussion of this review is presented. The major conclusion drawn from a review of the goals for the advanced hub was that meeting the requirements of invulnerability to a small HEI projectile hit while meeting the requirements for low drag and low weight would be a formidable design challenge.

During the next phase of the study several advanced hub concepts were examined. The designs were essentially bearingless, and different types of flexbeams were considered. Flexbeams investigated included flat-strap cruciform, tapered cruciform, flat-strap, "dual hemisphere", and composite V-straps. The designs chosen for further development were the laminated flat-strap cruciform and a Kevlar 29 V-strap.

The V-strap and flat-strap cruciform designs were sized to meet the hub design criteria. Both designs had stress levels below the estimated endurance limits for ±5 degree flapping and ±15 degree feathering. First order dynamic analyses verified the flap strap cruciform had an adequate rotor frequency placement with the flexbeam design stiffnesses. Also during this task, a flat-strap cruciform concept that incorporated kinematic couplings was designed.

The candidate hub concepts were then evaluated using the goals and specifications supplied by the Army and NASA. The flat-strap cruciform design rated higher than the V-strap design. Both designs paid a weight and drag penalty due to the survivability criteria.

Next, the hub concepts were examined to determine parametric variations that could be achieved with the existing designs. Fittings were designed that would allow variations in pitch-flap couplings and blade sweep variations. Dynamic analyses are also presented which show the effects of some of these couplings on rotor stability.

Finally the compatibility of the rotor hubs and control systems with the RSRA was investigated. A static mast system similar to the AH-64A helicopter was shown to simplify the attachment of the hubs to the fuselage. A conventional control system (external to mast) would also simplify the integration of the RSRA and the advanced hubs. A through-the-mast control system was also shown to be feasible with the RSRA, but more extensive modifications to the helicopter would be necessary.

REVIEW OF GOALS AND SPECIFICATIONS

The first major task accomplished during this program was the review of the Government goals and specifications for the ITR/FRR program. These goals and specifications were reprinted and are presented in Appendixes A, B, and C of this report. Appendix A presents the ITR/FRR Project Plan Summary which includes the ITR technical goals and system design specifications; Appendix B presents the Rotor Hub Design Specifications; and the Merit Factors/Merit Functions used for evaluating the hub concepts are shown in Appendix C.

Design goals posing significant challenges were the goals for hub weight, hub drag, and hub moment stiffness. The goals were as follows: rotor hub weight 2.5 percent of design gross weight (DGW), hub flat plate drag - 2.8 square feet, and the rotor hub moment stiffness of 100,000 foot-pound/radian.

Data from References 1 and 2 showed that hub weight as a percentage of DGW for a large sampling of helicopters was 6.4 percent. Reference 1 was also used to obtain the hub weight to DGW for the Army's latest attack helicopter (AH-64) and modern utility helicopter (UH-60). The average hub weight to DGW for these helicopters is 4.7 percent which is very respectable considering these hubs were designed to stringent vulnerability criteria. These percentages for the Army's most advanced helicopters illustrate the design challenge of meeting this study's design goal of hub weight equal to 2.5 percent DGW.

[1] Beltramo, M. N., and Morris, M. A., PARAMETRIC STUDY OF HELICOPTER AIRCRAFT SYSTEMS COSTS AND WEIGHTS, Science Applications, Inc., NASA CR152315, Ames Research Center, Moffett Field, California, January 1980.

[2] Schwartzberg, M. A., Smith, R. L., Means, J. L., Law, H. Y., and Chappell, D. P., SINGLE-ROTOR HELICOPTER DESIGN AND PERFORMANCE ESTIMATION PROGRAMS, Volume I Methodology, Systems Research Integration Office, Report Number 77-1, U.S. Army Air Mobility R&D Laboratory, Moffett Field, California, June 1977.

The rotor hub flat plate drag goal of 2.8 square feet was based on a DGW of 16,000 pounds, and for higher gross weights it is scaled by the 2/3 power of the DGW. Hub drag for the AH-64 is approximately 5.4 square feet (Reference 3). The RSRA is the vehicle on which the integrated technology rotor and the flight research rotor will be flight tested. The hub drag of the existing rotor on the RSRA is 8.9 square feet (Reference 4). Compared to the hub drag of the AH-64 and existing RSRA rotor, the design goal of 2.8 square feet is seen to be very difficult to achieve. The recommended design goal for future studies was 4.0 square feet, but 2.8 square feet was the hub flat plate drag criterion used to evaluate the rotors in this study.

The required hub moment stiffness was another major design challenge for this program. Using the UH-60 parameters (approximately 16,000 pounds DGW) a 100,000 foot-pound/radian hub moment stiffness is equivalent to an articulated rotor with a flapping hinge at 2.7 percent rotor radius. Existing flexbeam/hingeless rotors such as the Bolkow 105 and the Army/Boeing Vertol Bearingless Main Rotor (BMR) have equivalent flapping hinge locations of from 12 to 15 percent rotor radius (References 5 and 6).

---

[3] Logan, A.H., Prouty, R.W., and Clark, D.R., WIND TUNNEL TESTS OF LARGE- AND SMALL-SCALE ROTOR HUBS AND PYLONS, Hughes Helicopters and Analytical Methods, Inc., USAAVRADCOM-TR-80-D-21, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1980.

[4] Weiner, A., Niebanck, C., and Occhiato, J., PRELIMINARY EVALUATION OF RSRA DATA ACQUIRED ON PURE HELICOPTER, AUXILIARY PROPULSION AND COMPOUND HELICOPTER FLIGHT CHARACTERISTICS, Report SER-72050 by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS2-10182, Ames Research Center, Moffett Field, California, September 1980.

[5] Reichert, G., and Oelker, P., HANDLING QUALITIES WITH THE BOLKOW RIGID ROTOR SYSTEM, Proceedings of the 24th Annual National Forum of the American Helicopter Society, May 1968.

[6] Dixon, P.G.C., and Bishop, H.E., THE BEARINGLESS MAIN ROTOR, Journal of the American Helicopter Society, Volume 25, Number 3, July 1980.

These aforementioned rotors demonstrate the challenge in achieving a 100,000 foot-pound/radian hub-moment stiffness for a hingeless rotor of 16,000 pound DGW. The recommended criterion for future studies was a 281,500 foot-pound/radian hub moment which was equal to a flapping hinge location of approximately 7.5 percent rotor radius. Rotors considered during this program were judged on the 100,000 foot-pound/radian hub moment stiffness goal (for 16,000 pound DGW). A complete appraisal of the ITR/FRR Project Plan Summary, Rotor Hub Design Specifications, and Merit Factors/Merit functions is presented in Appendix D.

Hub designs for this study were based on the RSRA helicopter DGW of 18,400 pounds. The RSRA was selected as the baseline helicopter in order to evaluate the rotors on a known data base, meet the DGW criterion of from 16,000 to 23,000 pounds, and to ensure compatibility of the experimental rotors with the RSRA both for this study and for future phases of the Army/NASA's advanced rotor program. Table 1 presents the initial specifications chosen for the following conceptual study, Selection of Candidate Hub Concepts. These specifications were selected based on the ITR/FRR Project Plan and Hub Design Specifications, the geometry of the existing RSRA rotor, and values representative of a soft inplane bearingless rotor.

TABLE 1. PRELIMINARY DESIGN SPECIFICATIONS

Number of Blades	4
Radius	31 feet
Chord	23 inches
Rotational Speed	216 rpm
Tip Speed	701 fps
Centrifugal Force	100,000 pounds
Flapping Angle	±5 degrees
Feathering Angle	±15 degrees
First Chord Natural Frequency	0.6 to 0.7/rev

SELECTION OF CANDIDATE HUB CONCEPTS

During this phase of the program several hub concepts were defined to fulfill the requirements of the system design goals for the ITR. These preliminary studies separated the designs into their subsystems which consisted of flexbeams, pitch cases, control systems, and dampers. Figures 1 through 9 show the various flexbeam concepts which were considered. The concepts are identified as concepts A through G. Table 2 presents a summary of the figure numbers, drawing numbers, and concept listing for the different designs.

TABLE 2. FLEXBEAM CONCEPT SUMMARY

Flexbeam Design	Drawing Number	Concept	Figure Number
Flat-Strap Cruciform (Laminated Flexure)	484-1001	A	1
Tapered Cruciform (Laminated Flexure)	484-1002	B	2
Hemispherical Flexbeam (Nonlaminated)	484-1003	C	3
S-Beam, Variation No. 1 (Laminated Flexure)	484-1004	D-1	5
S-Beam, Variation No. 2 (Nonlaminated)	484-1024	D-2	6
Multiple Strap (Laminated Flexure)	484-1005	E	7
Flat-Strap (Nonlaminated)	484-1006	F	8
V-Strap, Variation No. 1 (Laminated Flexure)	484-1007	G-1	9
V-Strap, Variation No. 2 (Laminated Flexure)	484-1008	G-2	10

Figure 1 presents a flat-strap-cruciform design (Concept A). This design has a laminated flat-strap with hub shoes to achieve a low effective flapping hinge offset. The majority of the designs studied in this report use a laminated flexure in conjunction with hub shoes. This concept allows a relatively small bending radius of curvature with an acceptable stress level. The small radius of curvature allows the designer to achieve a low effective flapping hinge offset which is one of the design goals for this study. Laminated and solid flexure stresses due to flapping are compared on page 30 of this report.

The cruciform member (Figure 1) accommodates the feathering and lead-lag motion. The flexure structure extends through the hub to react the centrifugal force and simplify the flexure to hub attachment. An integral blade attachment fitting was also a feature of this concept. An elastomeric snubber, although not shown, would also be used in this design. These flexbeams would be fabricated from fiberglass due to compressive stresses. A variation of the flat-strap cruciform also using a laminated flexure is shown in Figure 2. This tapered cruciform design (Concept B) allowed more precise tailoring of the flexure stiffness outboard of the flat-strap at the expense of manufacturing complexity. The snubber design shown in this concept is the same as that envisioned for the flat-strap cruciform shown in Figure 1.

A hub design comprised of two metal hemispherical fittings joined by low angle helical wound composites is shown in Figure 3. An integral part of the outboard fitting is the blade attachment lug, while the inboard fitting forms part of the rotor retention system. Unidirectional straps through the hub attach to the hemispherical fittings and carry the centrifugal force from the opposing blades. The flexure is not laminated in this design.

The narrow part of this hourglass flexbeam, Concept C, fixes the flapping hinge location. The spanwise location of the flapping hinge can then be varied by changing the cone angles. Low effective flapping hinge locations would be difficult to achieve with this design. Unidirectional fibers on either side of the hourglass winding are used to tailor the flexure chordwise stiffness as well as provide redundancy for safety and survivability. Designs were also considered which would replace the unidirectional fibers with elastomeric dampers. The manufacturing feasibility of the concept was demonstrated by winding a small scale specimen which is shown in Figure 4.

A flexbeam concept (Concept D) designated the S-beam design is shown in Figure 5. This concept employs a laminated flat strap with hub shoes to achieve the desired flapping stiffness and a low effective hinge location. The blade retention strap also shown in Figure 5 is supported by essentially composite springs in the shape of an "S". This S-beam portion of the flexure accommodates the feathering and lead-lag motions.

This design was refined and is presented in Figure 6. The S-beam in this concept accommodates the flapping motion as well as lead-lag and feathering motion. The flexure is not laminated for this design. The blade centrifugal force is transmitted from the blade retention strap through the S-beam and into the integral hub and S-beam housing. The redundancy in this structure enhances its safety and survivability. Elastomeric snubbers and dampers could be enclosed within the hub of this concept.

Figure 7 presents Concept E which uses multiple straps (laminated flexure) to achieve redundancy and an elastomeric bearing to accommodate lead-lag motion. An elastomeric snubber for flapping restraint is also shown in this design. The major advantage of this design is its failsafe and survivable feature due to multiplicity of straps. A drawback to this concept is its relatively high torsional stiffness and the complexity of the strap arrangement.

A tapered flat strap flexbeam (Concept F) is shown in Figure 8. This hub concept uses a solid flexure without hub shoes. This concept is relatively simple in construction but this design does have some potential problems. The concept has an effective flap hinge further outboard than other designs and therefore may not meet the moment stiffness criterion.

Since hub shoes are not used, the flexure taper becomes very important in order to minimize the stresses due to flapping. The hub criteria of stress levels below endurance limits for ±5 degrees of flapping may be difficult to achieve with this concept. Although not shown, this design would use a composite pitchcase and elastomeric flapping snubber.

The final concept (Concept G) considered was a derivative of the rotor system on the AH-64 helicopter. Figure 9 presents this design. This hub uses elastomeric flapping/feathering snubbers along with elastomeric lead-lag bearings and elastomeric dampers. The laminated V-straps would be fabricated of Kevlar 29 epoxy. Kevlar 29 appears ideal for this application since the straps are not subjected to compressive loads and the Kevlar combines high fatigue strength with large strain capability. Table 3 presents a comparison of various composite materials which shows the advantages of Kevlar 29. In order to reduce part count and simplify the hub to flexbeam attachment, a through-the-hub strap arrangement was designed. This concept is shown in Figure 10. In this concept, the V-strap assemblies would be fabricated in pairs which would form the flexbeams for the total rotor.

TABLE 3. MATERIAL PROPERTY COMPARISON

Material	Allowable Alternating Stress, psi	E, 10^6 psi	ϵ, 10^{-6} inches/inch
S-2 Glass/Epoxy	18,000	7.2	2,500
T300 Graphite/Epoxy	34,000	18.9	1,800
Kevlar 49/Epoxy	34,000	10.7	3,200
Kevlar 29/Epoxy	34,000	5.1	6,700

Different pitchcase concepts were also considered during this phase of the program. A truss structure pitchcase is shown in Figure 11. Composite beams stabilized by composite hoop wound braces would form the load carrying members for this pitchcase. An additional design for this concept would have redundant structure to provide an invulnerable pitchcase. A monocoque pitchcase is depicted in Figure 12. This helically wound composite structure would integrate the pitchhorn and blade attachment fittings. One concern with this type of structure would be its survivability due to blast pressures from an explosive projectile.

Various control systems were investigated as well as different flexbeams and pitchcases. Figures 13 through 15 present three different control system concepts. All three designs are shown with a static mast system which has proven survivability (Reference 7). An internal rotating shaft provides the rotor torque while the external static mast reacts all other rotor forces and moments. This static mast design also allows flexibility in varying rotor hub mast height which would be a desired feature for the FRR.

[7] Neugebauer, A., TEST REPORT FOR THE MAIN AND TAIL ROTOR HUB ASSEMBLY INVULNERABILITY VERIFICATION, PART 1 - MAIN ROTOR HUB ASSEMBLY TESTS YAH-64 ADVANCED ATTACK HELICOPTER, Hughes Helicopters, Inc. Report No. 77-BT-1018, Culver City, California Revised February 1978.

Figure 13 depicts an external control system with a narrow profile. The controls are located close to the mast to minimize drag. One drawback to this system is the coupling between the cyclic inputs. This coupling is caused by the plane of the rotating swashplate being above the plane of the stationary swashplate as shown in Figure 13. Thus when one cyclic input is applied the other cyclic input arm is offset from the vertical. This conceptual study illustrates the difficulty of achieving a compact external control system.

A through-the-mast or internal control system is shown in Figure 14. A stationary and rotating swashplate located underneath the transmission provide inputs to the control rods (one for each blade). The control rods actuate torque tubes at the top of the mast which are connected to the blades' pitch horns. The control rods are stabilized by guides also depicted in Figure 14. This type of control system is also shown in the top view of Figure 9. Survivability of this system is enhanced by the control rods being protected by the static mast. Maintainability of this system would be compromised by the control rods being enclosed by the mast and the location of swashplates within the fuselage. In addition the parts count for this system would be greater than the external control system parts count which increases the maintenance requirements. Items that add to the system's parts count are the push-pull control rods and the torque tubes which connect the control rods and the pitch links.

The third control system concept investigated is presented in Figure 15. This design is also a through-the-mast system. The system is comprised of stationary control tubes located within the mast, a stationary swashplate consisting of two plates set at an inclined angle, and a rotating swashplate located at the top of the mast. The control tubes move in concert vertically to obtain collective pitch. This design is unique because of the method of obtaining cyclic pitch. As shown in Figure 15, the stationary swashplate is attached to the innermost control tube by a universal joint. The outer control tube attaches to an inclined input plate.

By rotating the control tubes relative to one another the stationary swashplate can be tilted at different angles. Note that Figure 15 depicts the control system in the neutral cyclic position (level). The stationary swashplate tilt is directly transmitted to the rotating swashplate thereby effecting blade cyclic pitch. Final design of this system would determine the geometry of the input plate and the control system mixer inputs to the internal control tubes. Advantages of this system include high survivability and high control system stiffness. A disadvantage of this system would be the complexity of the mixer system. This design might be more suited to a fly-by-wire/light system operated by a microprocessor which would control the turning of the control tubes relative to one another. These control systems were evaluated further during the next task of the project, hub configuration development.

The maintainability of this system is enhanced since the internal control tubes do not rotate (at rotor rpm). On the other hand, parts count for this internal control system is greater than the external control system due to the mixer system (not shown) and the input plate at the top of the mast. The higher parts count and control system mixer which could be quite complex (as stated above) would lead to high maintenance requirements.

Inplane damper concepts and a typical system design were considered before the hub concepts were evaluated. A conventional damper arrangement was shown in Figure 9. This design employs elastomeric dampers attached to a lead-lag link and the outside of the pitchcase. A more difficult design problem is locating the damper inside the pitchcase for a flexbeam concept without a lead-lag hinge. The damper has to be restrained in the chordwise direction while still maintaining the ability to twist torsionally with the pitchcase and flexbeam. A possible solution to this design challenge is shown in Figure 16. The damper is attached to the inside of the pitchcase by using flexible plates which could be fabricated from composite material. These plates allow the damper torsional freedom while still providing chordwise restraint for lead-lag damping. These dampers would be located where the largest chordwise differential motion occurs between the flexbeam and pitchcase. An additional damper design uses sandwich type construction with a thin layer of elastomeric damping material bonded between a graphite (high stiffness) plate and a fiberglass plate. These plate strips are then bonded (fiberglass side) to a flexbeam. These strips can be used as primary or auxiliary dampers. Reference 8 reports the use of these dampers with a bearingless main rotor.

In regard to system integration, Figure 17 presents an external control system mated with the S-Beam flexbeam concept (Figure 6). The control tube from the pitch horn to the blade would be stiff torsionally yet have flexibility in the flapwise and chordwise directions to accommodate the

---

8

Sheffler, M., Staley, J., and Warmbrodt, W., EVALUATION OF THE EFFECT OF ELASTOMERIC DAMPING MATERIAL ON THE STABILITY OF A BEARINGLESS MAIN ROTOR SYSTEM, Proceedings of the American Helicopter Society National Specialists Meeting, Rotor System Design, Philadelphia, Pennsylvania, October 1980.

motions of the flexbeam. A control tube using a composite material wound at ±45 degrees should meet the control tube criteria. As discussed previously, an internal control system with the V-strap flexbeam is shown in Figure 9. These designs and concepts were then evaluated to determine the most promising concepts to investigate further during the next phase of this program. These evaluations focused on the various flexbeam designs. Inputs were received from the technical specialists in the design team, and these evaluations were subjective and qualitative in nature.

Table 4 presents the rating of the flexbeam concepts (See Table 2) for general considerations. The three most promising designs based on these criteria were the cruciform, S-beam, and the V-strap. The more conventional designs such as the V-straps were rated much better than designs such as the hemispherical flexbeam in the technical risk section. The flat strap was given a low rating under technical risk since there were concerns that this concept could not accommodate the required loads and deflections and still achieve a long fatigue life. This was the same reason the flat strap rated low under reliability. Weight criteria reflected subjective estimates on the compactness of the flexbeam and total weight of the hub. The flat-strap cruciform design was rated high under weight criteria since the geometry of this concept can be tailored relatively easily to achieve a compact rotor hub. In addition, this design eliminates the weight of a lead-lag fitting. The flat strap and hemisphere designs were not rated high in regard to weight since it was thought their effective flapping hinges would be located further outboard than the other designs which would lead to weight penalties. The S-beam was not rated higher because it was thought the integral hub and S-beam housing would slightly increase the system weight above some of the other designs. It should be emphasized the dimensions shown in Figures 1 through 12 are approximate and these dimensions could change during final design.

Part count attempted to rate the concepts according to the total number of parts in the hub and an applicable control system. The number of parts before final bonding operations was also considered. For example, it was thought the cruciform flexbeams as well as the flat strap could be fabricated in one step, thus they each received a high rating. The S-beam (Figure 6) did not receive a high rating since the blade retention straps and S-beams would have to be fabricated separately and bonded together in a final operation.

If any difficulties were foreseen in manufacturing these concepts, these potential problems were reflected in the complexity and manufacturing cost criteria. The flat strap flexbeam concept rated the highest for these criteria since it would be the easiest to manufacture. The flat-strap cruciform and S-beam designs also rated high for these criteria. As stated previously, the flat-strap cruciform flexbeam concept could be fabricated

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 4. FLEXBEAM CONCEPT RANKING, GENERAL CONSIDERATIONS

	Concept						
	A	B	C	D-2	E	F	G-2
Criteria	Cruciform	Tapered Cruciform	Hemisphere	S-Beam	Multiple Strap	Flat Strap	V-Strap
Technical Risk	5	5	3	4	4	4	7
Weight	7	6	4	5	6	5	5
Part Count	7	7	6	5	6	7	5
Complexity	6	5	4	6	4	8	5
Manufacturing Cost	5	4	4	6	4	7	5
Reliability	5	5	4	7	3	4	5
Control Integration	7	7	6	8	7	7	8
Damper Integration	7	7	9	8	6	7	9
Hub Drag	5	5	4	6	4	4	4
Total	54	51	44	55	44	53	53

Rating 0 to 10 with 10 being best.

in one piece but the tooling would be more complex than for the simple flat strap. The S-beam concept was rated high since the fabrication of blade retention straps and S-beam flexbeams would be relatively easy. The S-beam would be wet-filament wound on an elliptical or circular mandrel, cured, and then bent (similar to a spring) to the shape shown in the drawings. Thus the tooling cost would be kept to a minimum.

Similar ratings were received by all the designs in regard to reliability except for the S-beam and the multiple strap concept. The multiple strap design was judged to have low reliability due to its many straps and joints (Figure 7) which could prove difficult to keep in working order. The S-beam concept was rated to have high reliability due to the redundancy of the S-beam flexures and simple construction.

No insurmountable problems were foreseen in integrating control systems with any of the flexbeam concepts. The V-strap is a standard design thereby rating high. Also, it was thought the hub of the S-beam design could easily accommodate a control system.

V-strap and hemispherical flexbeam designs were highly rated in regard to damper integration. The V-strap concept uses a proven damper design and the hemispherical flexbeam concept lends itself to the use of dampers on either side of the hourglass winding. The design of the S-beam concept also provides several locations within the hub for damper attachments thereby earning a high rating.

Hub drag ratings were based on qualitative estimates of the compactness and ease of fairing each flexbeam concept. The S-beam design rated slightly higher than the other designs due to its aerodynamically clean hub (Figure 6).

Next, these concepts were related based on structural considerations. [illegible] ess analysts subjectively evaluated the designs and these results are presented in Table 5. Since the torsional stiffness of these designs is a very important factor, it was evaluated separately. A qualitative ranking of the designs is shown in Table 6. Based on these criteria the V-straps, S-beam, and cruciform were the most promising designs.

Finally, the flexbeams were judged on their survivability. This subjective estimate was essentially based on the amount of material and area of the flexbeam. The top four concepts are ranked in Table 7.

Three concepts were then chosen to be further developed during the next phase of the program. The cruciform and S-beam were selected based on structural considerations, general considerations, and vulnerability. The Kevlar 29 V-strap design was chosen due to its low risk and high ranking under general considerations. Internal controls can also be investigated with the V-strap concept.

TABLE 5. FLEXBEAM CONCEPT RANKING, STRUCTURAL CONSIDERATIONS

	Concept						
	A	B	C	D-2	E	F	G-2
Criteria	Cruciform	Tapered Cruciform	Hemisphere	S-Beam	Multiple Strap	Flat Strap	V-Strap
Least Strain for a Given Flapping Displacement	5	5	3	8	6	8	10
Least Strain for a Given Feathering Displacement	7	5	5	8	4	3	8
Least Strain for Lead-Lag Blade Motion	5	4	5	7	3	2	5
Failsafe	3	4	5	4	6	5	5
Relative Level of Mean Stress	6	4	4	7	5	4	5
Totals	26	22	22	34	24	22	33

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 6. FLEXBEAM CONCEPT RANKING, TORSIONAL STIFFNESS

Relative Stiffness (in Order of Increasing Stiffness)	Concept
1	G-2, V-Strap
2	D-2, S-Beam
3	A, Cruciform
4	B, Tapered Cruciform
5	C, Hemisphere
6	E, Multiple Strap
7	F, Flat Strap

TABLE 7. FLEXBEAM CONCEPT RANKING, VULNERABILITY

Relative Vulnerability (in Order of Increasing Vulnerability)	Concept
1	F, Flat Strap
2	D-2, S-Beam
3	E, Multiple Strap
4	A, Cruciform

HUB CONFIGURATION DEVELOPMENT

During this portion of the program preliminary design criteria were finalized and hub concepts were sized using first order analyses.

Design criteria used for this phase of the study were the same as given in Table 1 with the exception of the centrifugal force. The choice of 100,000 pounds centrifugal force was used for initial hub sizing for both operating rpm and a nominal overspeed rpm (selection of Candidate Hub Concepts). During this phase of the study more accurate estimates were made of centrifugal force commensurate with a more detailed analysis of the hubs. The hubs were designed for rotors with a radius of 31 feet and a chord of 23 inches. Blade weight was estimated at 275 pounds using the given blade radius and chord.

The design rotational speed of these configurations was 216 rpm which produced a tip speed of 701 feet per second. Table 8 presents the hub design loads and deflections.

The endurance limit flapping and feathering angles are repeated in this table from Table 1. Five degree flapping as an endurance limit was selected because this is one of the hub technical goals. Fifteen degrees oscillatory feathering was chosen since this is compatible with the RSRA's control motions. In addition, studies investigating bearingless main rotors for the

TABLE 8. ITR/FRR DESIGN LOADS AND DEFLECTIONS

Blade Weight	275 pounds
Centrifugal Force at Operating RPM of 216	68,000 pounds
Centrifugal Force at 30 Percent Overspeed	115,000 pounds
Endurance Limit Flapping Angle	±5 degrees
Endurance Limit Feathering Angle	±15 degrees

RSRA have also used ±15 degrees feathering as a design criterion (Reference 9). Control motions for these hubs were based on the existing RSRA control motions which are shown in Table 9.

TABLE 9. ITR/FRR DESIGN CONTROL MOTIONS

Total Collective Travel	14 degrees
Longitudinal Cyclic	-11 to 15 degrees
Lateral Cyclic	±8 degrees

After the design criteria were finalized, work was conducted to refine and develop the selected hub concepts. The S-beam concept was first studied and the conceptual layout of this design is presented in Figure 18. The design has an internal control system with slots provided in the hub for the pitch links. An elastomeric snubber/pivot point was provided at the inboard end of the S-beam and blade retention strap to eliminate flapwise moments due to the pitch link loads. The snubber fitting would be an integral part of the blade retention strap. Lead-lag damping was provided by elastomeric dampers which enclose the snubber. Once the conceptual drawing had been completed the S-beam was sized to carry the centrifugal load from the blade retention strap to the hub. The S-beam strap was one quarter inch thick and had a length of ten inches to accommodate the blade centrifugal force. This geometry produced a torsional feathering stiffness of 1,384 inch-pounds/degree which was deemed excessive. The uniqueness of the S-beam concept caused difficulties in making sound qualitative judgements for the initial ranking process. Work on the S-beam was discontinued due to the high torsional stiffness.

Both the Kevlar 29 V-strap and flat strap cruciform designs were carried through this conceptual predesign study. Sizing of the V-strap was straightforward due to its similarities to the existing AH-64 rotor hub. Figure 19 presents the Kevlar 29 V-strap hub configuration. The straps were fabricated in pairs which fit into a metal hub in an "over and under" configuration. This hub was scaled from the AH-64 rotor hub to meet load

[9] Krauss, T.A., BEARINGLESS HELICOPTER MAIN ROTOR DEVELOPMENT, Report SER-70238 by Sikorsky Aircraft Division of United Technologies Corporation, NASA CR-145188, NASA, Washington, D.C., June 1977.

and survivability criteria. The aluminum hub has documented invulnerability (Reference 7). It is thought hubs shoes or clamp plates using fiberglass or other composite materials could also be designed to provide invulnerability with some weight benefits. This study concentrated on the design of the flexbeams using the known properties of the metal hubs. An elastomeric flapping/feathering snubber was employed along with an elastomeric lead-lag bearing. In addition, elastomeric dampers were also used for this rotor hub.

A composite spacewound pitchcase is also shown in Figure 19. This pitchcase was designed for small HEI projectile invulnerability. Survivability and load criteria also dictated the size of the pitchhorn and flapping/feathering snubber fitting, as well as the lead-lag bearing fitting. Additional details of this type of pitchcase are presented later during the discussion regarding the flap-strap cruciform design.

The control system used for the V-strap design was an internal mast system which was a variation of the system shown in Figure 14. One major difference is that the latest V-strap concept (Figure 19) placed the rotating and stationary swashplates on the top of the mast. Survivability of the control system was not compromised by placing the swashplates on the top of the mast. The control system components were sized to survive a small HEI projectile hit regardless of whether the swashplates were placed below or on top of the rotor hub. The control system maintainability requirements should also be unchanged due to swashplate placement. Servicing the control system with the swashplates on top of the rotor hub could be more difficult due to their greater height above the work platforms. The drag of this system is greater than for a conventional control system as discussed on page 41 of this report. The reason the swashplates were not located beneath the transmission was to simplify the integration of this concept with the RSRA. Another difference between this design (Figure 19) and the control system of Figure 14 was that the small diameter internal control rods and guides were replaced by larger diameter concentric tubes located in the mast. The control system shown in Figure 15 was also considered for this V-strap system but not pursued further due to the necessity of a complicated control mixer system. The control system of Figure 15 appears to have a great deal of potential when used with a fly-by-wire/light and microprocessor system.

The hub shoes and flapping/feathering snubber were designed to place the effective flapping hinge 12 inches from the rotor centerline. This hinge location allows the rotor to meet the hub moment stiffness criteria. The combination of material selection (Kevlar 29), hub design (with hub shoes), and laminated flexbeam construction allowed a relatively low hinge offset (3.2 percent rotor radius) with acceptable flexbeam stresses.

Details of the V-straps are shown in Figure 20. Fiberglass fabric is used to reinforce the V-straps both at the end fittings and the hub attachment area. At the center of the hub, the V-straps are bonded to metal fittings which are clamped into the hub along with the center portion of the straps. This fitting arrangement insures that the straps would not extrude through the hub due to a centrifugal force imbalance. Also presented in Figure 20 are two variations in the strap design. Both strap designs have essentially the same cross sectional areas but with different widths and strap pack thicknesses. The geometry of the straps and hub configuration are presented in Figure 21. During a complete preliminary design study these strap variations could be analyzed for survivability but for the purposes of this program both designs were assumed to be equally survivable. Stress analyses were conducted of both V-strap designs.

In addition to the deflection and load criteria given in Table 8, a mean flapping angle of two degrees and a mean feathering angle of five degrees were assumed for the stress analysis of the V-strap concepts. Figure 22 shows the equations used to obtain the stresses due to flapping for a laminated flexure. Strap dimensions for these equations are given in Figure 21. Shoe bending stress is due to the bending of the fibers around the hub shoe while pack bending is due to the elongation of the fibers.

The laminated flexures greatly reduce stresses due to flapping compared to a solid flexure. Figure 23 presents a comparison of the flapping equations for a solid and laminated flexure. Denoting a factor "K" as the ratio of laminated flexure stress to solid flexure stress and referring again to Figure 23:

$$K = \frac{F_{laminated}}{F_{solid}} = \frac{\sigma}{N} + \frac{R\,\beta_{Rad}}{L}$$

Using as an example the geometry of strap concept one shown in Figure 21:

$$\text{Laminate solidity} = 0.84$$

$$\beta_{Max\ angle} = 7 \text{ degrees}$$

and

$$K = 0.104$$

Thus, the laminated flexure has approximately 10 percent the stress of a solid flexure for the same flapping angles. Even though this simplified comparison does neglect the fact the solid flexure may be somewhat reduced in thickness (more load carrying material without the shims), it does illustrate the benefits of the laminated concept. Rotors with larger effective flapping hinge offsets would not benefit as much from the laminated concepts since the hub shoe radius would greatly increase.

Equations for obtaining the V-strap stresses produced by centrifugal force and drag forces are given in Figure 24. The drag loads used for these equations were estimated from the AH-64 rotor loads, and the value of the drag forces was 1800 pounds ±3600 pounds. The value of the steady stress, F_p, from the above equations was also used to obtain the strap stresses due to feathering. Feathering stress equations are shown in Figure 25.

Using the design loads and deflections along with the previously discussed equations, stresses were determined for both the V-strap concepts. Table 10 presents a summary of these calculations. The alternating stresses were added vectorially. Alternating stresses were considered one per rev in character with feathering leading flapping by 90 degrees.

In addition to stress levels, the torsional stiffness of the V-strap designs were calculated. Simple cable tension equations were used to determine the stiffnesses, and Figure 26 presents the equations and the results of the calculations. The wider strap design (Concept No. 2) has the higher stiffness since the center of the strap (for each leg) is further from the pitch change axis than the narrow strap design (Concept No. 1). These flexbeam feathering stiffnesses under centrifugal force were deemed acceptable for a helicopter of this size (18,400 pounds GW).

Upon completion of the V-strap conceptual study, the flat strap cruciform design was studied. This design eliminated the lead-lag joint which required that the flexure geometry be tailored to achieve a first inplane natural frequency between 0.6 and 0.7/rev. Dynamic analyses as well as stress analyses were conducted of this concept. Aeroelastic couplings to enhance rotor stability were also investigated with the flat strap cruciform design. The initial studies with this hub concept did not incorporate couplings in order to clearly ascertain a given coupling's effect on the design.

TABLE 10. ITR/FRR V-STRAP STRESS SUMMARY

Type of Stress	Concept No. 1		Concept No. 2	
	Mean (psi)	Alternating (psi)	Mean (psi)	Alternating (psi)
Shoe Bending (F_{SB})	3,910	±3,910	3,910	±3,910
Pack Bending (F_{PB})	3,970	±9,930	2,530	±6,320
Steady (F_P) CF + Steady Drag	27,830	-	27,730	-
Cyclic Drag (F_D)	-	±9,900	-	9,870
Feathering (F_θ)	8,290	±19,940	10,880	±23,150
Combined (F_T)*	44,000	±32,890	45,050	±34,570
Endurance Limit (F_{EL})	-	±36,500	-	±36,100
Infinite Life Fatigue Margin-of-Safety (Non-Dim.)	0.11		0.04	

*Mean $F_T = F_{SB} + F_{PB} + F_P + F_\theta$

Alt $F_T = (F_{SB} + F_{PB}) \rightarrow (F_D + F_\theta)$

First, an inplane (chordwise) stiffness distribution was estimated to achieve the desired chordwise natural frequency. The following equation was used:

$$\omega_{n_\zeta}/\Omega = \sqrt{3/2\,\frac{\ell}{R} + \frac{K}{I\Omega^2}}$$

where:

$\omega_{n\zeta}/\Omega$ = inplane natural frequency, per rev, 0.65

ℓ = estimated virtual lead-lag hinge, 20 inches

I = blade moment of inertia, 2736 slug-ft^2

K = effective inplane spring

R = blade radius, 31 feet, 372 inches

Ω = rotational speed, 22.62 radian/second

This equations was solved to obtain the value of the effective inplane spring which was determined to be 473,000 ft-lb/rad.

By integrating a chordwise stiffness distribution over a given length, an effective inplane lead-lag spring can be calculated. After several iterations, a chordwise stiffness distribution was determined which is presented in Figure 27. Fiberglass was the material chosen for this flexure due to the compressive stresses. A flexbeam flapwise geometry and stiffness distribution was also estimated which is shown in Figure 28. These stiffness distributions along with estimated blade properties were used in the Dynamic Analysis Research Tool (DART) computer program (Reference 10) to verify the rotor's natural frequencies.

Figure 29 presents the flat strap cruciform resonance diagram which shows an excellent frequency placement for a conceptual study. The inplane and flapping mode shapes are shown respectively in Figures 30 and 31. These figures verified the adequacy of the initial equations used to size the flexure.

Figure 32 shows the completed design of the flat-strap cruciform. A laminated flat-strap with metal hub shoes was also used in this design to meet the hub moment design criterion. The flapping hinge was located further

[10] Banerjee, D., and Johnston, R.A., INTEGRATED TECHNOLOGY ROTOR METHODOLOGY ASSESSMENT, Hughes Helicopters, Inc., NASA Contract NAS2-10871, Ames Research Center, Moffett Field, California, November 1981.

inboard than the V-strap design in order to better the system flapping stiffness criteria and to achieve a more compact control system for lower drag. The flapping hinge location was 9.3 inches from the center of the hub. The cruciform portion of the flexure accommodated both lead-lag and feathering motion. Also presented in Figure 32 are an elastomeric snubber and damper. The hub and controls were sized not only to meet the strength requirements but also to meet the vulnerability requirements. As stated previously, the metal hub shoes have documented survivability.

The details of a highly survivable pitchcase are shown in Figure 33. The major structural portion of this pitchcase was comprised of fiberglass wound at ±45 degrees. This winding angle ensured a high torsional stiffness to eliminate control system softness between the pitch link and blade attachment fitting. A lattice arrangement for the filament winding was used in order to vent pressures from explosive projectiles. A thin fiberglass overwrap was used on the outside of the fiberglass lattice for an aerodynamic fairing. The fiberglass was wound around the inboard and outboard fittings which were also designed to survive in a combat environment. Also shown in Figure 33 are unidirectional fibers, designated longos, which were placed both on the sides and top and bottom of the pitchcase as additional reinforcements.

Note that both V-strap and flat-strap cruciform flexures and pitchcases are shown in untwisted positions which are representative of cruise flight. This would be accomplished by fabricating a noseup pretwist at the blade root end equal to the estimated collective pitch at cruise. Since the blades would be fabricated from composite materials, no difficulties are expected from a pretwist at the blade root end. The pretwist minimizes the straps' mean torsional stresses and also minimizes the frontal area of the pitchcase during cruise which lowers the hub drag. Even though the flexures are shown with zero pitch at cruise, the flexure stresses were calculated with five degrees mean feathering angle to be conservative.

Stress analyses were next conducted of the flat-strap cruciform flexbeam. The applied loads, deflections, and flexure geometry are shown in Figure 34. The laminated portion of the flexure consists of five laminates each 0.1 inch thick. The laminates are separated by shims each 0.025 inch thick for a total pack thickness of 0.6 inch.

As verified by the dynamic analyses, flapping occurs primarily in the flat strap section and feathering motion occurs in the cruciform section. Equations presented previously for the V-strap flexure were used to obtain stresses due to flapping for this laminated flat-strap. Critical stresses in the cruciform were determined by inspection to be shear stresses. Standard equations from Reference 11 were used to calculate the shear stresses. The stress summary for the flat-strap cruciform is presented in Table 11. Shear stress allowables for the cruciform were obtained from fiberglass properties and the estimated effects of using a unique fabrication technique for the cruciform. The middle of the cruciform would be comprised of woven 0 degree and 90 degree fiberglass as shown in Figure 35. It is hypothesized this fabric would provide a shear tie at the center of the cruciform, thereby allowing relatively high shear stresses. Specimen testing would be conducted during a preliminary design phase to verify the strength of this construction. As shown in Table 11 all stresses are below the estimated endurance limits therefore meeting the design criteria.

Torsional stiffness of the design was also calculated. Figure 36 presents the fiberglass properties, cruciform geometry, and equations used to obtain the feathering stiffness under centrifugal force. The value of 348 inch-pound/degree was comparable to the V-strap design.

As well as stress analysis and the previously discussed dynamic analysis, additional dynamic analyses were conducted to investigate rotor stability. Rotor stability characteristics were studied using a computer program designated E927 (Reference 12). Since the hub and rotor were designed for the RSRA, the fuselage characteristics of the RSRA (presented in References 13 and 14) were also used for these stability studies. In addition to these calculations, data in the available literature were used to qualitatively guide the design of the rotor/hub structural and kinematic couplings.

[11] Roark, R. J., and Young, W. C., FORMULAS FOR STRESS AND STRAIN, Fifth Edition, New York, McGraw-Hill Book Company, 1975.

[12] Johnston, R. A., and Cassarino, S. J., AEROELASTIC ROTOR STABILITY ANALYSIS, Sikorsky Aircraft Division of United Technologies Corporation, USAAMRDL-TR-75-40, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1976, AD-A020871.

[13] Ham, E., and Klusman, S., AEROELASTIC AND MECHANICAL STABILITY ANALYSIS REPORT (RSRA), Report SER-72024 by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, April 1975.

[14] Ham, E., RSRA ACTIVE ISOLATION SYSTEM SHAKE TEST, Report ETR-G2-143, by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, February 1979.

TABLE 11. FLAT STRAP CRUCIFORM STRESS SUMMARY

Stress (psi) / Portion of Strap	Flat (Tension)		Cruciform (Shear)	
	Mean	Alternating	Mean	Alternating
Centrifugal	13,600	-	13,600 (Tension)	-
Shoe Bending	6,480	±6,480	-	-
Pack Bending	6,790	±16,970	-	-
Feathering	-	-	820	±2,460
Combined	26,870	±23,450	820	±2,460
Endurance Limit	-	±23,500	-	±2,500
Infinite Life Fatigue MS (Non-Dim.)	0.00		0.01	

First the flat-strap cruciform rotor and RSRA fuselage were modeled with E927 for the ground resonance condition. Fixed system pitch and roll properties were taken from Reference 13. Blade structural damping was excluded in the model but fixed system damping was included. All cases were run at flat pitch, i.e. zero thrust. Figure 37 shows the RSRA roll and pitch frequencies and the variation with rotor speed of the regressing first chord (inplane) mode natural frequency in the nonrotating system. While the roll mode is well separated, the pitch mode has a crossover with the regressing chord mode just below the rotor operating speed of 216 rpm. The corresponding damping of the regressing first chord mode is presented in Figure 38. Note, that although no structural damping was used the system is stable. Initially, this baseline case was run without aerodynamic effects. Figure 38, dashed line shows that without aerodynamics the regressing first chord mode is slightly unstable. With aerodynamics, the first chord mode is stable. These baseline calculations were performed without structural and kinematic couplings.

Structural and kinematic pitch-flap (δ_3) and pitch-lag (δ_4) couplings were then studied with E927. Results are for flat pitch and without any structural damping. Figure 39 shows the effects of pitch-flap couplings (positive δ_3: pitch up with flap up) on rotor stability for the ground resonance case are negligible. Figure 40 presents the influence of pitch-lag couplings on the first chord stability. Positive δ_4 (pitch up with blade lag) does improve the rotor stability. References 15 and 16 also present results showing the beneficial effects on rotor stability from positive pitch-lag couplings.

Air resonance was also studied using the RSRA fuselage model. The analysis was done at operating rpm in hover with a thrust of 18,400 lbs, corresponding to the vehicle gross weight. Figure 41 presents the results from E927 showing the effects of pitch-flap couplings. Negative pitch-flap couplings are

---

[15] Bousman, W.G., Sharpe, D.L., and Ormiston, R.A., AN EXPERIMENTAL STUDY OF TECHNIQUES FOR INCREASING THE LEAD-LAG DAMPING OF SOFT INPLANE HINGELESS ROTORS, Proceedings of the 32nd Annual National Forum of the American Helicopter Society, May 1976.

[16] Ormiston, R.A., CONCEPTS FOR IMPROVING HINGELESS ROTOR STABILITY, Proceedings of the American Helicopter Society Mideast Region Symposium on Rotor Technology, August 1976.

slightly beneficial for rotor stability and these couplings did have an effect on stability for a hingeless main rotor as reported in Reference 17. Major improvements in rotor stability for air resonance are achieved by using pitch-lag couplings. Figure 42 shows the benefits of positive pitch-lag couplings which enhance the rotor stability by a factor of ten. Figures 41 and 42 also present the frequency as well as the damping plots. These are plots of body roll and first-chord frequencies as a function of rotor rpm. The body pitch mode, in accordance with Reference 13 was not modeled.

Flap-lag couplings could not be easily investigated by using these first order analyses and would more appropriately be analytically studied during a preliminary design program. Flap-lag couplings were considered qualitatively based on results in the literature. References 6, 15, 16, and 18 document the benefits of positive flap-lag coupling. Thus, a concept variation of the flat strap cruciform was designed which incorporated flap-lag and pitch-lag coupling.

This design is depicted in Figure 43. Pitch-lag coupling was obtained by canting the pitch link relative to the pitch horn attachment as shown in Section BB of the drawing. Flap-lag coupling was achieved by pretwisting the flexure. The pretwist occurs at two locations, the flat strap and cruciform. The flat strap pretwist was set at 10 degrees as shown in Section BB. This allowed the center portion of the flexure to hub attachment to remain flat and the pretwist to occur in the hub shoes. Thus the center of this hub is no thicker than the baseline design (Figure 32). Additional pretwist of 20 degrees was provided at the transition region between the flat strap and cruciform as shown in Section DD of Figure 43. Thus, the total pretwist for this concept was 30 degrees. The pretwist of the bearingless rotor from Reference 6 was only 12.5 degrees but the rotor had a much stiffer flexure. It is hypothesized that for softer flexures (such as the flat strap cruciform), large amounts of pretwist to achieve flap-lag coupling must be provided since the coupling may "wash-out" due to centrifugal force and other blade loads.

---

[17] Huber, H. B., EFFECT OF TORSION-FLAP-LAG COUPLING ON HINGELESS ROTOR STABILITY, Proceedings of the 29th Annual National Forum of the American Helicopter Society, May 1973.

[18] Hodges, D.H., AN AEROMECHANICAL STABILITY ANALYSIS FOR BEARINGLESS ROTOR HELICOPTERS, Journal of the American Helicopter Society, Volume 24, Number 1, January 1979.

Again this item would be studied during a preliminary design program since coupling effects are configuration dependent. Impact of these couplings on the flat strap cruciform design were minimal except that the cruciform and transition sections had to be lengthened 10 inches. This was due to the additional mean feathering loads that had to be accommodated by the cruciform portion of the flexure. Previous designs without flap lag couplings would allow the flexure and blade to be oriented such that the flexure was relatively unloading during cruise flight. Since the couplings must be effective for the ground resonance conditions, the flexure pretwist must provide the couplings at a blade pitch (3/4 radius) of zero degrees. Thus, the flexure and blade feathering pretwist cannot be tailored for minimal stresses at cruise but must meet the coupling criteria. Hence, the blade was not pretwisted and the flexure was lengthened to reduce the steady feathering stresses.

The pitchcase was oriented at an angle to minimize hub drag. Shown in Figure 43 was a pitchcase torsional pretwist of -8 degrees which was the estimated collective pitch at cruise. Thus, the use of flap-lag coupling affected the flexure length but not the pitchcase feathering angle in cruise.

Kinematic pitch-flap coupling with blade sweep, and pitch-lag coupling with blade or hub precone and droop are additional coupling parameters that have a pronounced influence on rotor dynamics. In addition, these blade offsets provide different trim elastic deflections of the blade, resulting in coupled flap/lag/torsion structural coupling in the rotor. Reference 19 presents the significant effects of hub to flexure precone/droop and flexure to blade precone/droop for a bearingless rotor. Detailed consideration of these couplings and their implications would be more appropriately studied in the preliminary design phase of the ITR program.

[19] White, R. P., and Nettles, W. E., EXAMINATION OF THE AIR RESONANCE STABILITY CHARACTERISTICS OF A BEARINGLESS MAIN ROTOR, Proceedings of the 34th Annual National Forum of the American Helicopter Society, May 1978.

PHYSICAL PROPERTY DETERMINATION AND EVALUATION OF CANDIDATE CONFIGURATIONS

Properties of the V-strap and flat strap cruciform were calculated and estimated following the initial design of these hubs. The physical properties and hub characteristics to be obtained were those identified as rotor hub technical goals and rotor hub design specifications which were listed in Appendix B. Additional hub parameters which were estimated were given in Appendix C, Merit Factors/Merit Function. The values of these various parameters were then used to obtain merit factors which were combined in the merit function to obtain ratings for these hub concepts. The various parameters and hub properties are presented in the same order in this section of the report as listed in Appendix C for both the V-strap and flat strap cruciform concepts.

First, qualitative estimates were made of the vulnerability of the concepts to a small HEI projectile hit. As stated in previous sections, the rotor head and controls of the ITR concepts were similar in size and material to the AH-64 helicopter. In addition, a static mast system which is used for the AH-64 was also proposed for the ITR/FRR designs. Since the AH-64 rotor head, controls, and drive systems are documented invulnerable (Reference 7) there is a high probability the ITR concepts will be invulnerable.

The pitchcase was thought to be the item that determined the hub's survivability. Although the spacewound pitchcase appears to be the best design solution for a lightweight, stiff, survivable pitchcase, the design would have to be tested in order to ensure invulnerability to a small HEI projectile hit. The pitchcase for the flat strap cruciform flexure was slightly larger in cross section than the pitchcase for the V-strap. Thus, the flat strap cruciform pitchcase was judged to have the better probability of being invulnerable due to slightly less overpressure. Qualitative probability of surviving a hit were 65 percent for the V-strap and 75 percent for the flat strap cruciform.

Next, the subject of rotor stability was addressed. The stabilizing effects of various couplings appears very promising as shown from studies conducted during this program and as reported in the literature. The effect of a given coupling is very dependent upon the rotor/hub configuration. A thorough investigation of the rotor stability of the configurations with various couplings was outside the scope of this conceptual study program. Thus, it could not be stated with any degree of confidence that dampers could be eliminated with these designs. The concepts were evaluated with dampers in which case their probability of freedom from instability was 100 percent.

The drag of the hub and controls of these experimental concepts was next analyzed. Both V-strap and flat strap cruciform hub drag were estimated with these concepts mounted on the RSRA. The V-strap hub and controls are shown in Figure 48 in the report section, ITR Compatibility with the RSRA. Although not shown, the flat strap cruciform hub centerline was placed at the same location relative to the RSRA fuselage as the V-strap hub for the estimation of hub drag.

Drag estimation methods from Reference 20 and data from Reference 3 were used in order to estimate the drag of these configurations. The frontal area of the hub and controls was estimated and data from Reference 20 was used to obtain the drag. Swept area of the rotating pitch links was considered as part of the frontal area. Drag estimates were also obtained of the hub and exposed swashplates without the pitch links.

The drag estimates included the area of the flexure and pitchcase up to the blade attachment bolts. The blade bolt attachment for the V-strap hub was 50 inches from the rotor centerline and 53 inches for the baseline flat strap cruciform.

Blade bolt attachment was at rotor station 63 for the flat strap cruciform with couplings. This extra length for the flat strap cruciform was required in order to incorporate the flexure pretwist for flap-lag coupling.

Drag for the V-strap hub concept was evaluated both with internal fixed controls and swashplates mounted on top of the rotor hub (Figure 48) and with conventional controls. Table 12 presents the drag estimates for these hub concepts and their variants. In order to be consistent, these experimental hub concepts with conventional controls and without couplings were used for evaluation in the merit function.

Weight of the hub designs was also evaluated. Figures 19 and 32 were used to obtain respective weights of the V-strap and flat strap cruciform hub. These figures were used to estimate the volume of the various hub components

---

[20] Sheehy, T.W., and Clark, D.R., A METHOD FOR PREDICTING HELICOPTER HUB DRAG, Sikorsky Aircraft Division of United Technologies Corporation, USAAMRDL TR-75-48, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, January 1976, AD A021201.

TABLE 12. HUB DRAG SUMMARY

	Equivalent Flat Plate Drag
V-strap	
Conventional Controls	7.4 ft^2
Conventional Controls (Swept Area of Pitchlinks not included)	6.8 ft^2
Concentric Tube Controls (Figure 48)	9.4 ft^2
Flat-Strap Cruciform	
Conventional Controls	8.5 ft^2
Conventional Controls (Swept Area of Pitchlinks not included)	8.1 ft^2
Conventional Controls with Flexure Pretwist	9.0 ft^2

which along with standard material densities allowed the calculation of the concept weights. The weights are as follows:

	V-Strap	Flat-Strap Cruciform
Pitchcase Assembly Includes: Fittings, Pitchhorns, Dampers, and Snubbers	375 pounds	375 pounds
Flexbeam Assembly Includes: Blade Attachment Fittings	225 pounds	205 pounds
Hubs Assembly Includes: Hub Shoes and Mast Bearings	150 pounds	145 pounds
TOTALS	750 pounds	725 pounds

Weight savings were effected in the flat-strap cruciform design mainly due to the elimination of the lead-lag joint. These weight estimates are very preliminary due to the conceptual nature of this study.

Next, the number of parts in the two rotor hubs was estimated. The parts judged necessary for the V-strap and flat-strap cruciform hub are shown in Tables 13 and 14. Figures 19 and 32 were also used to guide the estimation of the part count although not all parts presented in Tables 13 and 14 are shown in Drawings 484-1502 and 484-1503 (Figures 19 and 32). Standard fasteners are not included in the part count.

Hub moment and flapping criteria were next evaluated for the V-strap and flat-strap cruciform designs. Hub moment due to the flexure stiffness was essentially nil due to their laminated construction. Hub shoes and the snubbers fixed the flapping hinge location for these concepts. Thus the following simple equation was used to obtain an estimate of the hubs' stiffnesses.

$$\text{Hub Moment } \frac{\text{foot-pounds}}{\text{rad}} = \text{centrifugal force} \times \text{hinge location (feet)} \times \sin 1 \text{ degree} \times 57.3 \frac{\text{deg}}{\text{rad}} \times 2$$

(Two blades contribute to the hub moment.)

As presented previously the flapping hinge locations were 12 inches for the V-strap design and 9.3 inches for the flat-strap cruciform design. Hub stiffnesses were 136,000 foot-pounds/rad and 105,400 foot-pounds/rad for the V-strap and flat-strap cruciform respectively.

The flexure stresses were calculated in previous sections of this report for five degrees of flapping. As shown in Tables 10 and 11 the flexure stresses were slightly below the estimated endurance limits. Thus, the five degree rotor hub tilt angle criterion was met. In addition, the minimum rotor hub moment was calculated based on five degrees flapping and the stiffness of the hubs. The calculated minimum hub moments were 11,870 foot-pounds for the V-strap and 9,200 foot-pounds for the flat-strap cruciform.

TABLE 13. V-STRAP FLEXURE PARTS

Top of Rotor Head	
Retention Ring	1
Hub Nut	1
Hub Fairing	1
Damper	
Damper Assembly	8
Rod End	8
Special Nut for Rod End	8
Trunnion	8
Pitch Case Assembly	
Elastomeric Lead-Lag Bearing	4
Lead-Lag Pin	4
Lead-Lag Fitting	4
Lead-Lag Bushing	4
Pitch Case	4
Rotor Head	
Elastomeric Flapping/Feathering Snubber	4
Stud	4
Strap Assembly	2
Droop Stop	4
Droop Stop Roller	4
Droop Stop Inner Race	4
Lower Hub and Shoe	1
Upper Hub and Shoe	1
Hub Bearings	2
Retainer Seal	1
TOTAL PARTS	78

TABLE 14. FLAT-STRAP CRUCIFORM PARTS

Top of Rotor Head	
Retention Ring	1
Hub Nut	1
Hub Fairing	1
Damper	
Damper Assembly	8
Pitch Case Assembly	
Pitch Case	4
Rotor Head	
Elastomeric Flapping/Feathering Snubber	8
Strap Assembly	2
Droop Stop	4
Droop Stop Roller	4
Droop Stop Inner Race	4
Lower Hub and Shoe	1
Upper Hub and Shoe	1
Hub Bearings	2
Retainer Seal	1
TOTAL PARTS	42

Table 15 compares ITR/FRR program goals with the estimated properties of the V-strap and flat-strap cruciform hubs. Note the goals are referred to a gross weight of 18,400 pounds. Discussion of other hub parameters follows.

TABLE 15. ITR/FRR HUB PROPERTY COMPARISON, 18,400 POUNDS GROSS WEIGHT

Design Parameter	Goal	V-Strap	Flat Cruciform
Flat Plate Drag	3.1 ft^2	7.4	8.5
Hub Weight-Percent of Gross Weight	2.5 percent	4.1	3.9
Parts Count	50	78	42
Moment Stiffness	115,000 foot-pounds/rad	135,000	105,000
Minimum Hub Moment	11,500 foot-pounds	11,870	9,200
Flapping Endurance Limit	5 degrees	5	5

Reliability of the designs was qualitatively estimated. The V-strap design was similar in several aspects to the AH-64 hub. The AH-64 hub mean time before removal (MTBR), based on flight test experience, is greater than 4890 hours. Other features of the V-strap concept enhancing its reliability include the composite strap pack, composite pitchcase, and elastomeric feathering snubber and lead-lag bearing. The probability of the V-strap design meeting or exceeding the 3000 hour MTBR goal was estimated at 100 percent.

Similarly, the reliability of flat strap cruciform design was also judged to be high. The basic metal parts of the flat-strap cruciform hub such as the hub shoes and plates were similar to the AH-64 hub. This concept eliminates the lead-lag joint and uses a composite pitchcase and flexure, all items which enhance its reliability. The flat-strap cruciform concept was also estimated to have a 100 percent probability of meeting or exceeding the 3000 hour MTBR goal.

Manufacturing cost of these designs was then evaluated. Estimates were to range between 1 and 10, varying inversely with cost. The existing AH-64 hub was used as the baseline design with a value of 5.0. The V-strap flexure assemblies would be highly automated using wet filament winding techniques to keep the cost low. In addition, the four flexures would be wound in pairs which would be cost effective. It was also estimated the composite pitchcase was less expensive than the metallic pitchcase. The V-strap hub concept was assigned a qualitative cost rating of 7.0.

The flat-strap cruciform was also rated high due to its composite flexure and pitchcase. Automated manufacturing techniques would also be used to fabricate the flat strap cruciform flexure but the design is more complex than the V-strap concept. One feature of this design which simplifies its manufacture is that structural cross sectional areas of the flat strap and cruciform members are the same. Figure 44 presents the area distribution of this flexure which was shown in Figure 32. The additional material in the transition regions is used to shape the flexure, but this material does not react the blades' forces or moments. These flexures would also be fabricated in pairs, and load carrying composite plies would extend through the hub and form blade attachment fittings for opposite blade pairs.

The flat-strap cruciform design eliminated the lead-lag assembly which also lowered the cost relative to the baseline design (AH-64). Due to the added complexity of the flexure, the flat-strap cruciform design was judged slightly more expensive to manufacture than the V-strap design and hence was assigned a rating of 6.5.

The fatigue life for both hub concepts was next evaluated, and the life was judged to have a high probability of exceeding 10,000 hours. Flexures of both experimental designs were previously shown to have stresses below the estimated endurance limits. Life of the metallic components was also estimated above 10,000 hours. Similarities between the metal parts of the conceptual hubs and the AH-64 hub aided in this qualitative evaluation. Discussions were held with elastomeric bearing/damper manufacturers who thought 10,000 hour part life was difficult but probably obtainable for the next generation rotor systems. Thus, the probability that the fatigue life of the V-strap and flat strap cruciform will be 10,000 hours was estimated at 90 percent.

Ease of obtaining auxiliary damping for the conceptual hub designs was then evaluated. Dampers were provided for both the V-strap and flat-strap cruciform designs. If additional damping would be required for the V-strap design, new dampers could be fabricated that are wider than those shown in Figure 19 which would then provide greater damping. The wider dampers would be compatible with the existing pitchcase and the same attachment hardware would be used.

Additional damping could be incorporated on the cruciform member of the flat-strap cruciform design by using damper pads similar to those described in Reference 8. Figure 45 presents a pictorial of a representative damper pad. Damper pads are easily applied to the cruciform section since the cruciform surfaces are flat. Up to eight auxiliary dampers could be used on the cruciform flexure.

Based on the above reasons, both concepts were rated two (2), the highest rating, for ease and practicality of incorporating auxiliary damping.

The final criterion for evaluation was the torsional stiffness of the rotor system. The objective was to compare the forces of the pitch control system of the conceptual designs to those produced by a standard hub. AH-64 steady control loads were scaled to an 18,400 pound gross weight helicopter to obtain baseline rotor system loads. The total baseline system stiffness was estimated to be 651 inch-pounds/degree. This stiffness value included torsional moments due to the retention system, moments due to chordwise mass distribution ("tennis racket moments"), and aerodynamic moments. The scaled AH-64 hub retention system had a stiffness of 151 inch-pounds/degree with the remaining stiffness of 500 inch-pounds/degree produced by dynamic and aerodynamic effects.

The V-strap and flat-strap cruciform flexures stiffnesses with centrifugal force were respectively 342 and 348 inch-pounds/degree as reported previously. The torsional stiffness of the elastomeric feathering snubbers was estimated to be 80 inch-pounds/degree. Total torsional stiffness including dynamic and aerodynamic forces was 922 inch-pounds/degree and 928 inch-pounds/degree for the V-strap and flat strap cruciform systems respectively. These results are presented in Table 16 which also refers the stiffness values to the baseline hub. The control system forces for the conceptual designs did not exceed 1.5 times the baseline hub, and hence the merit factor for torsional stiffness was zero for both designs. A minus two would have been the merit factor if the forces generated by the experimental designs had exceeded the baseline forces by 1.5.

TABLE 16. ITR TORSIONAL STIFFNESS COMPARISON

Design	Stiffness, $\frac{\text{inch-pounds}}{\text{degree}}$	Referred to Baseline Hub
Baseline (Scaled AH-64)	651	1.0
V-Strap	922	1.42
Flat-Strap Cruciform	928	1.43

The conceptual hub configurations were then evaluated using the merit factors and merit function from Appendix C. Merit factor values were either presented during the preceding discussion or were calculated based on the hub properties. Tables 13 through 15 presented a comprehensive overview of the V-strap and flat-strap cruciform hub properties. Values of the merit factors for both concepts are shown in Table 17. The equation and values for the merit function (Appendix C) are as follows:

$$\text{Merit Function} = K_v \times K_a \times (\text{Sum of Other Factors})$$

$$\text{V-Strap} = 0.65 \times 1.0 \times (32.5) = 21.2$$

$$\text{Flat Strap Cruciform} = 0.75 \times 1.0 \times (33.5) = 25.1$$

As shown above, the merit functions before multiplying by vulnerability and rotor stability for the V-strap and flat-strap cruciform designs were 32.5 and 33.5. These factors compare favorably to a score of 42 if every design goal was met exactly.

TABLE 17. ITR MERIT FACTORS

Parameter	V-Strap	Flat-Strap Cruciform
K_v = Probability of surviving small HEI projectile hit	0.65	0.75
K_a = Probability rotor system will be free from instabilities	1.00	1.00
K_d = Percent reduction from hub drag goal	-1.38	-1.74
K_w = Percent reduction from hub weight goal	-0.64	-0.56
K_p = Percent reduction from parts count	-0.56	1.16
K_e = Hub moment stiffness parameter. See Appendix C	5	5
K_m = Minimum moment. 1/2 percent parameter exceeds goal	0.985	1.1
K_b = Rotor tilt angle. 1/2 percent parameter exceeds goal	1.0	1.0
K_r = Reliability. 10 times probability of meeting or exceeding MTBR goal	10	10
K_c = Cost parameter. Qualitative estimate from 1 to 10	7.0	6.5
K_f = Fatigue life. 10 times probability of meeting or exceeding goal	9.0	9.0
K_z = Lead-lag damping. 0 to 2, qualitative estimate of ease of adding auxiliary damping	2.0	2.0
K_s = Torsional stiffness. See Appendix C	0	0

FRR HUB CONFIGURATION VARIATIONS

Modifications to the basic ITR rotor hub were considered during this section of the report. Since the flat-strap cruciform design was more highly rated than the V-strap design, the flat strap cruciform concept was chosen for the flight research rotor.

Variations of the flat-strap cruciform depicted in Figure 32 were first designed. Figure 46 shows methods of obtaining different pitch-flap couplings and blade sweep angles. The FRR would use a slightly different pitchcase from the one used on the ITR. A spacewound composite pitchcase would still be used but with a different inboard fitting as shown in Figure 46. Various pitch horns would bolt onto the inboard fitting which would allow the pitch-flap coupling to vary between 0 and 35 degrees. The pitchcase could be rotated 180 degrees to obtain negative pitch-flap couplings. The manufacturing techniques and tooling to wind the pitchcases would not be changed from the ITR, which would allow these FRR pitchcases to be fabricated relatively inexpensively.

Blade sweep adapters would also be produced as presented in Figure 46. These adapters are simple in construction and allow the blade sweep angle to be changed after detail design and analyses have been conducted. Blade sweep angles can be reversed with the same adapter by rotating the adapter 180 degrees. During preliminary and detail design studies the radius of the blades will be established to ensure the sweep adapters will not cause blade interference with the tail rotor.

Different flexure pretwists to achieve various pitch-flap couplings were also considered. A total flexure pretwist of 15 degrees is shown in Figure 47 as compared to a 30 degree flexure pretwist which was shown in Figure 43. The flat strap flexure pretwist is kept at 10 degrees for both these designs. Thus the hub clamping plates would be unchanged and could be used for both the ITR and FRR. The manufacturing techniques would not change for these two flexures but different tooling would be needed to change the cruciform pretwist from 20 degrees to 5 degrees. Tooling costs could be kept reasonable by using "soft" tooling (composite-phenolic forms) for these one-of-a-kind flexures. The desirable pretwist angles would be calculated during the preliminary and detail design phase of the program.

As discussed during the evaluation section of this report, different amounts of auxillary damping could be investigated for the FRR by the use of damper pads. Up to 8 damper pads could be placed on the cruciform section to achieve higher levels of inplane damping.

ITR COMPATIBILITY WITH THE RSRA

Analyses and design studies conducted during the NASA Predesign Study for Modern Four-Bladed Rotor for the RSRA (Reference 21) were used to guide the integration of the ITR with the RSRA.

The support system for both the V-strap and flat-strap cruciform design consisted of a new mast support truss/platform and a static mast which attaches to the platform. This rotor support arrangement is similar to the system presently used on the AH-64. Figure 48 shows this support system with the V-strap hub concept. Only torque is supplied and reacted by the transmission. Other forces and moments from the rotor are transmitted through the static mast to the platform and truss to the balance isolation system. The existing transmission gearbox will be used and thus, the redesign, fabrication, and testing of a new main rotor transmission case will be eliminated. A new drive shaft will be required but this cost will be relatively low compared to a totally new transmission case.

Also depicted in Figure 48 is the concentric tube control system with the swashplates mounted on top of the hub. Design studies first investigated placing the swashplates underneath the transmission but these conceptual studies indicated there was not enough space in that area. The internal mast controls and swashplates will be further investigated during preliminary design studies, but if space problems are verified then a compact external control system will be considered.

The concentric tube control system design was carried through these conceptual studies to obtain comparisons with the external control system on the RSRA. Note the evaluation of the V-strap and flat-strap cruciform concepts were both compared on an equal basis with external control systems. Existing RSRA hydraulic actuators were used since these actuators are capable of

[21] Hughes, C. W., and Logan, A. H., PRE-DESIGN STUDY FOR A MODERN FOUR-BLADED ROTOR FOR THE ROTOR SYSTEMS RESEARCH AIRCRAFT (RSRA), Hughes Helicopters, Inc., NASA CR 166154, Ames Research Center, Moffett Field, California, March 1981.

forces in excess of 9,700 pounds retracted and 12,000 pounds extended (Reference 22). These forces are adequate to obtain the necessary control motions which were set during the design criteria study to match the existing RSRA blade motions (Table 9.)

It was determined there was adequate space in the fuselage to mount the actuators underneath the balance/isolation platform and connect the actuators to the fixed system concentric tube controls as shown in Figure 48. With the concentric tube control system, design studies verified there was 1.5 inches clearance in the center tube to accommodate the blade severance system primer chord.

Table 18 presents the parts required to mate the V-strap concept with the RSRA. These parts are shown in Figure 48 except for the isolation platform control motion compensators.

TABLE 18. PART REQUIREMENTS INTEGRATION OF V-STRAP CONCEPT AND CONCENTRIC TUBE CONTROLS WITH THE RSRA

EXISTING PARTS	
RSRA Main Transmission Assembly	72350-08500
RSRA Active Balance/Isolation Platform	72959-02212
RSRA Actuators	72400-00400
NEW PARTS	
Static Mast	
Mast Support Truss	
Isolation Platform Control Motion Compensators and Bellcranks	
Drive Shaft	
Swashplate(s)	

[22] Folks, L. A., FLIGHT CONTROL SYSTEM STRUCTURAL ANALYSIS, Report SER 72027 by Sikorsky Aircraft Division of United Technologies, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, June 1976

The integration of the flat-strap cruciform concept with the RSRA was straightforward. Since external controls were used and the desired blade motions with the flat-strap cruciform were the same as the existing RSRA, the only changes required were those necessary to accommodate differences in pitch horn arm. The existing RSRA pitch horn arm is 8 inches long while the flat-strap cruciform pitch horn arm is 9.3 inches long. Bellcranks (Reference 22) connect the hydraulic actuators with the control links to the fixed swashplate. New bellcranks would be fabricated to provide slightly greater motion at the swashplates to compensate for the differences in pitch horn arms. Table 19 presents the existing and new parts necessary to mate the flat-strap cruciform design with the RSRA. Also shown in Table 19 are the new required bellcrank ratios. During preliminary design, stress analyses would be conducted to verify the strength of the swashplates and linkages.

TABLE 19. PARTS REQUIREMENTS INTEGRATION OF FLAT STRAP CRUCIFORM AND EXTERNAL CONTROLS WITH THE RSRA

EXISTING PARTS	
RSRA Main Transmission Assembly	72350-08500
RSRA Active Balance/Isolation Platform	72959-02212
All Controls Except Three Bellcranks	
NEW PARTS	
Static Mast	
Mast Support Truss	
Drive Shaft	
Bellcranks (Similar to 72402-00413)	
Swashplate(s)	
CONTROL SUMMARY	
Existing Bellcrank	New Bellcrank
Ratio 1.357 (10/7.373)	Ratio 1.578 (10.65/6.75)

Finally the gear changes necessary to change the ITR rotor speed from the existing RSRA 203 rpm to the required rpm of 216 were considered. Table 20 presents the required gear changes based on Reference (23).

TABLE 20. ITR TRANSMISSION CHANGES FOR THE RSRA

Gear	Existing RSRA Rotor 203 rpm	ITR/FRR 216 rpm
Input Spur	2.34	1.85
Freewheel Unit Mesh	2.54	3.00
Bevel Mesh	3.40	3.40
Planetary Set	4.63	4.63

[23] Monteleone, R. A., SYSTEMS REQUIREMENTS HANDBOOK FOR THE RSRA, Report SER 72039 by Sikorsky Aircraft Division of United Technologies, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, March 1977.

CONCLUSIONS

A study has been conducted to investigate advanced rotor hubs under the Army/NASA's ITR/FRR program. This work also included a review and critique of the rotor and hub design goals and specifications. Conceptual design studies led to two rotor hubs which were further developed and evaluated. These concepts were designated the V-strap hub and the flat-strap cruciform hub. Rotor hub parametric variations and integration of the hub concepts with the RSRA were also investigated. Based on these evaluations and studies the following conclusions were drawn:

- An advanced rotor hub which offers significant improvements over existing technology hubs is the flat-strap cruciform design which consists of:
  - laminated flapping flexure with hub shoes
  - cruciform flexure to accommodate feathering and lead-lag motion
  - elastomeric snubbers and dampers
  - composite pitchcase
- The V-strap design, rated only slightly lower than the flat strap cruciform design, also offers improvements over existing technology hubs, and the salient features of this concept are:
  - laminated, Kevlar-29 flexure with hub shoes
  - elastomeric bearings and dampers
  - composite pitchcase
- The laminated flexure concept with hub shoes is an important design feature which allowed this study's hub goals of moderate hub moment stiffness and high fatigue life at 5° flapping to be met.
- The flat-strap cruciform hub can accommodate parametric variations which include blade sweep, pitch-flap coupling, pitch-lag coupling, and flexure pretwist to obtain flap-lag coupling.

- The V-strap and flat-strap cruciform designs are compatible with the RSRA, and could be installed and tested on the RSRA with modifications.

- The design goals and specifications are generally complete and achievable with todays advanced technology, but the vulnerability goal unduly influences the concepts and eliminates from consideration otherwise meritorious designs.

RECOMMENDATIONS

Based on results of these studies, it is recommended that:

- The flat-strap cruciform hub design be considered for further development

- Based on the evaluation of the design goals and specifications

    - For an invulnerable hub (to a small HEI projectile), the flat plate drag area goal be changed from 2.8 ft^2 to 4.0 ft^2.

    - The hub moment stiffness goal be changed from 100,000 foot-pound/radian to 281,500 foot-pound/radian.

    - The merit function be changed so that the importance of the vulnerability merit factor (K_V) be reduced by multiplying the other merit factors by $1 + K_V$ not K_V.

REFERENCES

1. Beltramo, M. N., and Morris, M. A. PARAMETRIC STUDY OF HELICOPTER AIRCRAFT SYSTEMS COSTS AND WEIGHTS, Science Applications, Inc., NASA CR152315, Ames Research Center, Moffett Field, California, January 1980.

2. Schwartzberg, M. A., Smith, R. L., Means, J. L., Law, H. Y., and Chappell, D. P., SINGLE-ROTOR HELICOPTER DESIGN AND PERFORMANCE ESTIMATION PROGRAMS, Volume I Methodology, Systems Research Integration Office, Report Number 77-1, U.S. Army Air Mobility R&D Laboratory, Moffett Field, California, June 1977.

3. Logan, A. H., Prouty, R. W., and Clark, D. R., WIND TUNNEL TESTS OF LARGE- AND SMALL-SCALE ROTOR HUBS AND PYLONS, Hughes Helicopters and Analytical Methods, Inc., USAAVRADCOM-TR-80-D-21, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1980.

4. Weiner, A., Niebanck, C., and Occhiato, J., PRELIMINARY EVALUATION OF RSRA DATA ACQUIRED ON PURE HELICOPTER, AUXILIARY PROPULSION AND COMPOUND HELICOPTER FLIGHT CHARACTERISTICS, Report SER-72050 by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS2-10182, Ames Research Center, Moffett Field, California, September 1980.

5. Reichert, G., and Oelker, P., HANDLING QUALITIES WITH THE BOLKOW RIGID ROTOR SYSTEM, Proceedings of the 24th Annual National Forum of the American Helicopter Society, May 1968.

6. Dixon, P. G. C., and Bishop, H. E., THE BEARINGLESS MAIN ROTOR, Journal of the American Helicopter Society, Volume 25, Number 3, July 1980.

7. Neugebauer, A., TEST REPORT FOR THE MAIN AND TAIL ROTOR HUB ASSEMBLY INVULNERABILITY VERIFICATION, PART 1 - MAIN ROTOR HUB ASSEMBLY TESTS YAH-64 ADVANCED ATTACK HELICOPTER, Hughes Helicopters Report No. 77-BT-1018, Culver City, California, Revised February 1978.

8. Sheffler, M., Staley, J., and Warmbrodt, W., EVALUATION OF THE EFFECT OF ELASTOMERIC DAMPING MATERIAL ON THE STABILITY OF A BEARINGLESS MAIN ROTOR SYSTEM, Proceedings of the American Helicopter Society National Specialists Meeting, Rotor System Design, Philadelphia, Pennsylvania, October 1980.

9. Krauss, T.A., BEARINGLESS HELICOPTER MAIN ROTOR DEVELOPMENT, Report SER-70238 by Sikorsky Aircraft Division of United Technologies Corporation, NASA CR-145188, NASA, Washington, D.C., June 1977.

10. Banerjee, D., and Johnston, R.A., INTEGRATED TECHNOLOGY ROTOR METHODOLOGY ASSESSMENT, Hughes Helicopters, Inc., NASA Contract NAS2-10871, Ames Research Center, Moffett Field, California, November 1981.

11. Roark, R.J., and Young, W.C., FORMULAS FOR STRESS AND STRAIN, Fifth Edition, New York, McGraw-Hill Book Company, 1975.

12. Johnston, R.A., and Cassarino, S.J., AEROELASTIC ROTOR STABILITY ANALYSIS, Sikorsky Aircraft Division of United Technologies Directorate, USAAMRDL-TR-75-40, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1976, AD-A020871.

13. Ham, E., and Klusman, S., AEROELASTIC AND MECHANICAL STABILITY ANALYSIS REPORT (RSRA), Report SER-72024 by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, April 1975.

14. Ham, E., RSRA ACTIVE ISOLATION SYSTEM SHAKE TEST, Report ETR-G2-143 by Sikorsky Aircraft Division of United Technologies Corporation, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, February 1979.

15. Bousman, W.G., Sharpe, D.L., and Ormiston, R.A., AN EXPERIMENTAL STUDY OF TECHNIQUES FOR INCREASING THE LEAD-LAG DAMPING OF SOFT INPLANE HINGELESS ROTORS, Proceedings of the 32nd Annual National Forum of the American Helicopter Society, May 1976.

16. Ormiston, R. A., CONCEPTS FOR IMPROVING HINGELESS ROTOR STABILITY, Proceedings of the American Helicopter Society Mideast Region Symposium on Rotor Technology, August 1976.

17. Huber, H. B., EFFECT OF TORSION-FLAP-LAG COUPLING ON HINGELESS ROTOR STABILITY, Proceedings of the 29th Annual National Forum of the American Helicopter Society, May 1973.

18. Hodges, D. H., AN AEROMECHANICAL STABILITY ANALYSIS FOR BEARINGLESS ROTOR HELICOPTERS, Journal of the American Helicopter Society, Volume 24, Number 1, January 1979.

19. White, R. P., and Nettles, W. E., EXAMINATION OF THE AIR RESONANCE STABILITY CHARACTERISTICS OF A BEARINGLESS MAIN ROTOR, Proceedings of the 34th Annual National Forum of the American Helicopter Society, May 1978.

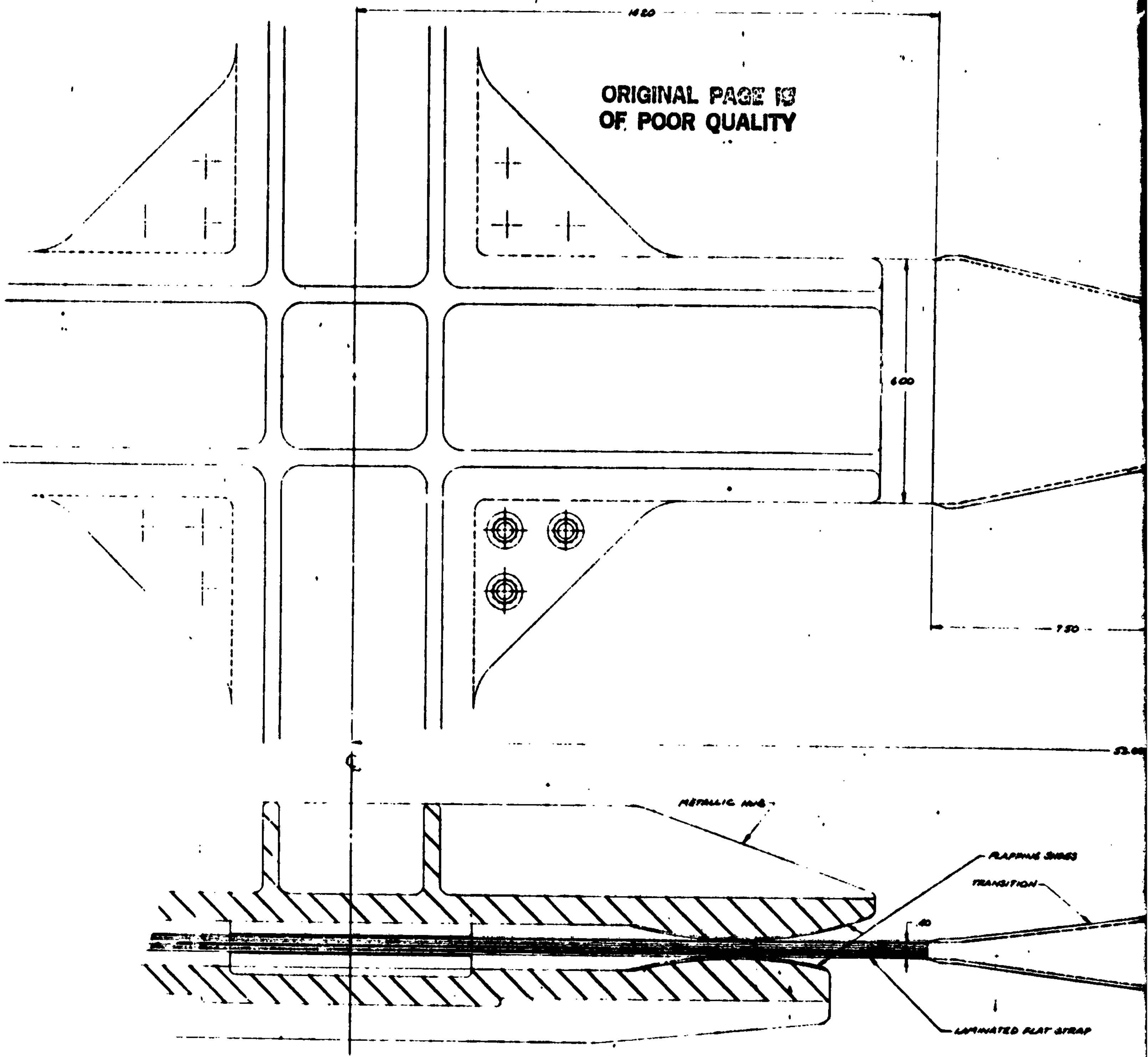
20. Sheehy, T. W., and Clark, D. R., A METHOD FOR PREDICTING HELICOPTER HUB DRAG, Sikorsky Aircraft Division of United Technologies Corporation, USAAMRDL TR-75-48, U. S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, January 1976, AD A021201.

21. Hughes, C. W., and Logan, A. H., PRE-DESIGN STUDY FOR A MODERN FOUR-BLADED ROTOR FOR THE ROTOR SYSTEMS RESEARCH AIRCRAFT (RSRA), Hughes Helicopters, Inc., NASA CR 166154, Ames Research Center, Moffett Field, California, March 1981.

22. Folks, L. A., FLIGHT CONTROL SYSTEM STRUCTURAL ANALYSIS, Report SER 72027 by Sikorsky Aircraft Division of United Technologies, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, June 1976.

23. Monteleone, R. A., SYSTEMS REQUIREMENTS HANDBOOK FOR THE RSRA, Report SER-72039 by Sikorsky Aircraft Division of United Technologies, NASA Contract NAS1-13000, Ames Research Center, Moffett Field, California, March 1977.

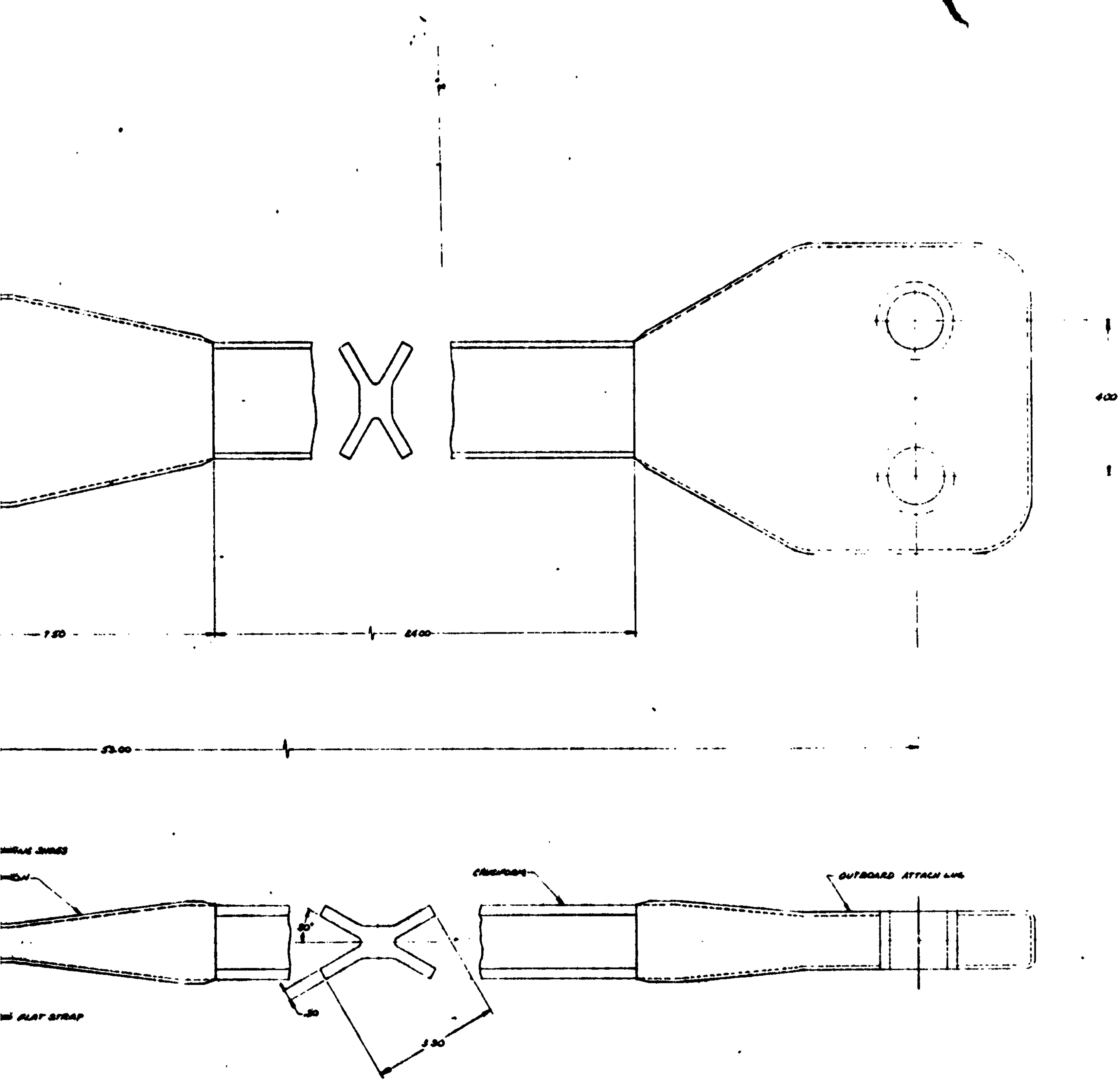
ORIGINAL PAGE IS
OF POOR QUALITY



PRECEDING PAGE BLANK NOT FILMED

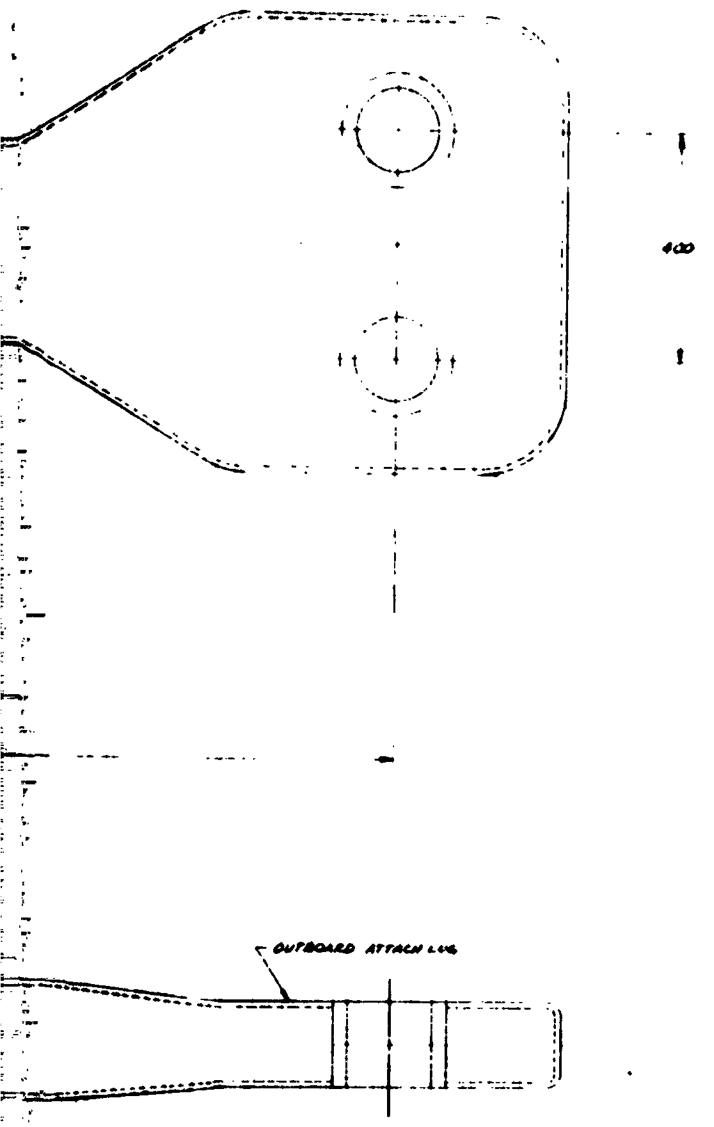
Figure 1. Flat-Strap Cruciform

FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

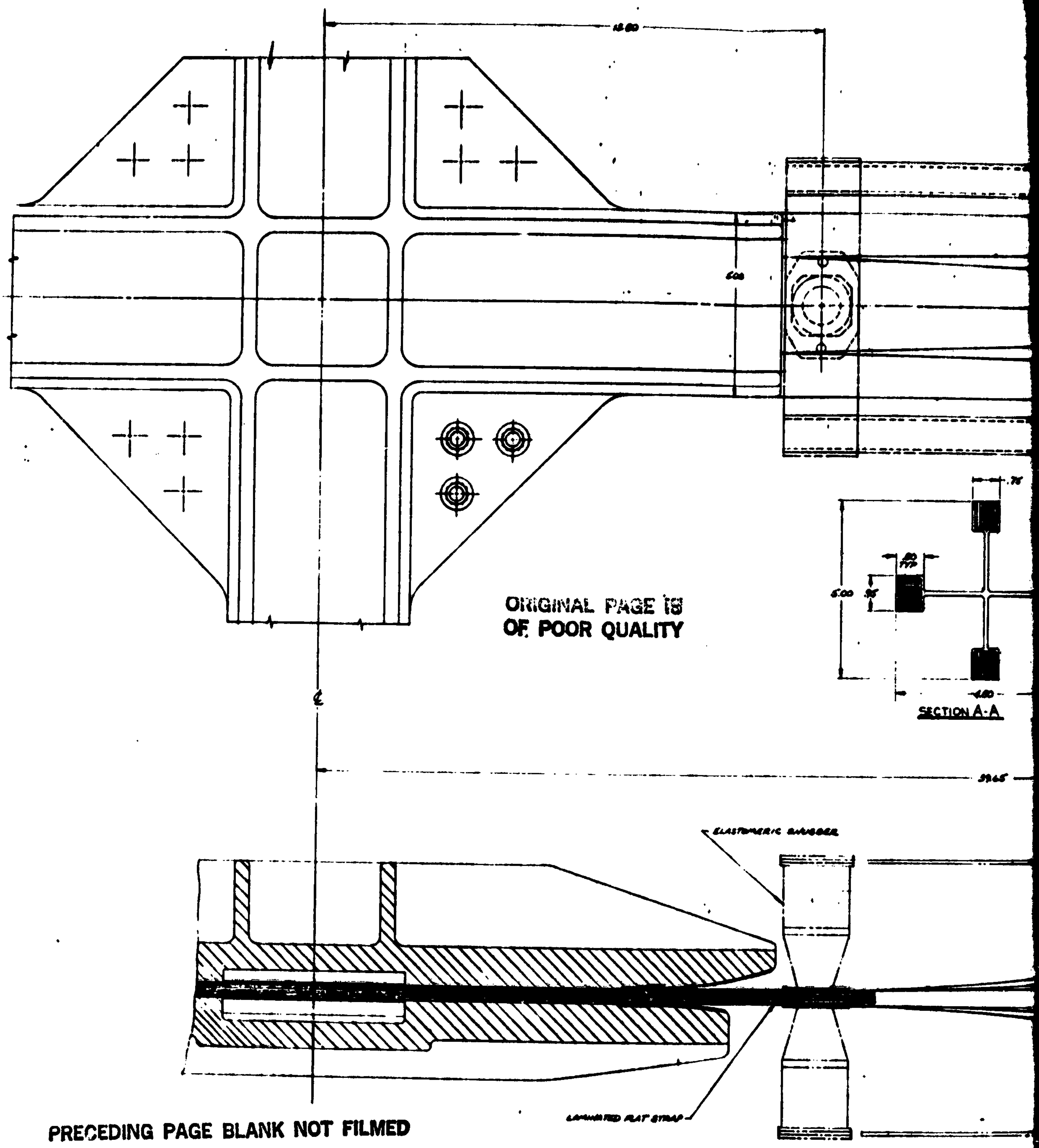
2 FOLDOUT FRAME



Hughes Helicopters, Inc.

02731

3 FOLDOUT FRAME

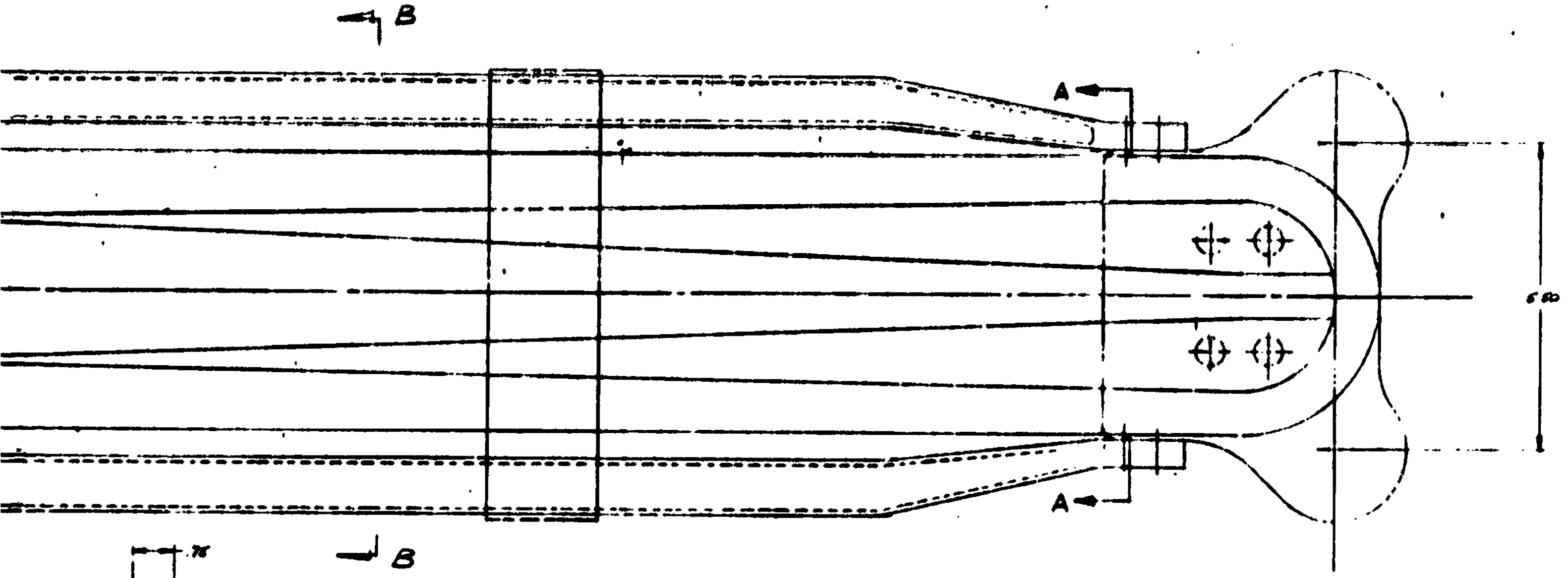


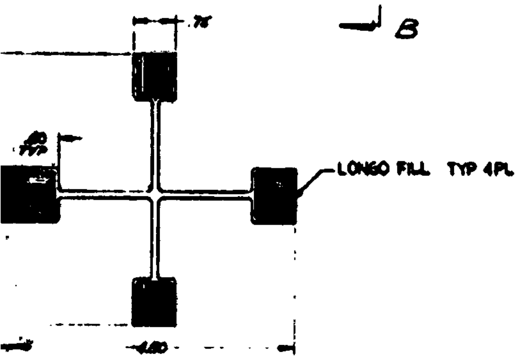
PRECEDING PAGE BLANK NOT FILMED

Figure 2. Tapered Cruciform

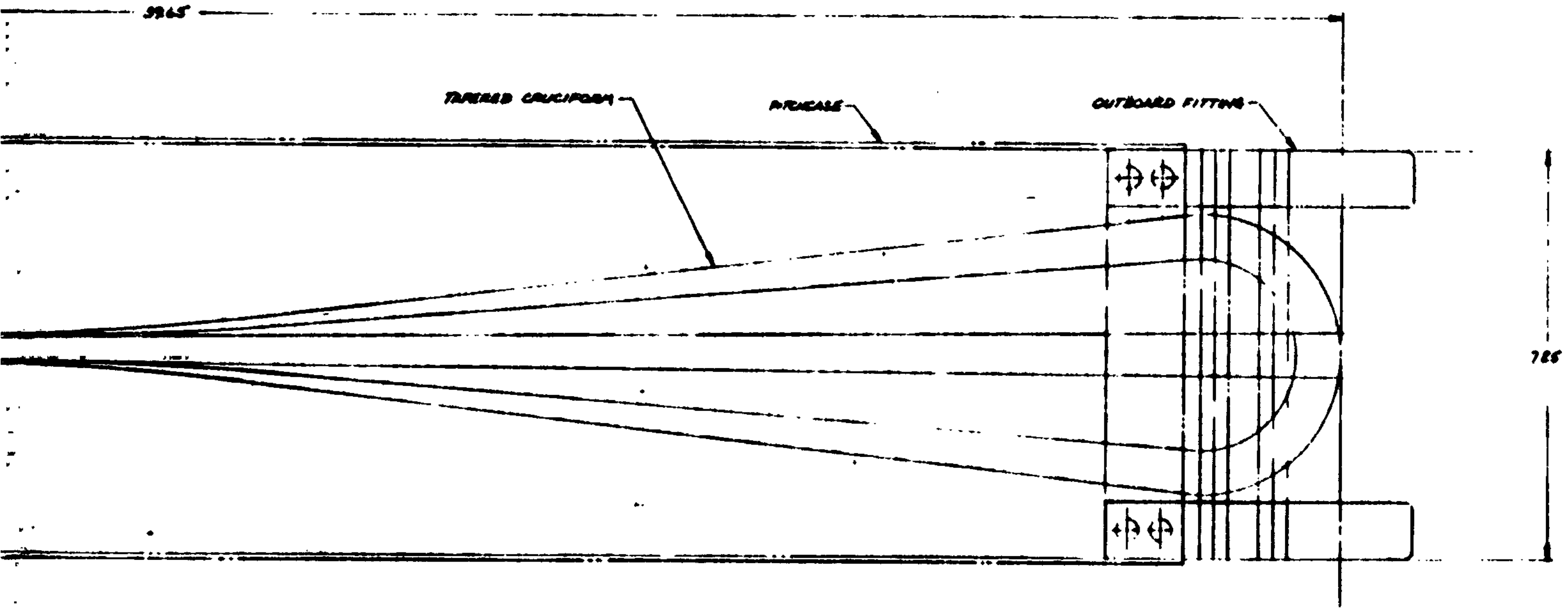
FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

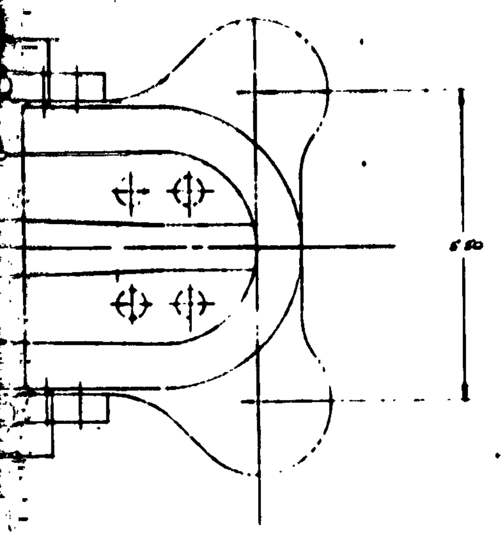


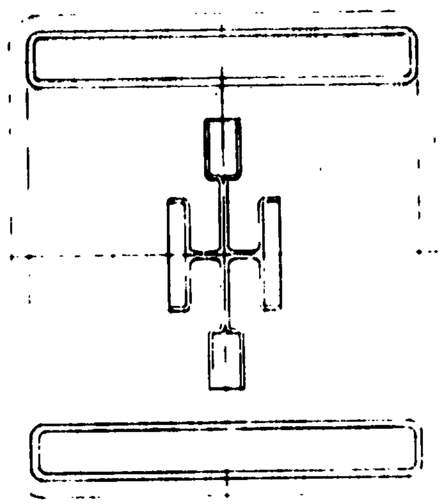


SECTION A-A

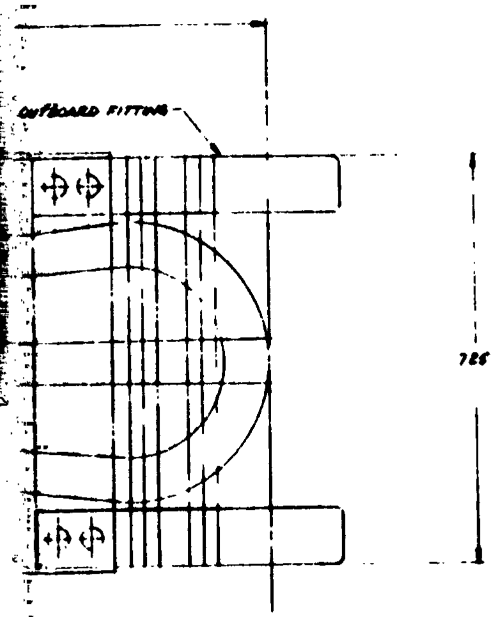


2





SECTION B-B

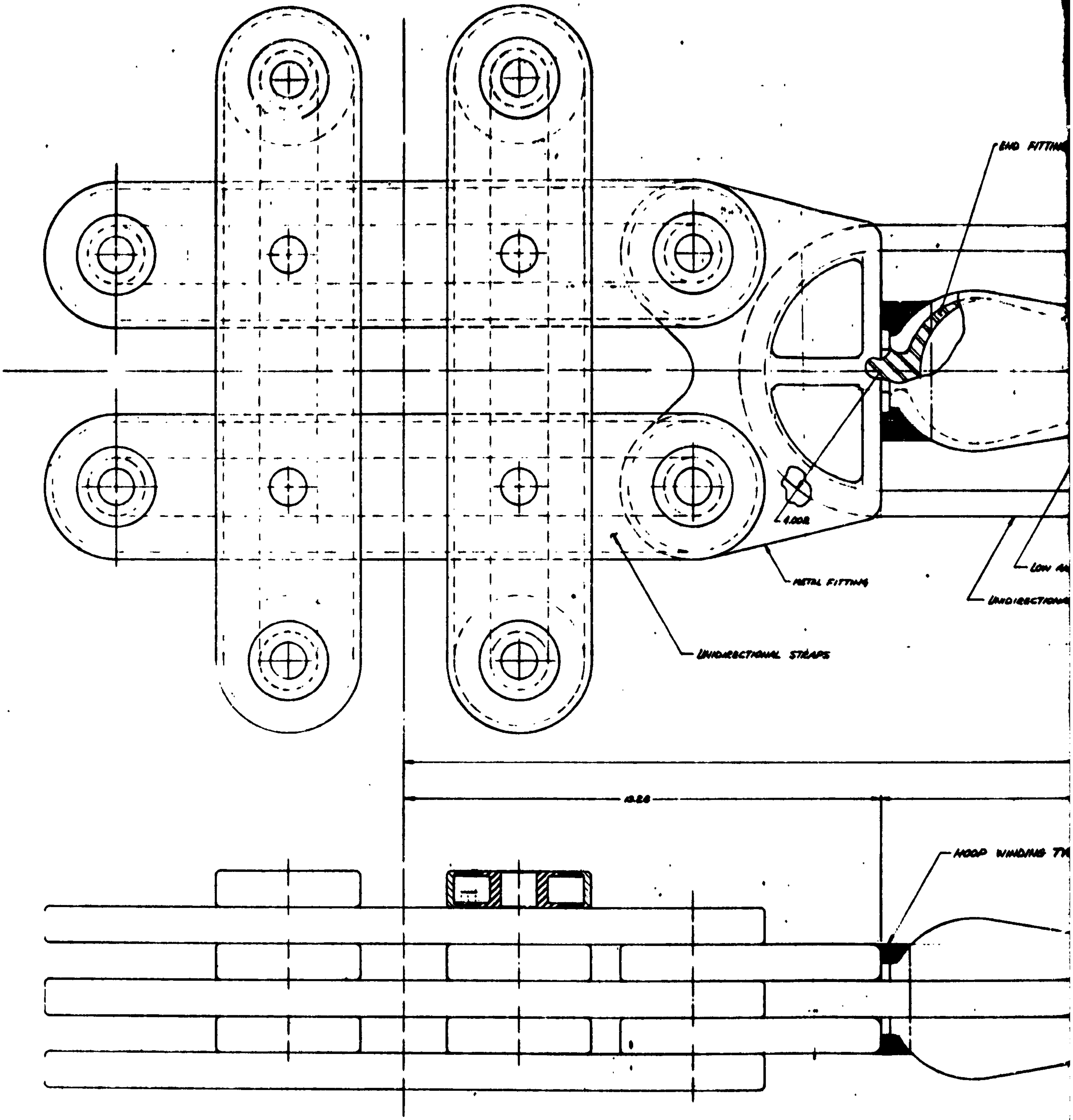


10 IN-ES

3

Hughes Helicopters, Inc.

02731

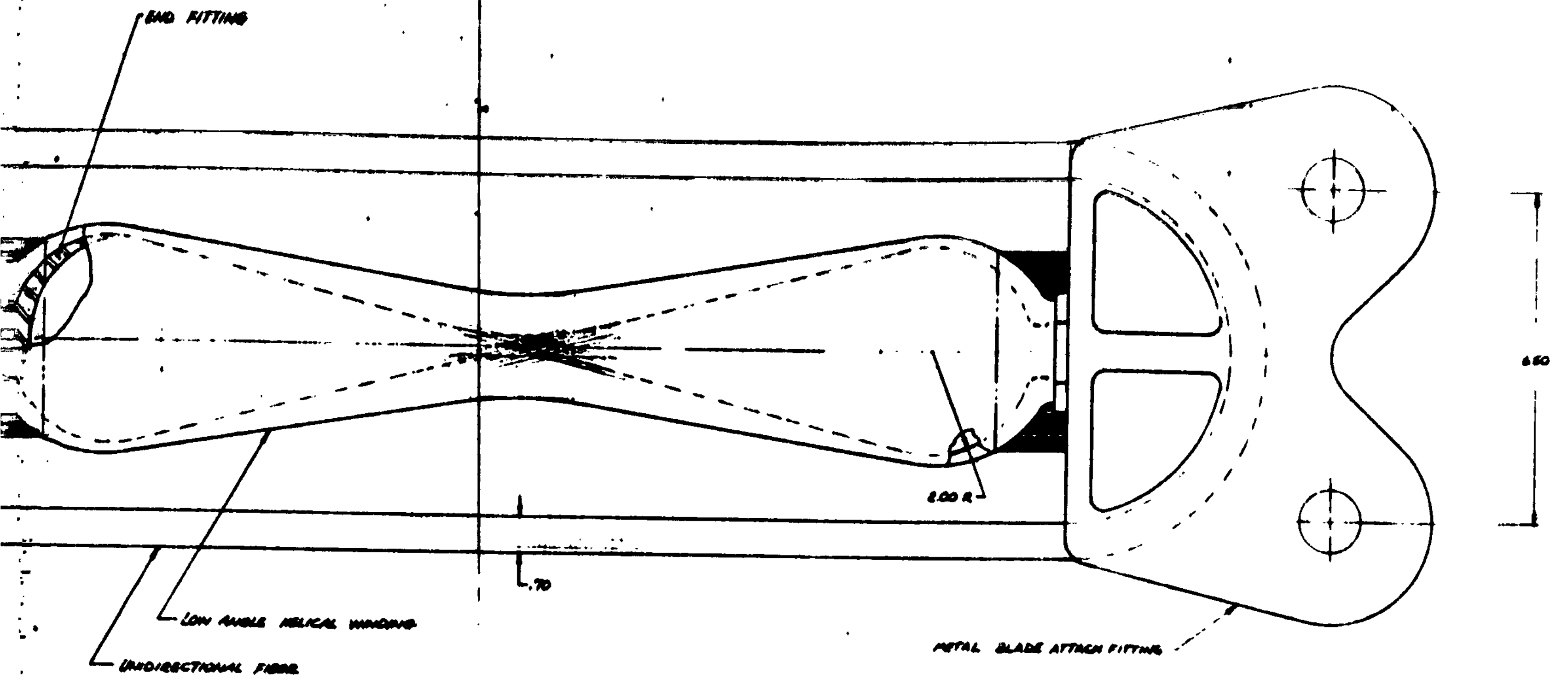


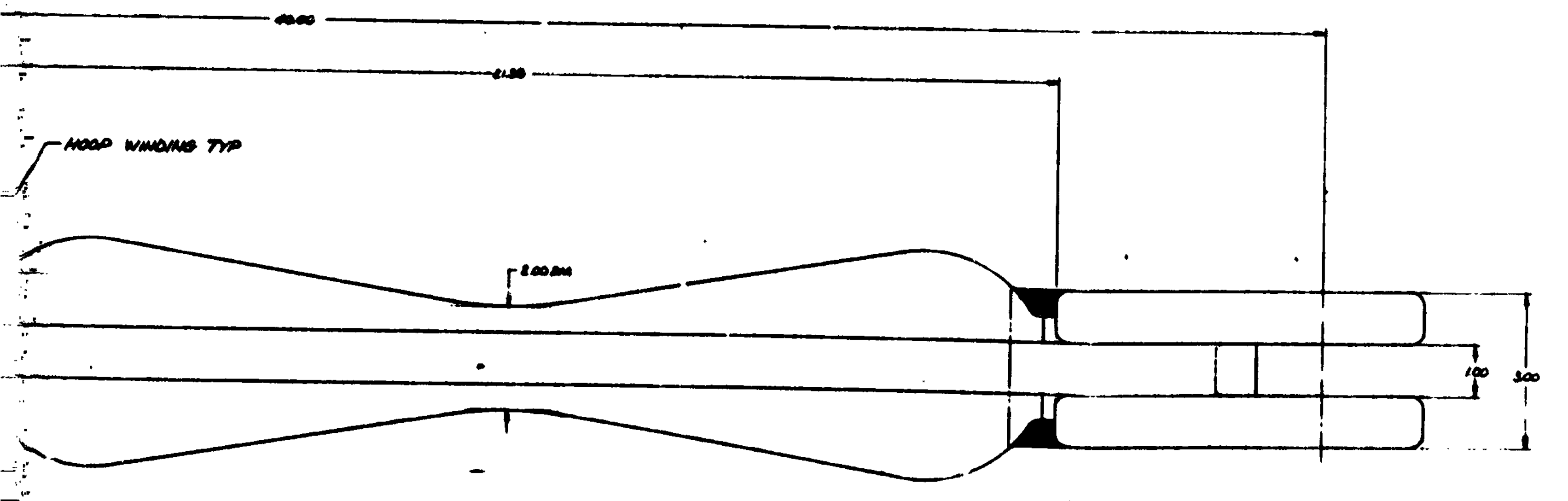
PRECEDING PAGE BLANK NOT FILMED

Figure 3. Hourglass Flexbeam

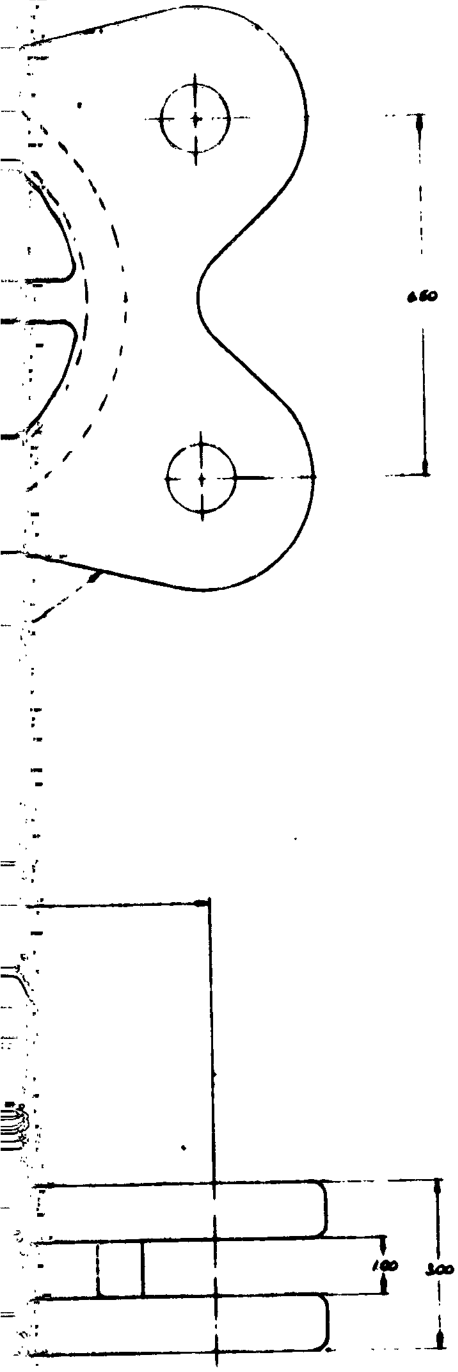
ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY





2 FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

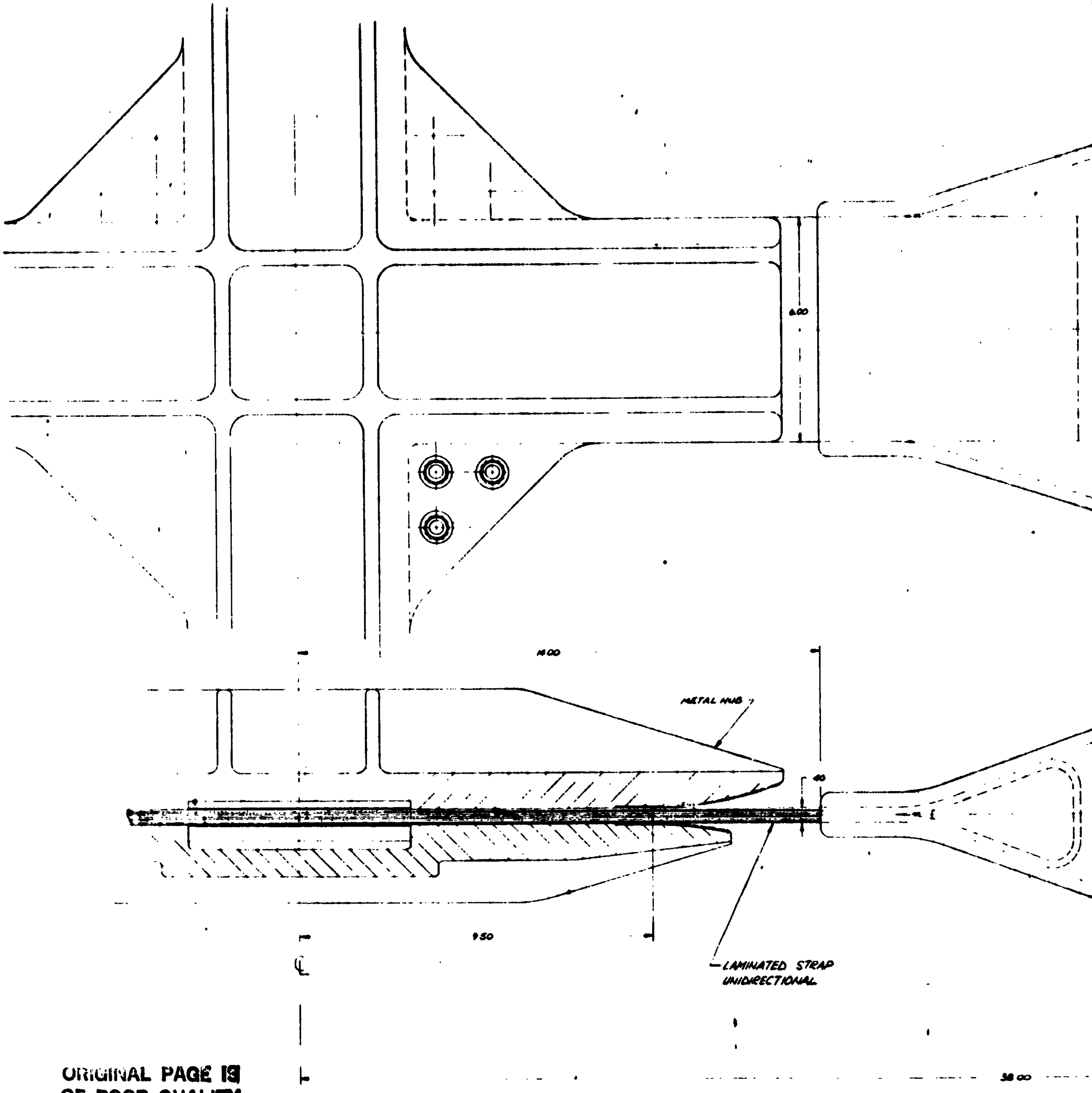
10 INCHES

Hughes Helicopters, Inc.

02731

3 FOLDOUT FRAME

Figure 4. Scale Model of Hourglass Flexbeam

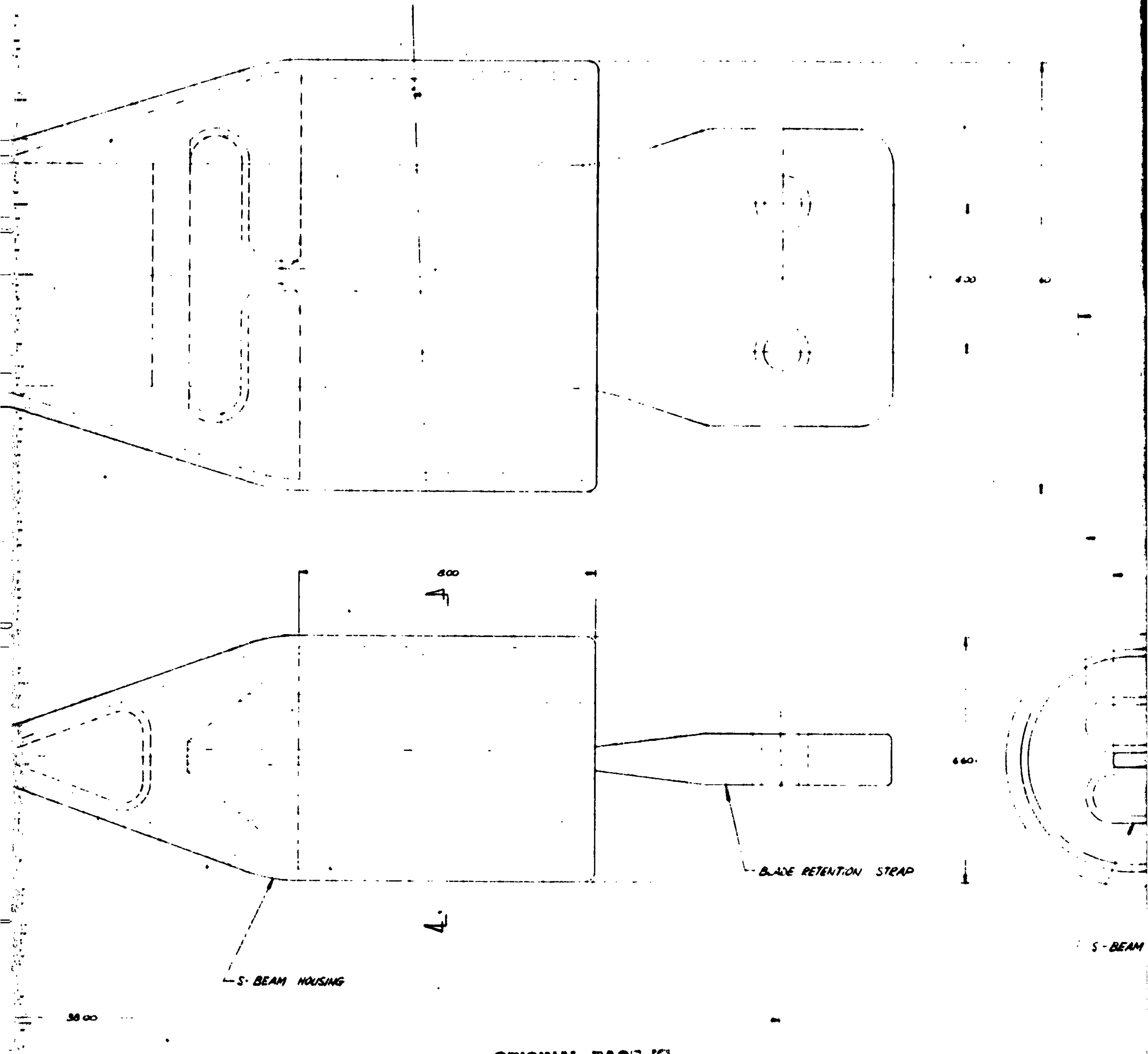


ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

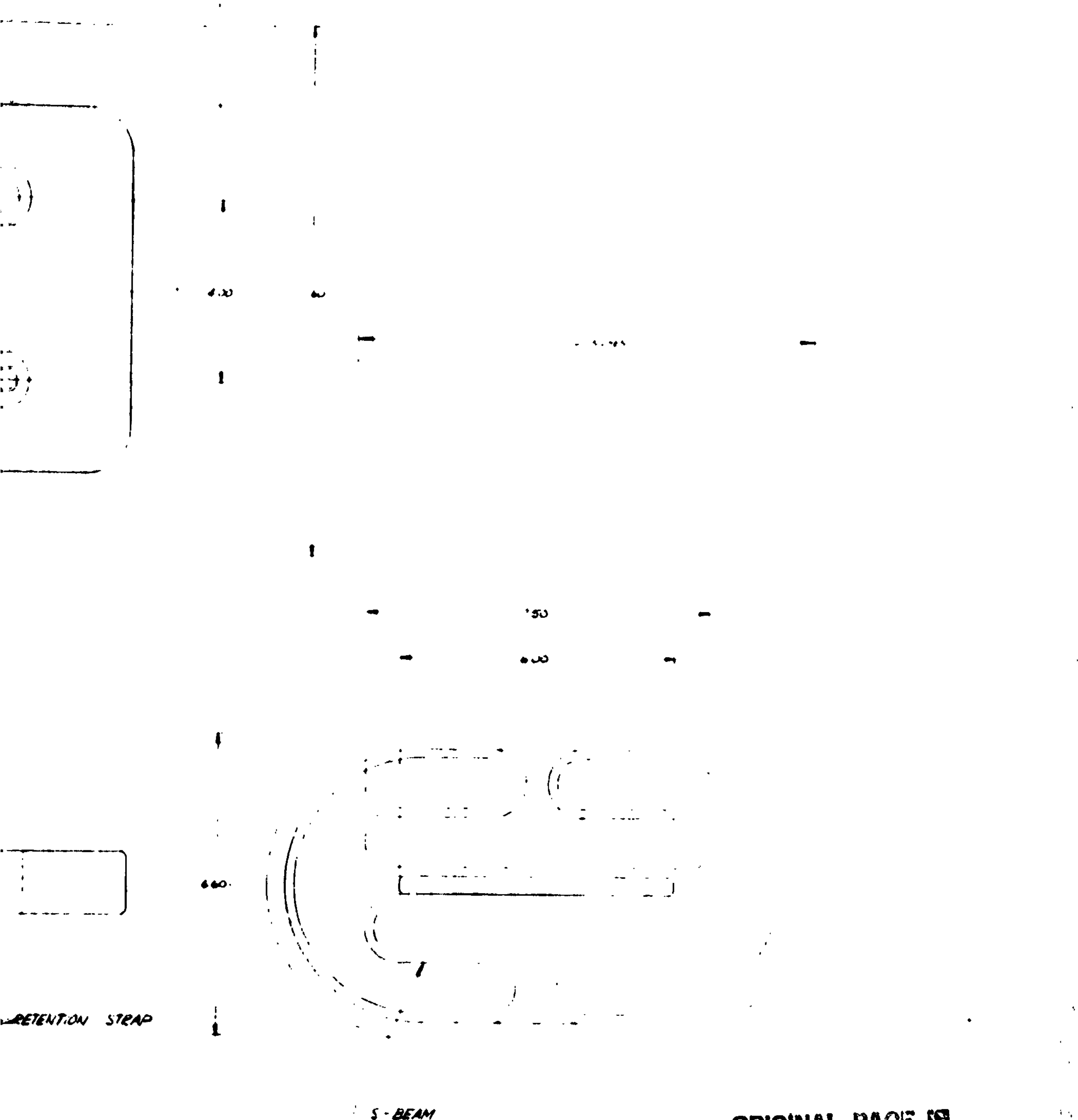
Figure 5. S-Beam Flexure

PRECEDING PAGE BLANK NOT FILMED



ORIGINAL PAGE IS
OF POOR QUALITY

2 FOLDOUT FRAME



ORIGINAL PAGE IS OF POOR QUALITY

02731

3 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

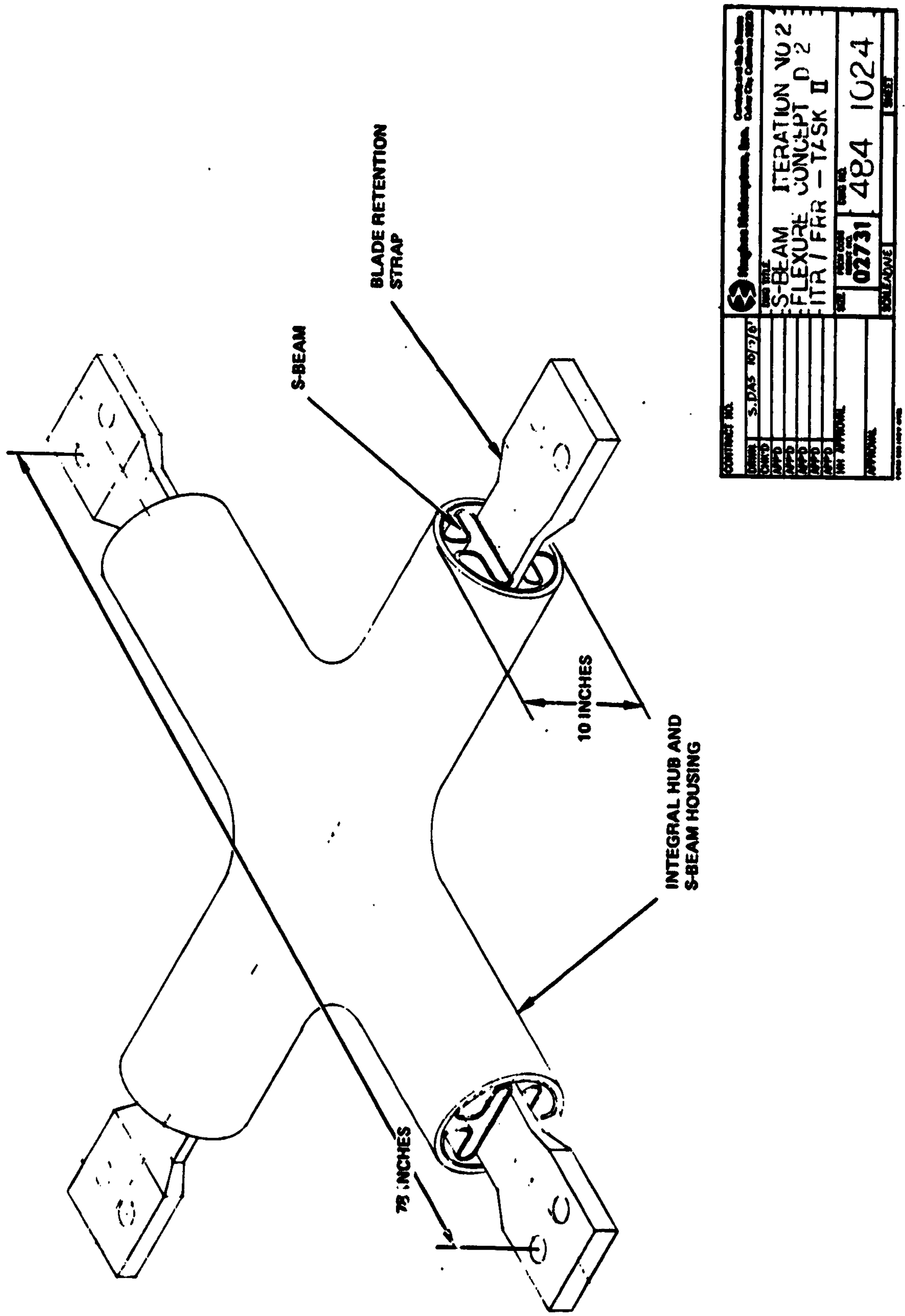


Figure 6. Refined Concept for S-Beam Flexure

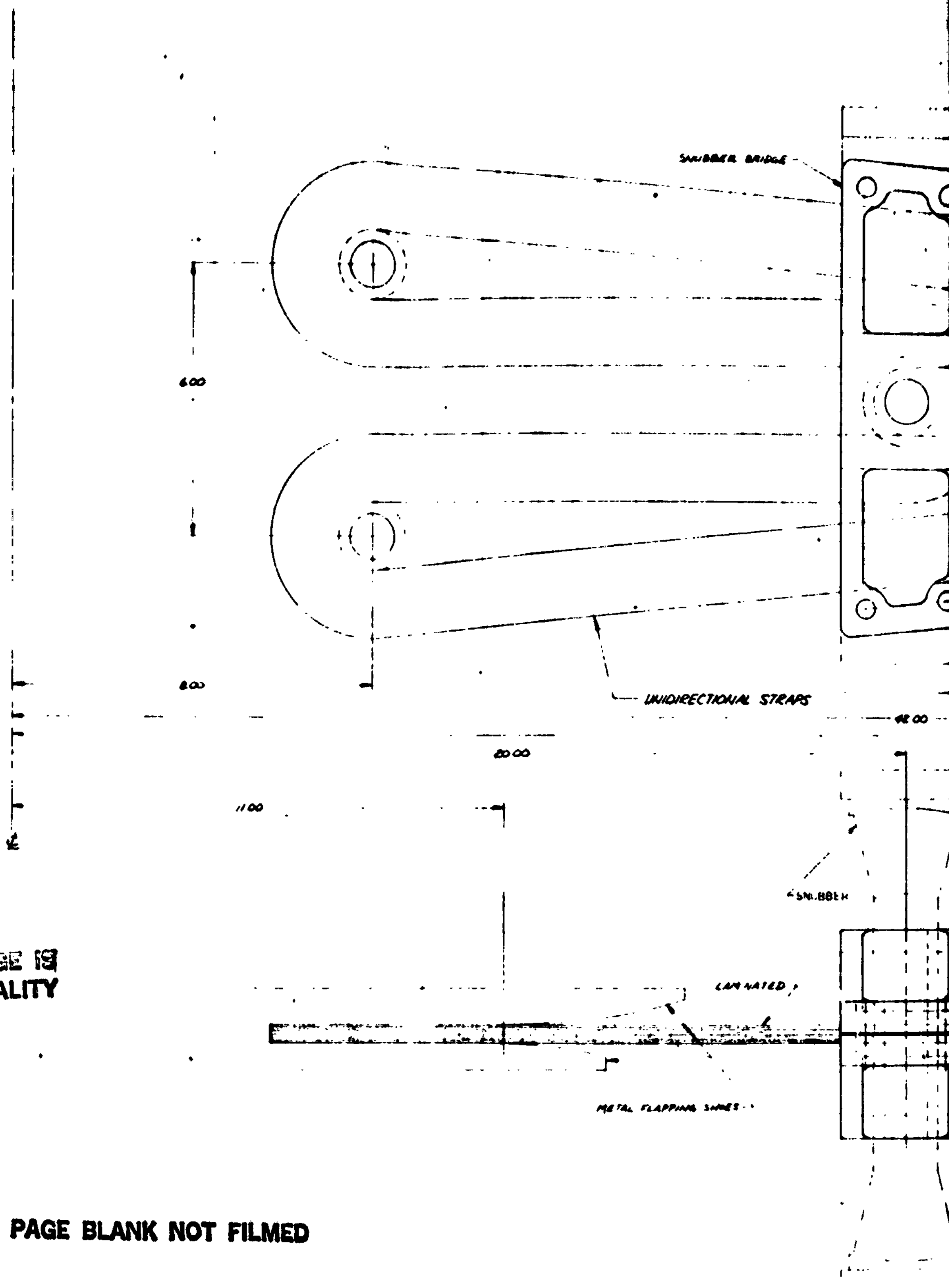
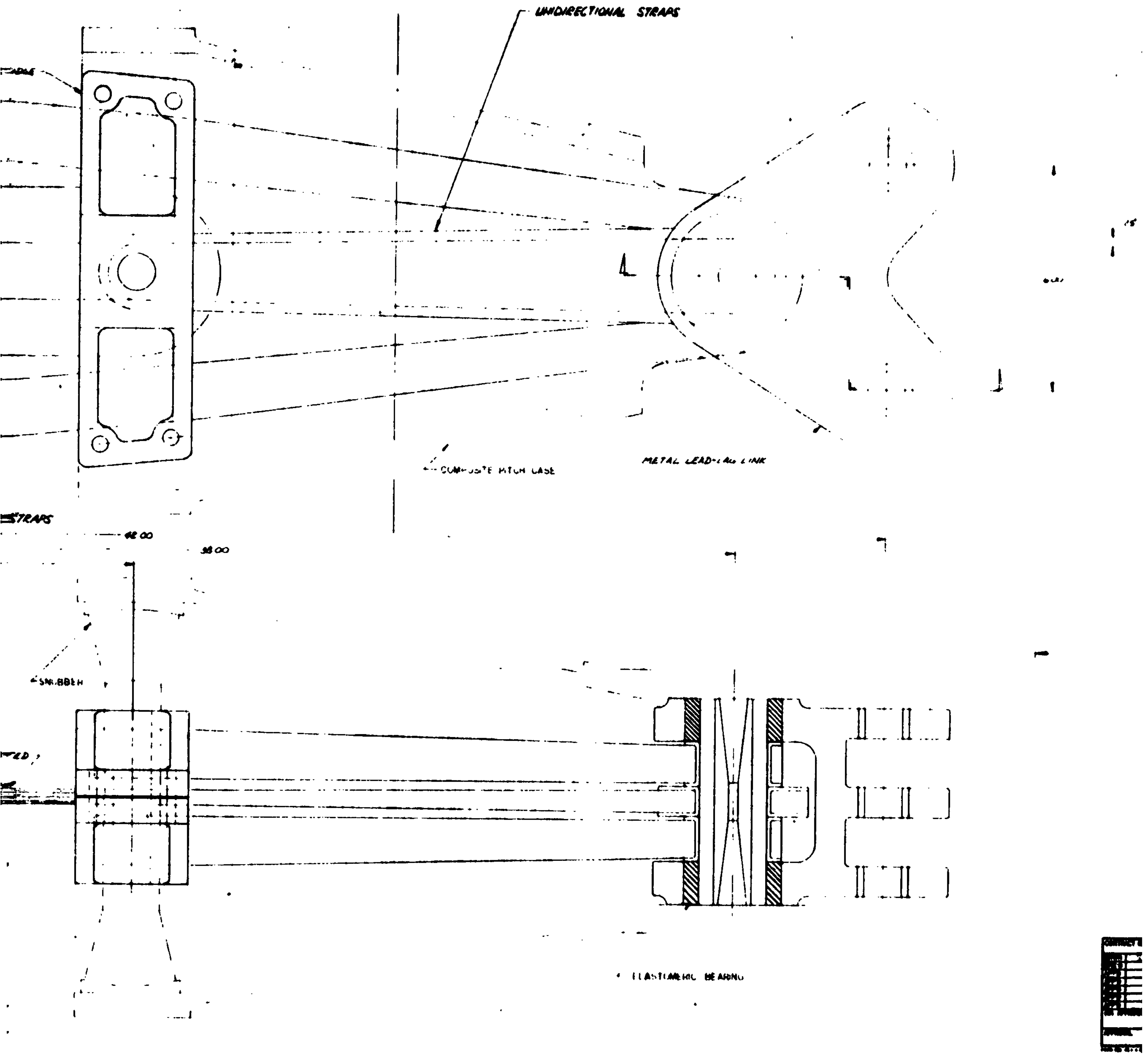
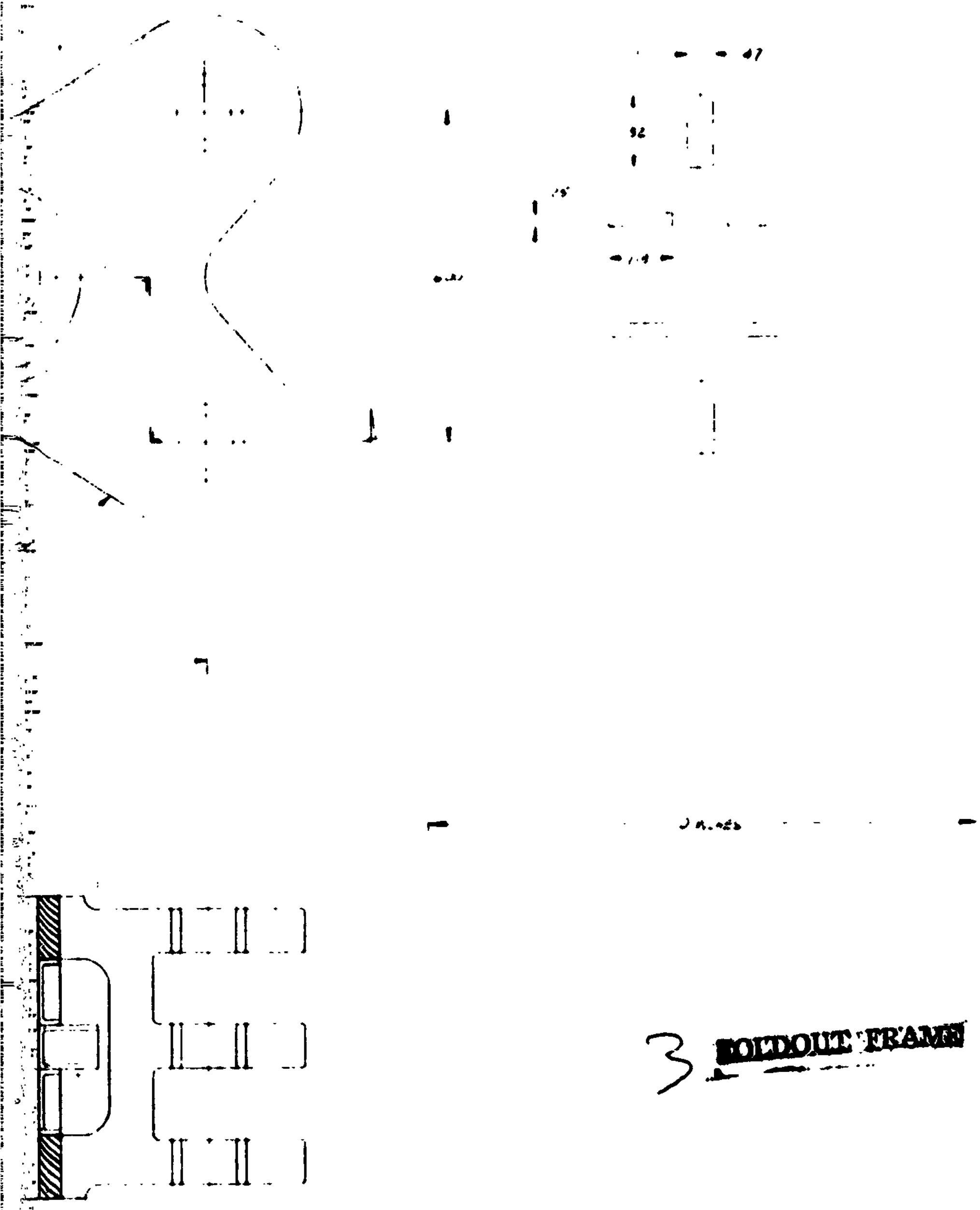


Figure 7. Multiple Strap Flexbeam

FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY



3 FOLDOUT FRAME

Hughes Helicopters, Inc.

02731

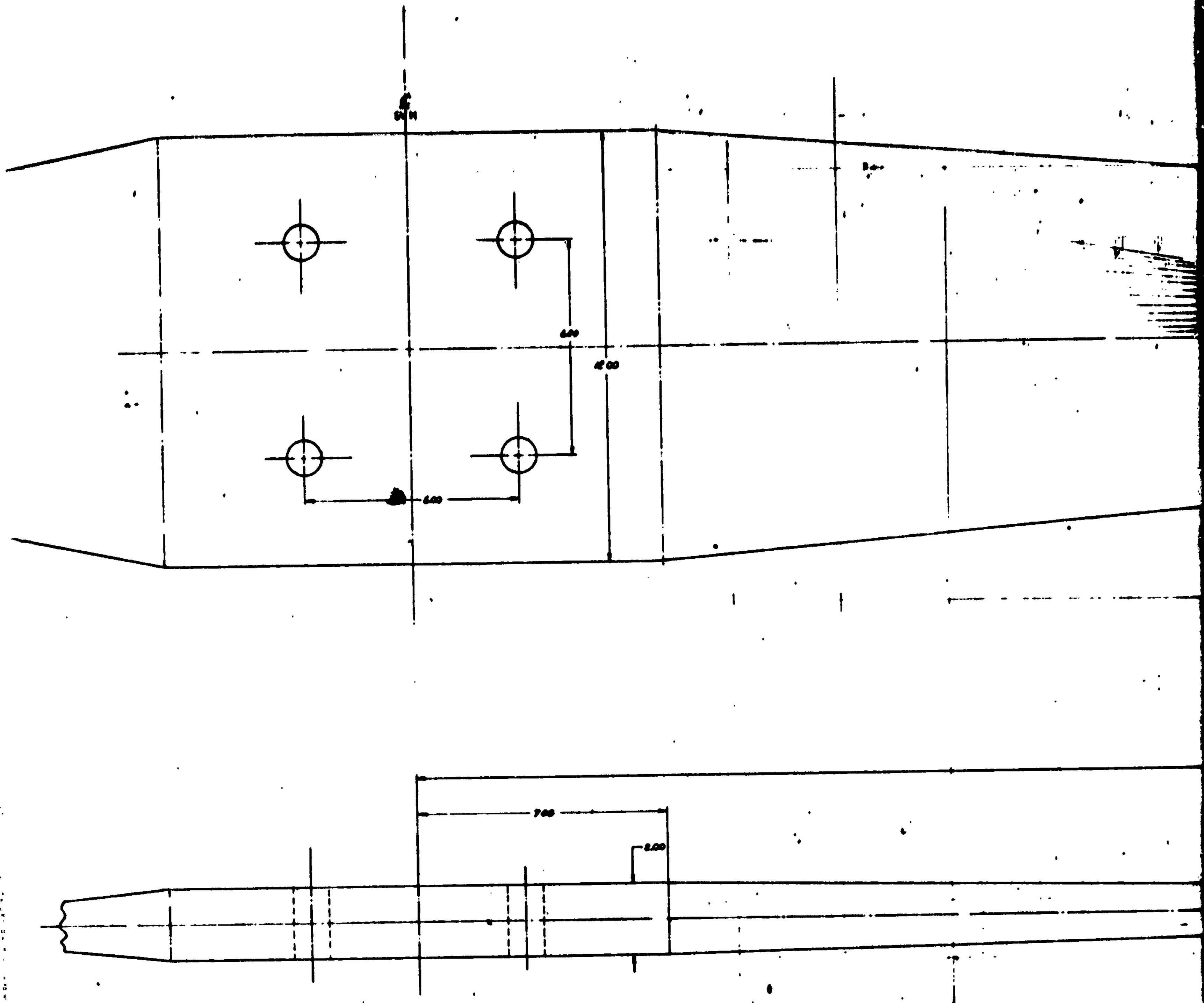
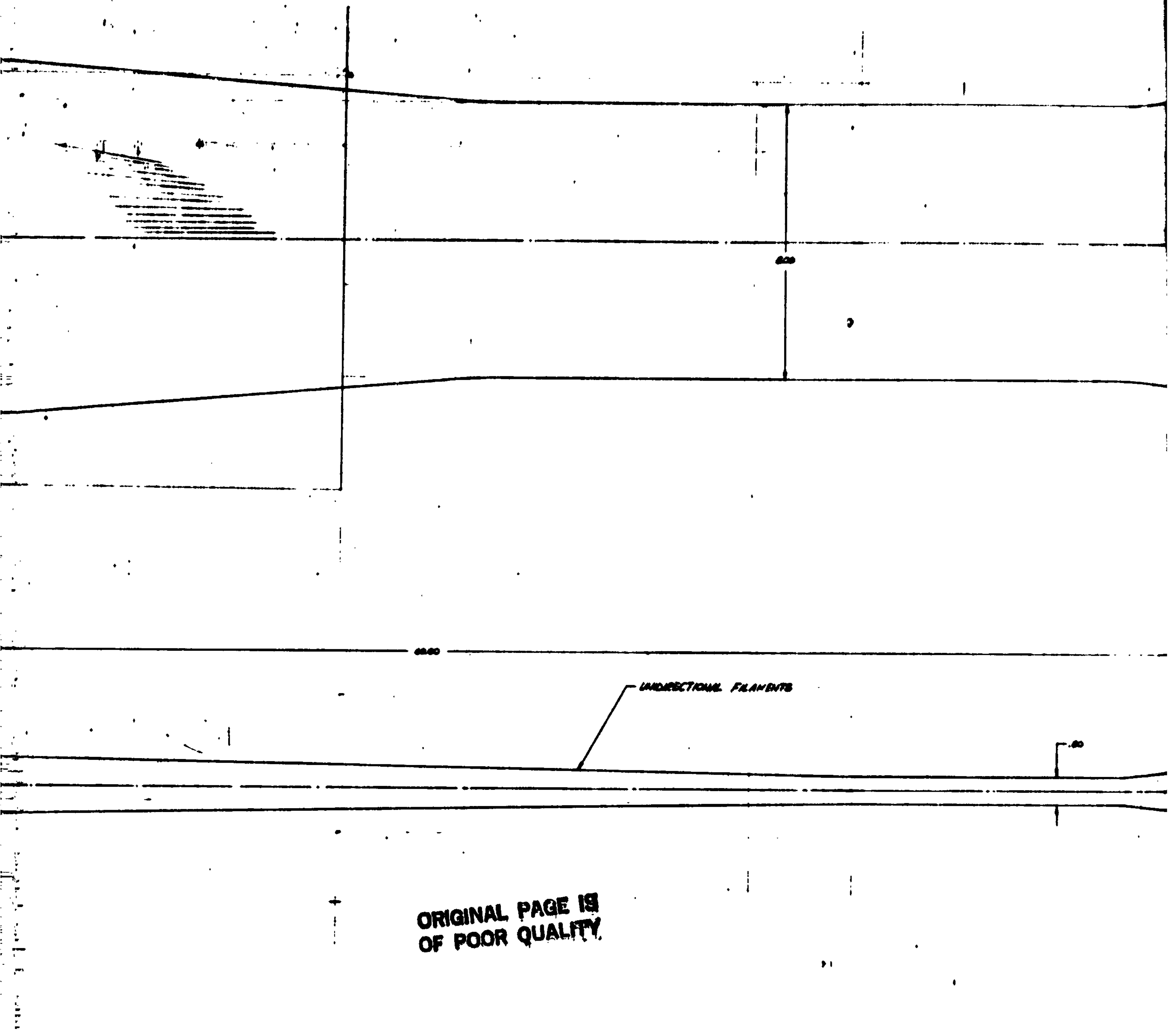
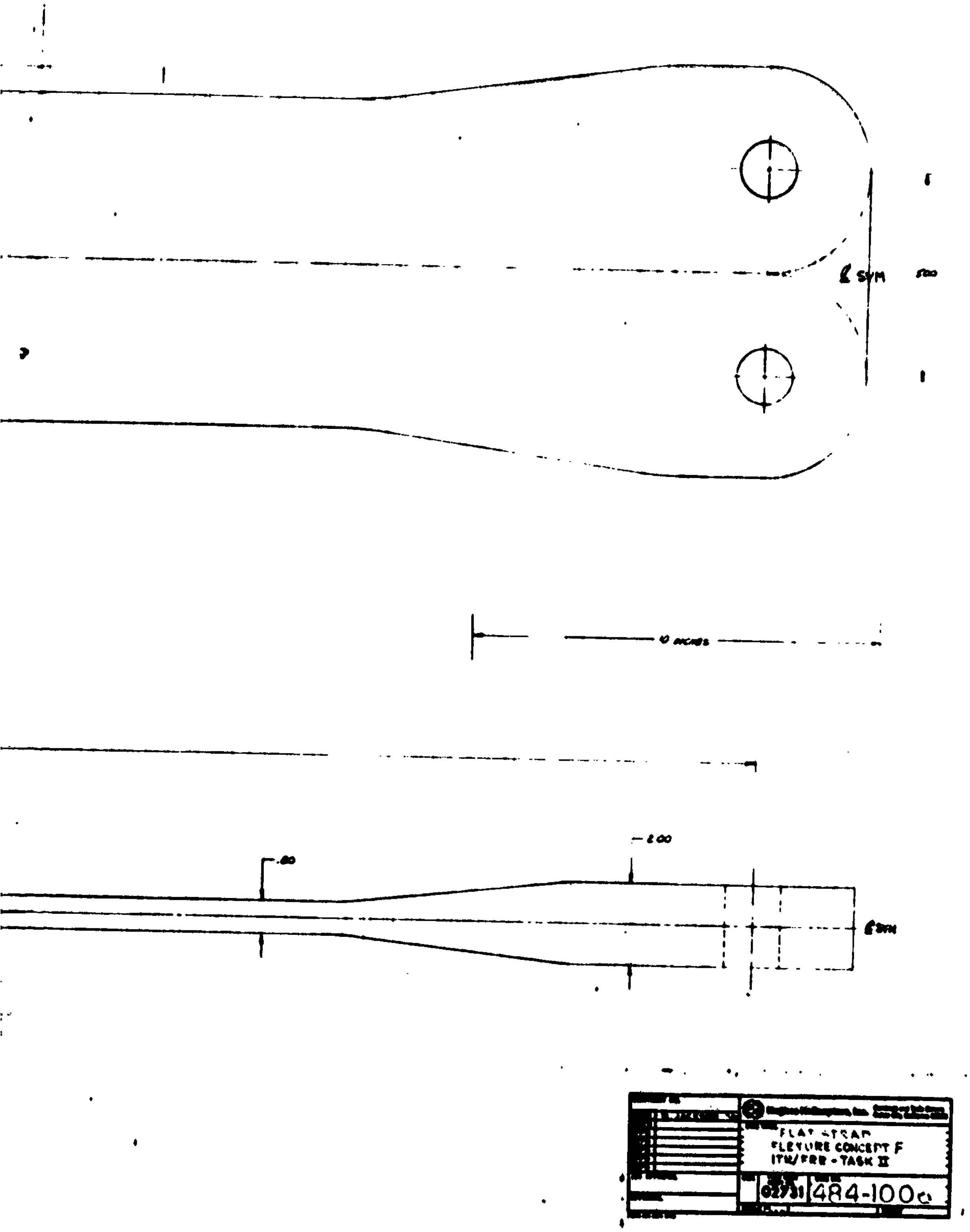


Figure 8. Flat-Strap Flexbeam

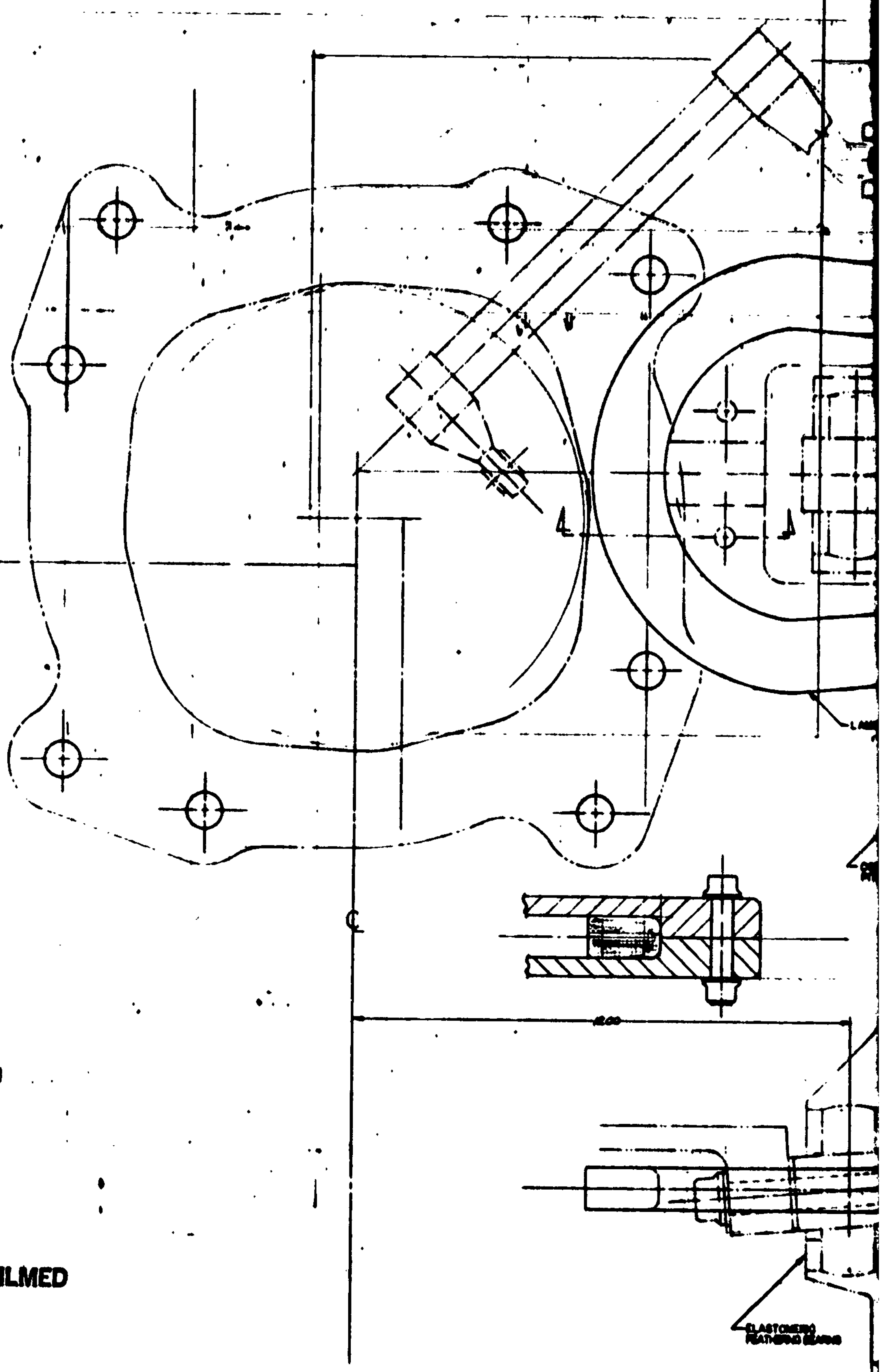


2 FOLDOUT FRAME



3 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

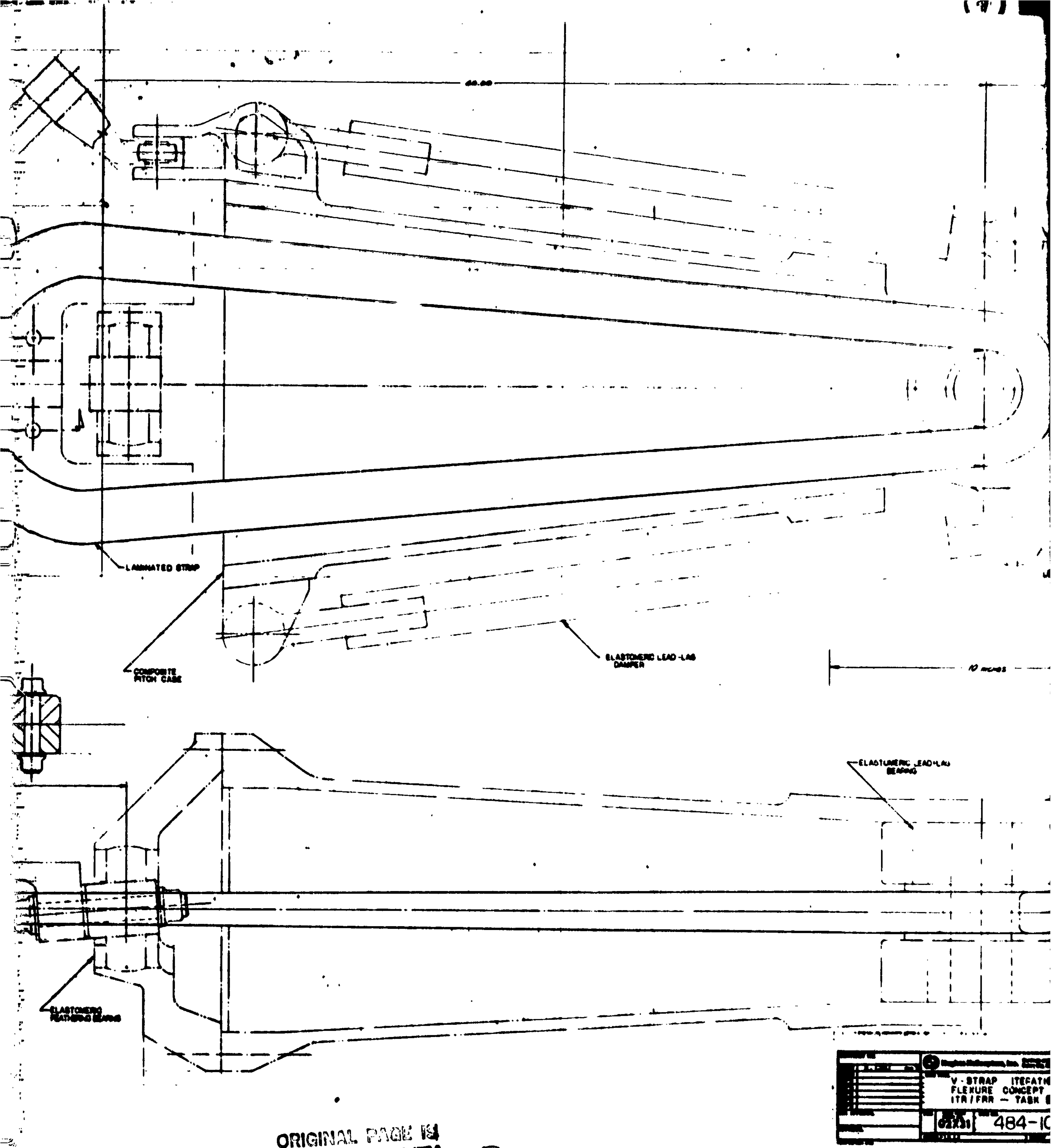


ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

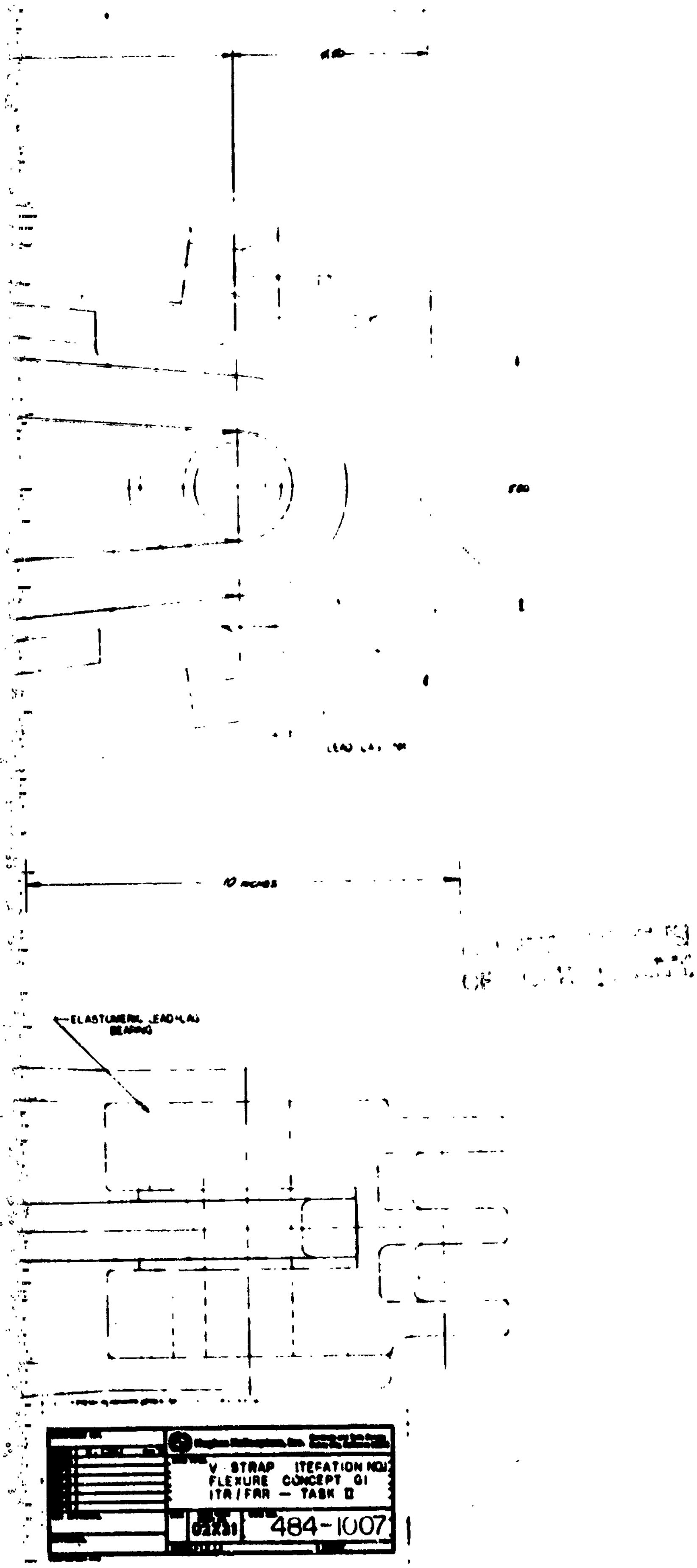
PRECEDING PAGE BLANK NOT FILMED

Figure 9. V-Strap Flexbeam, Concept No. 1

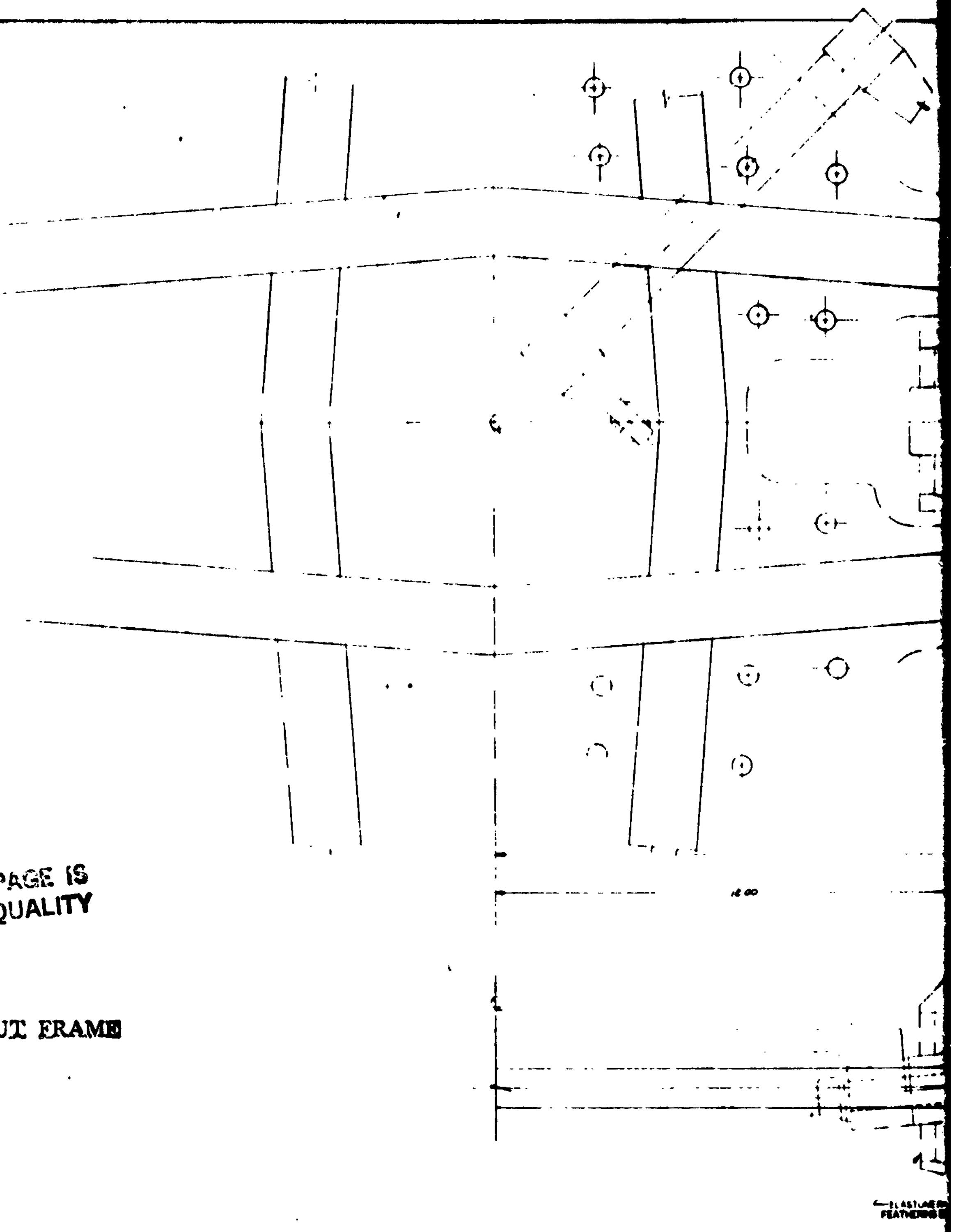


ORIGINAL PAGE IS
OF POOR QUALITY

2 FOLDOUT FRAME



3 FOLDOUT FRAME

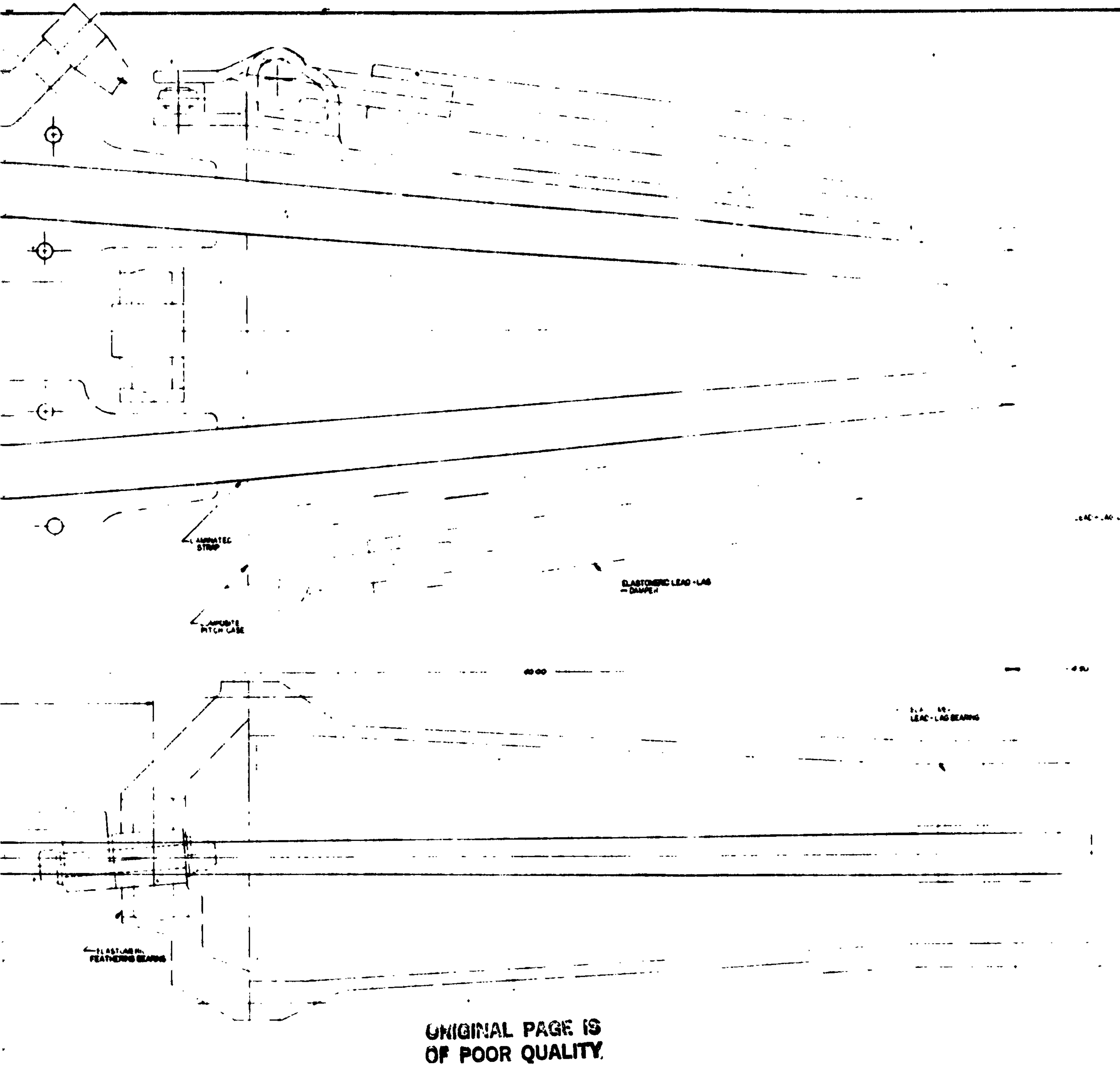


ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

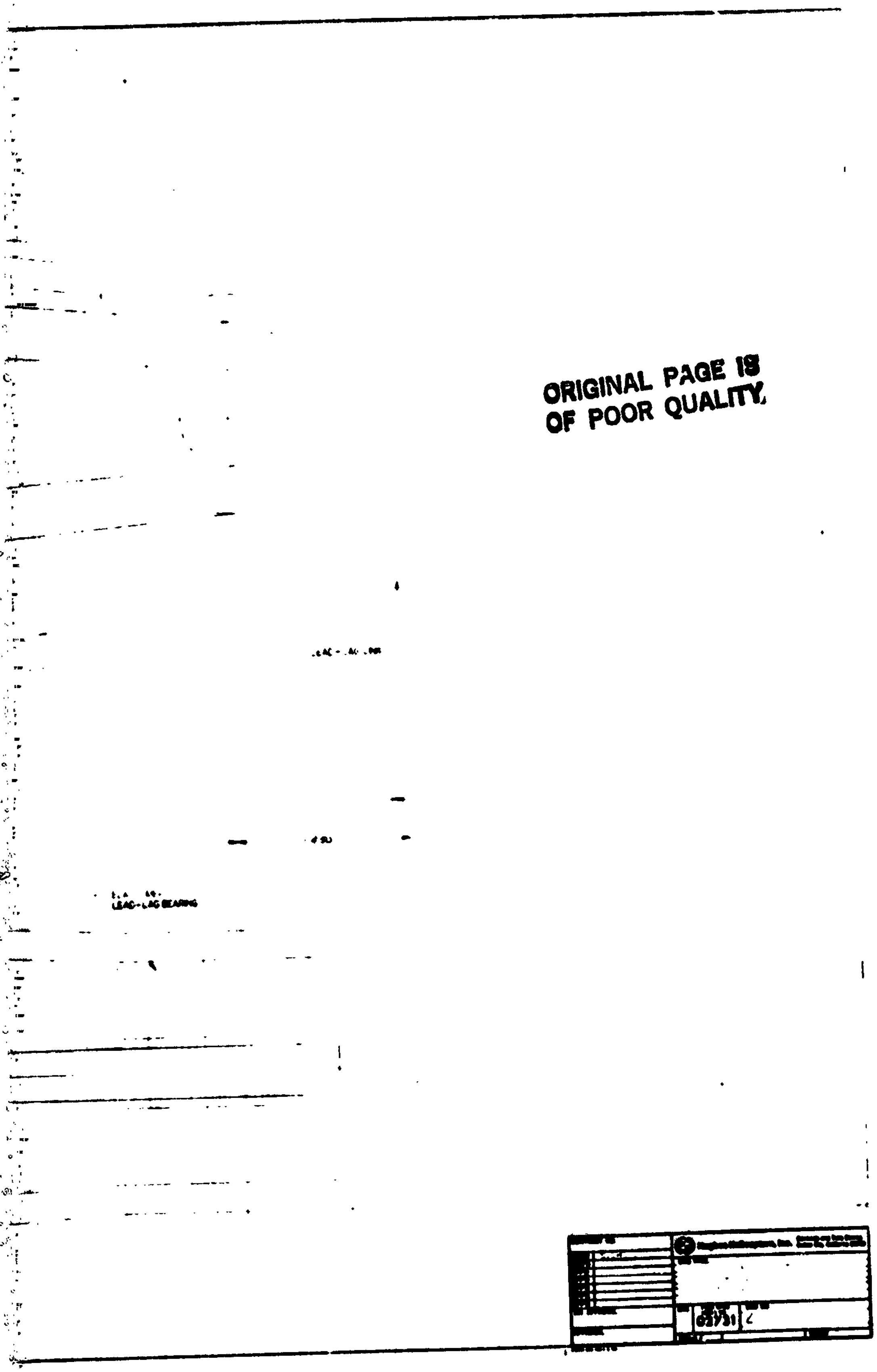
PRECEDING PAGE BLANK NOT FILMED

Figure 10. V-Strap Flexbeam, Concept No. G-2


LAMINATED STRIP
ELASTOMERIC LEAD-LAG DAMPER
PITCH CASE
LEAD-LAG BEARING
FEATHERING BEARING

2 FRAME

ORIGINAL PAGE IS
OF POOR QUALITY



FOLDOUT FRAME

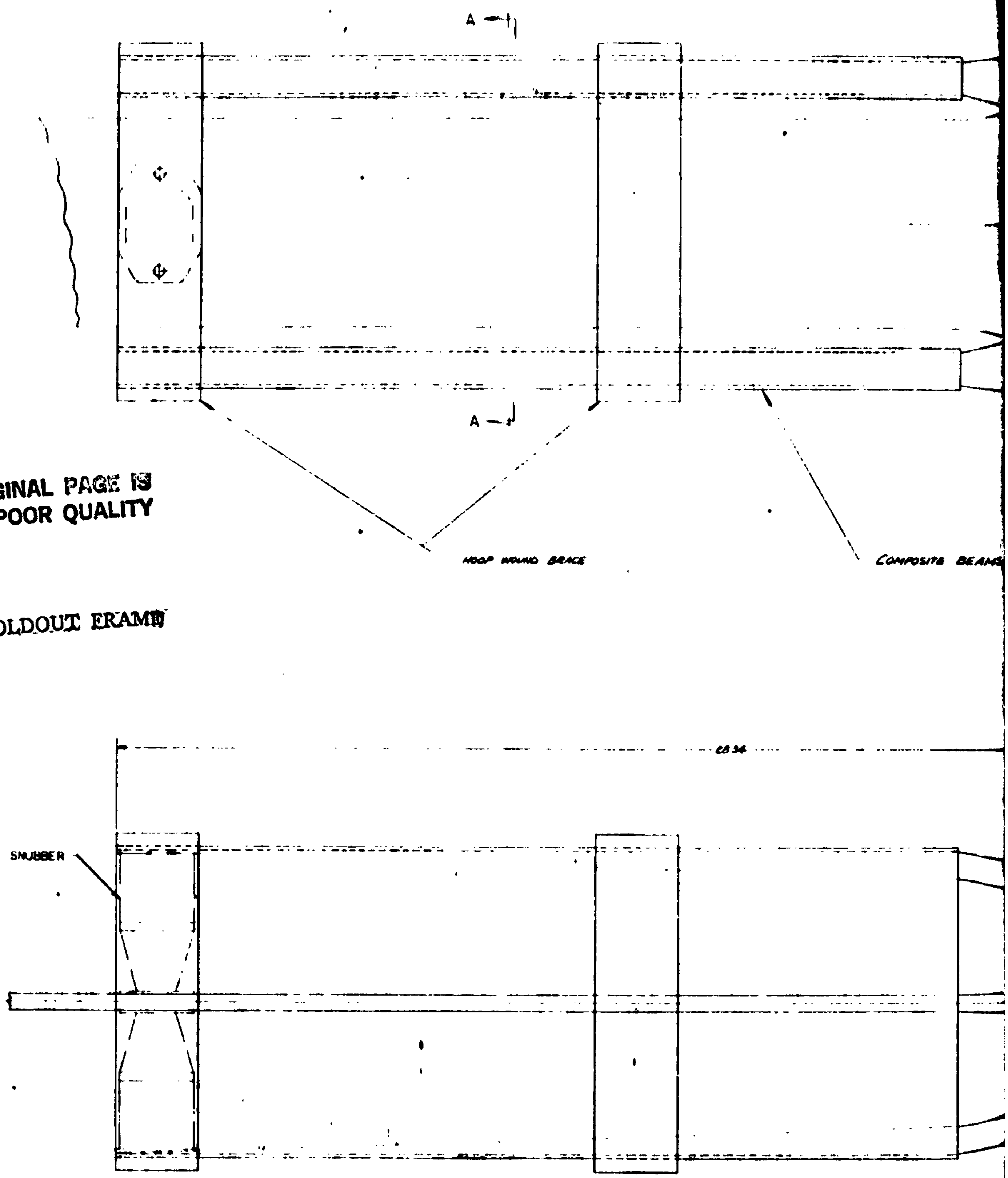
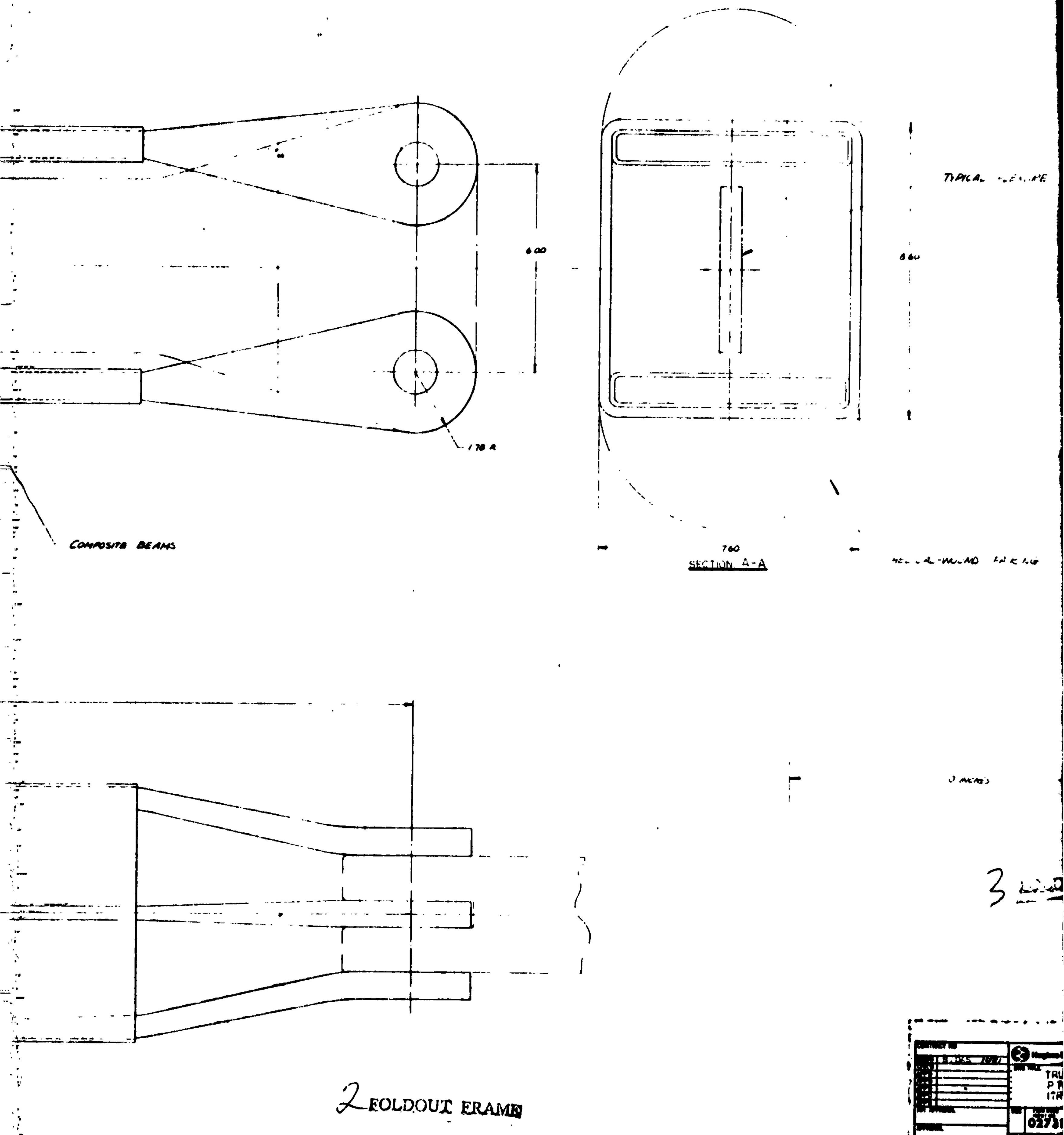
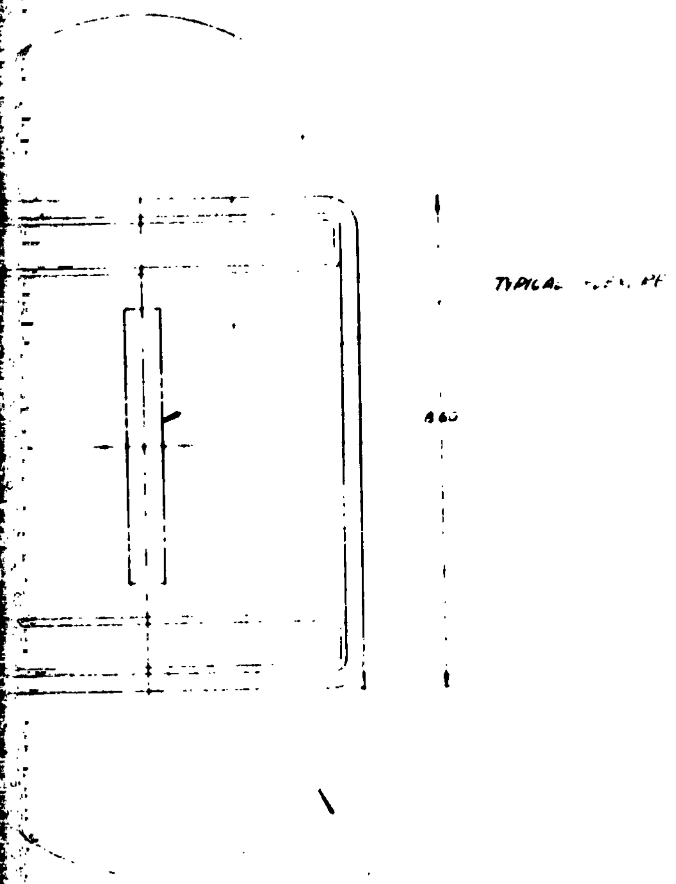


Figure 11. Truss Pitchcase



2 FOLDOUT FRAME



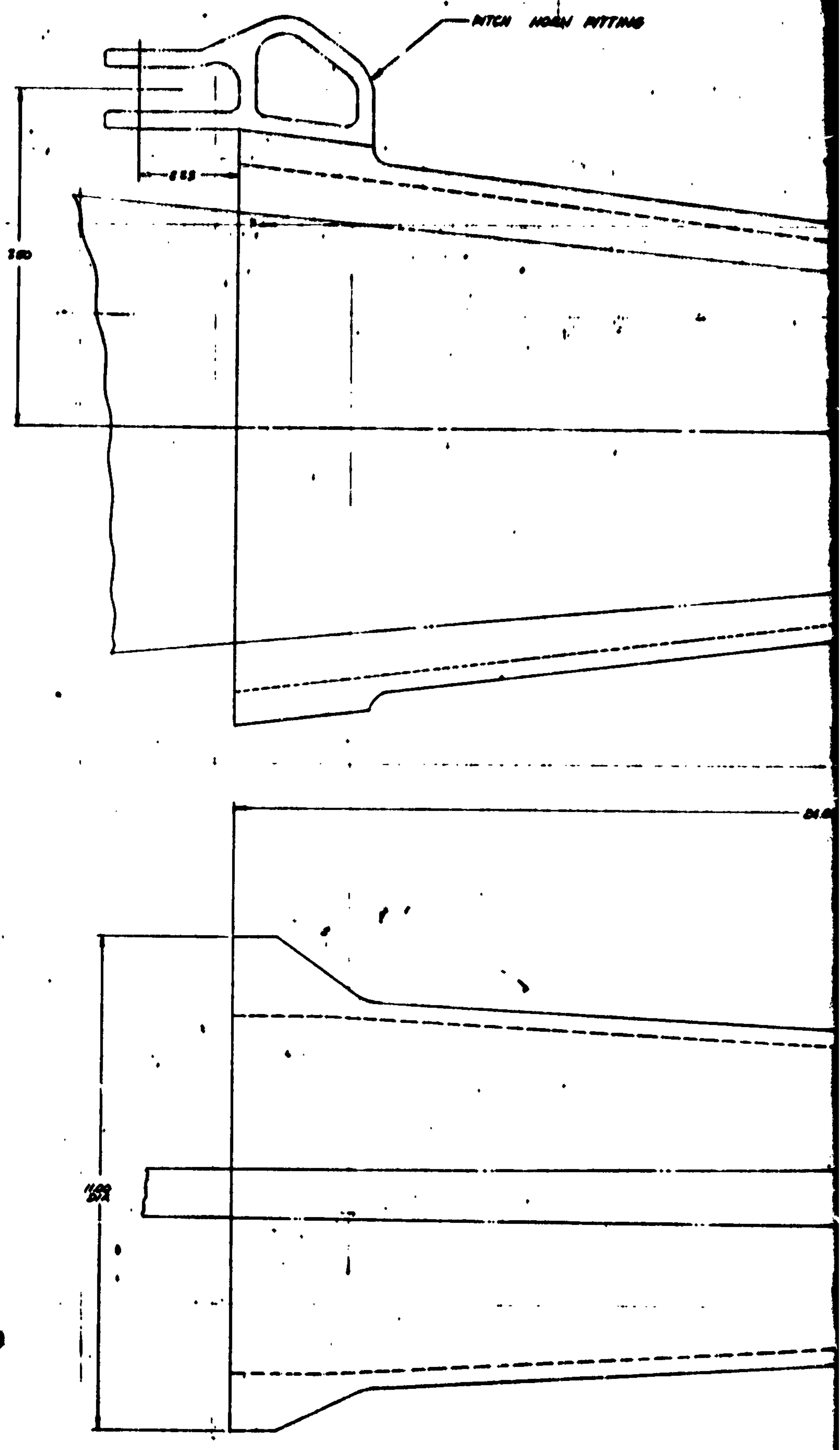
SECTION A-A

ORIGINAL PAGE IS
OF POOR QUALITY

Hughes Helicopters, Inc.

TRUSS STRUCTURE
PITCH CASE CONCEPT I
ITH FRR - TASK II

02731 484-10

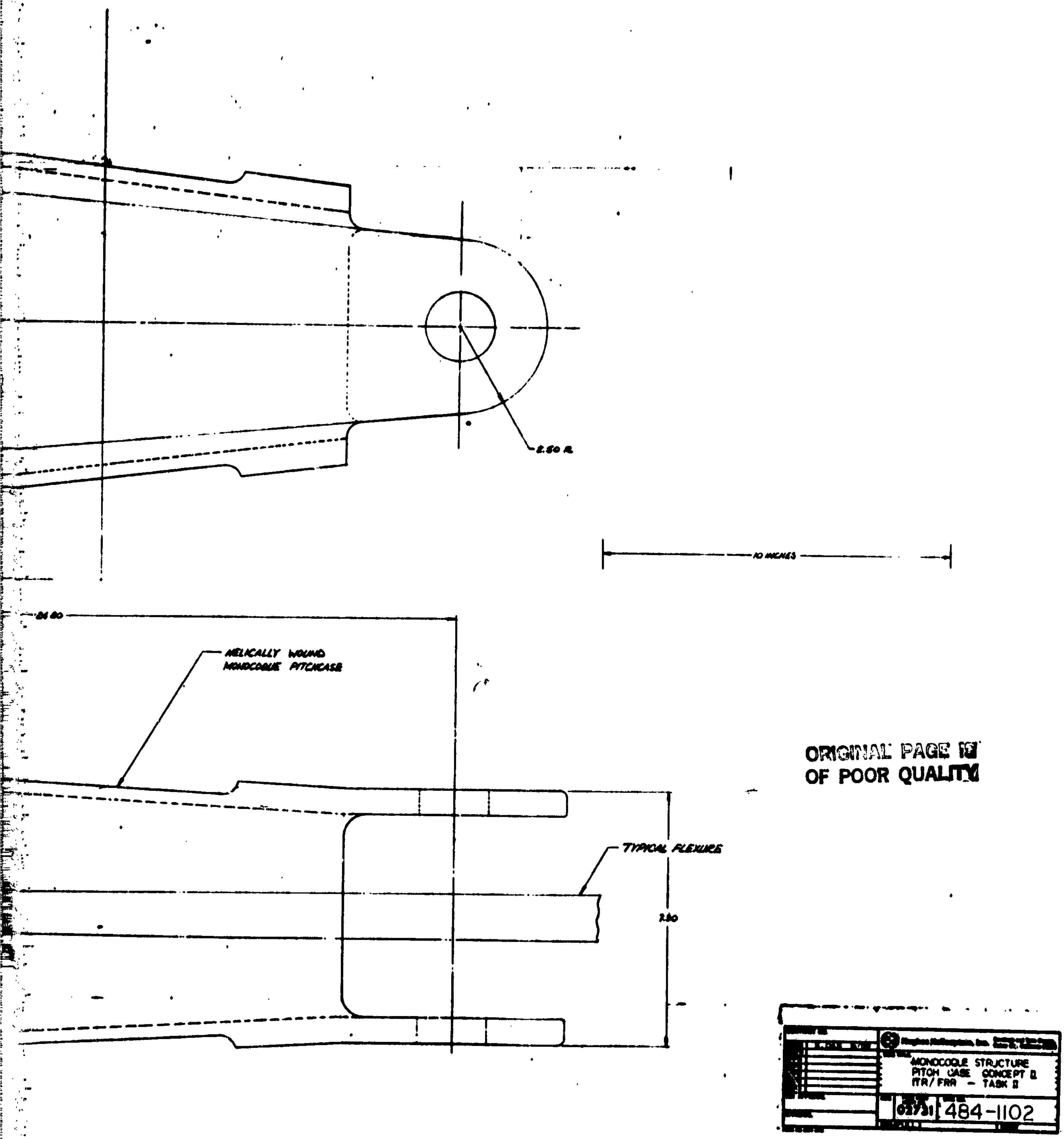


ORIGINAL PAGE IS
OF POOR QUALITY

PRECEDING PAGE BLANK NOT FILMED

Figure 12. Monocoque Pitchcase

FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

2 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

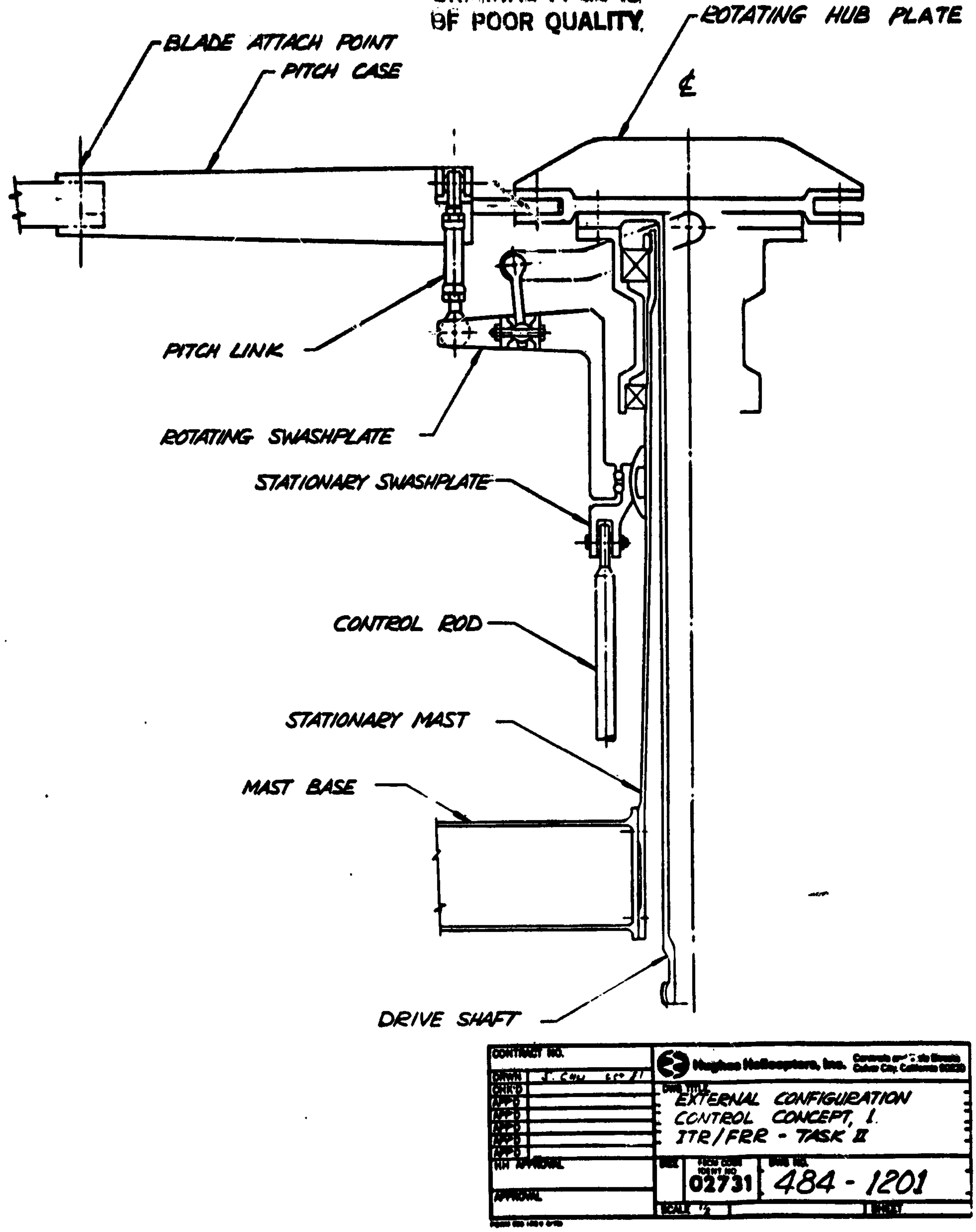


Figure 13. External Control System Configuration

PRECEDING PAGE BLANK NOT FILMED

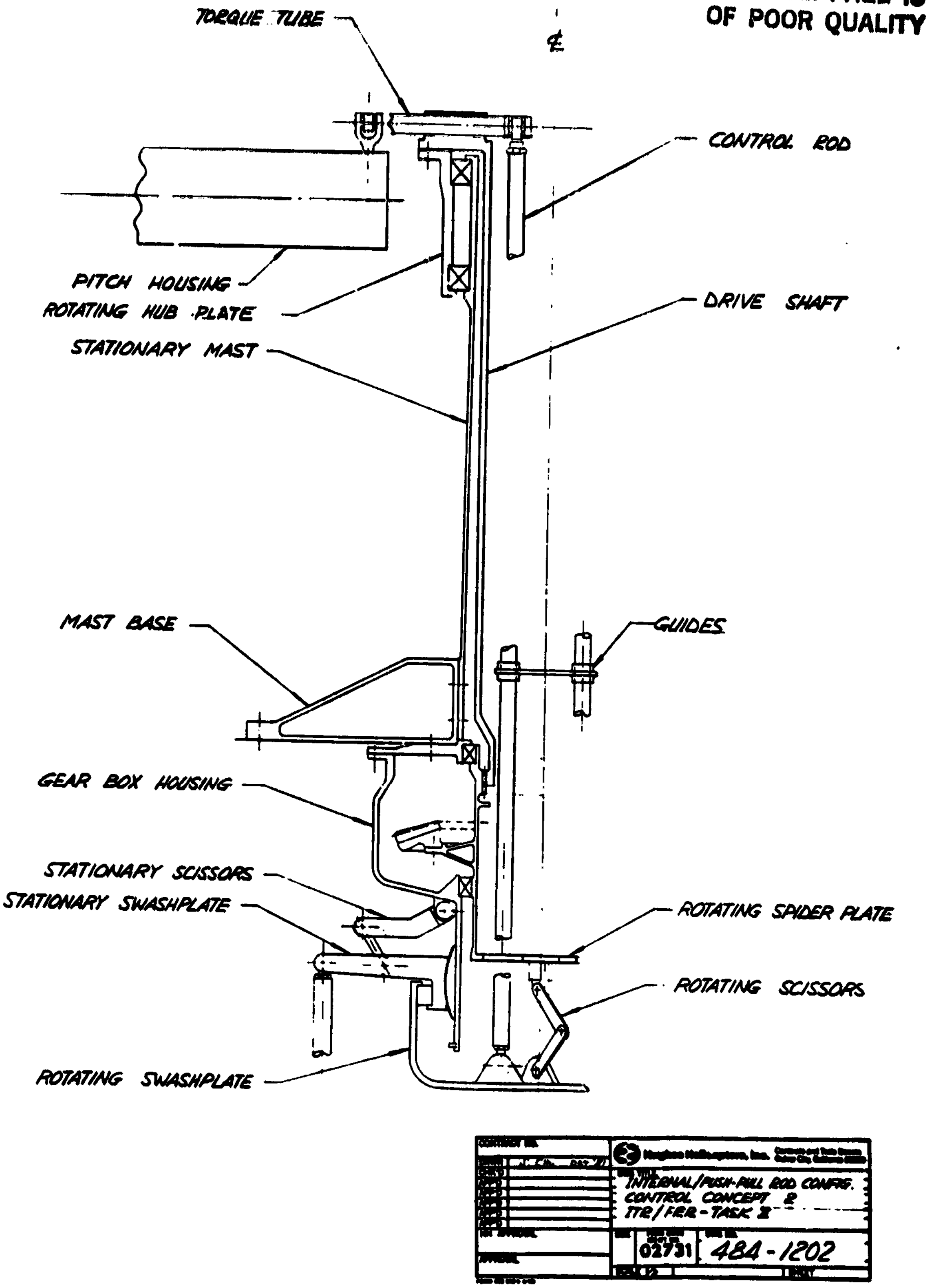


Figure 14. Internal Control System Configuration, Push-Pull Rods

ORIGINAL PAGE IS
OF POOR QUALITY

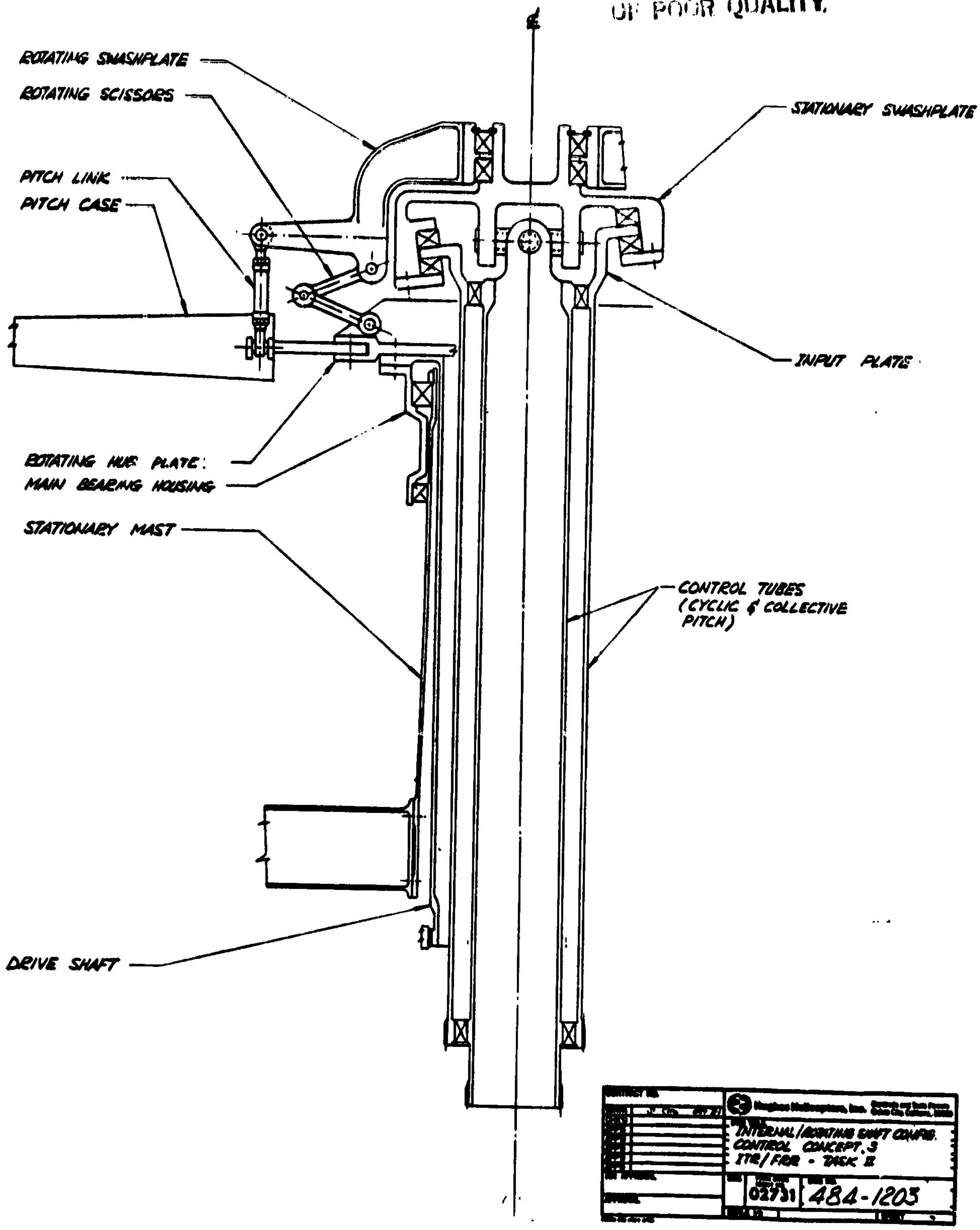


Figure 15. Internal Control System Configuration, Rotating Shaft

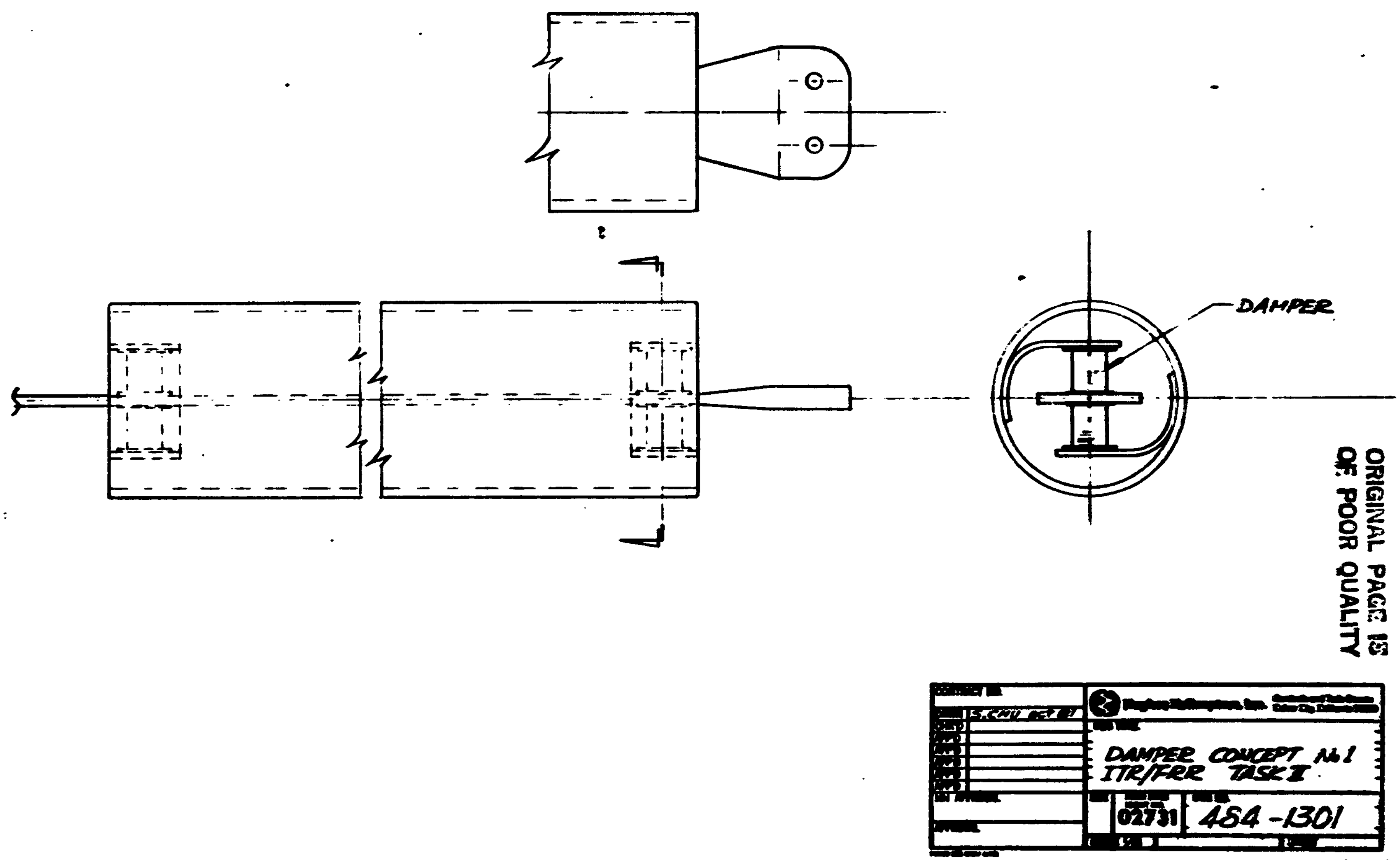


Figure 16. Damper Concept.

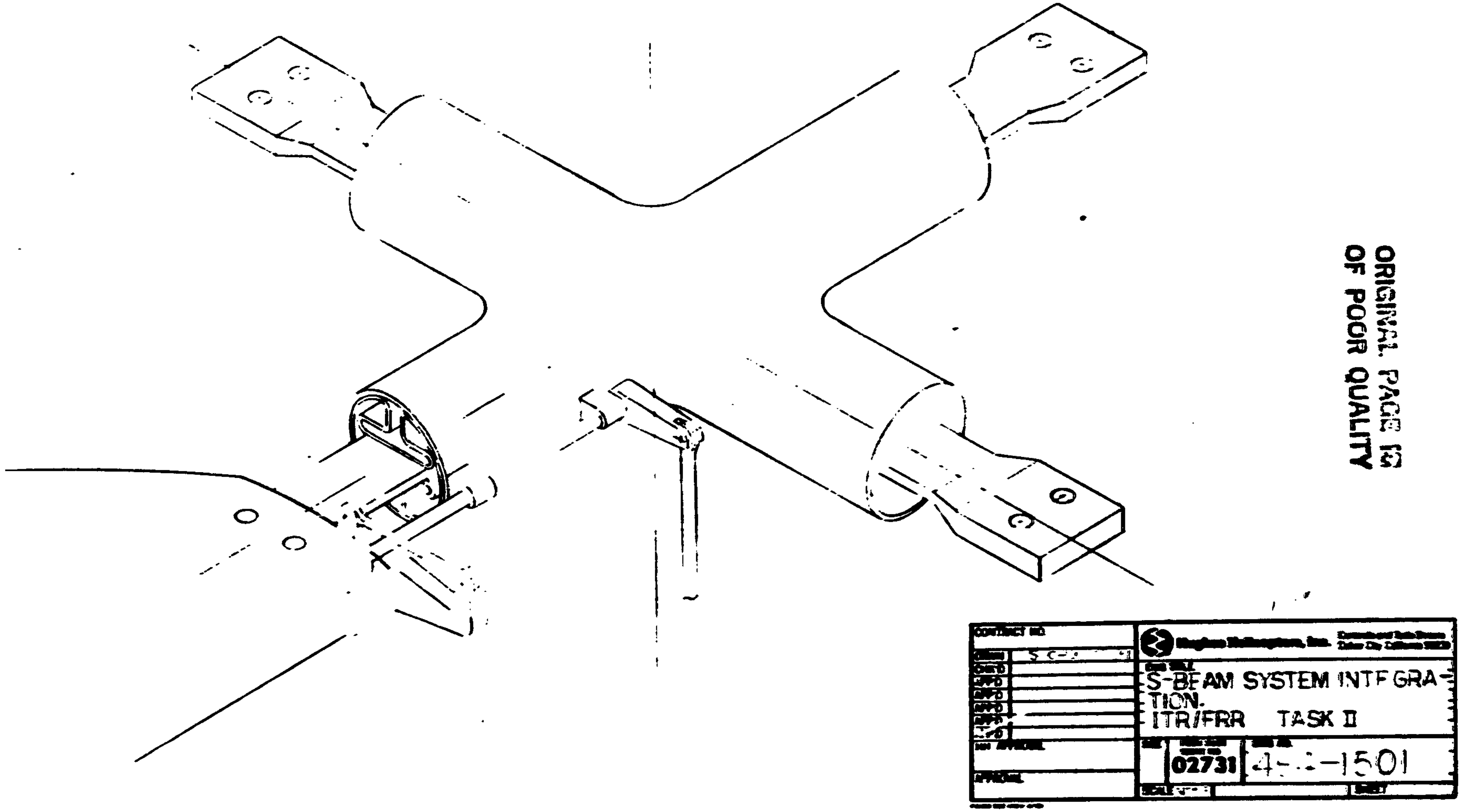
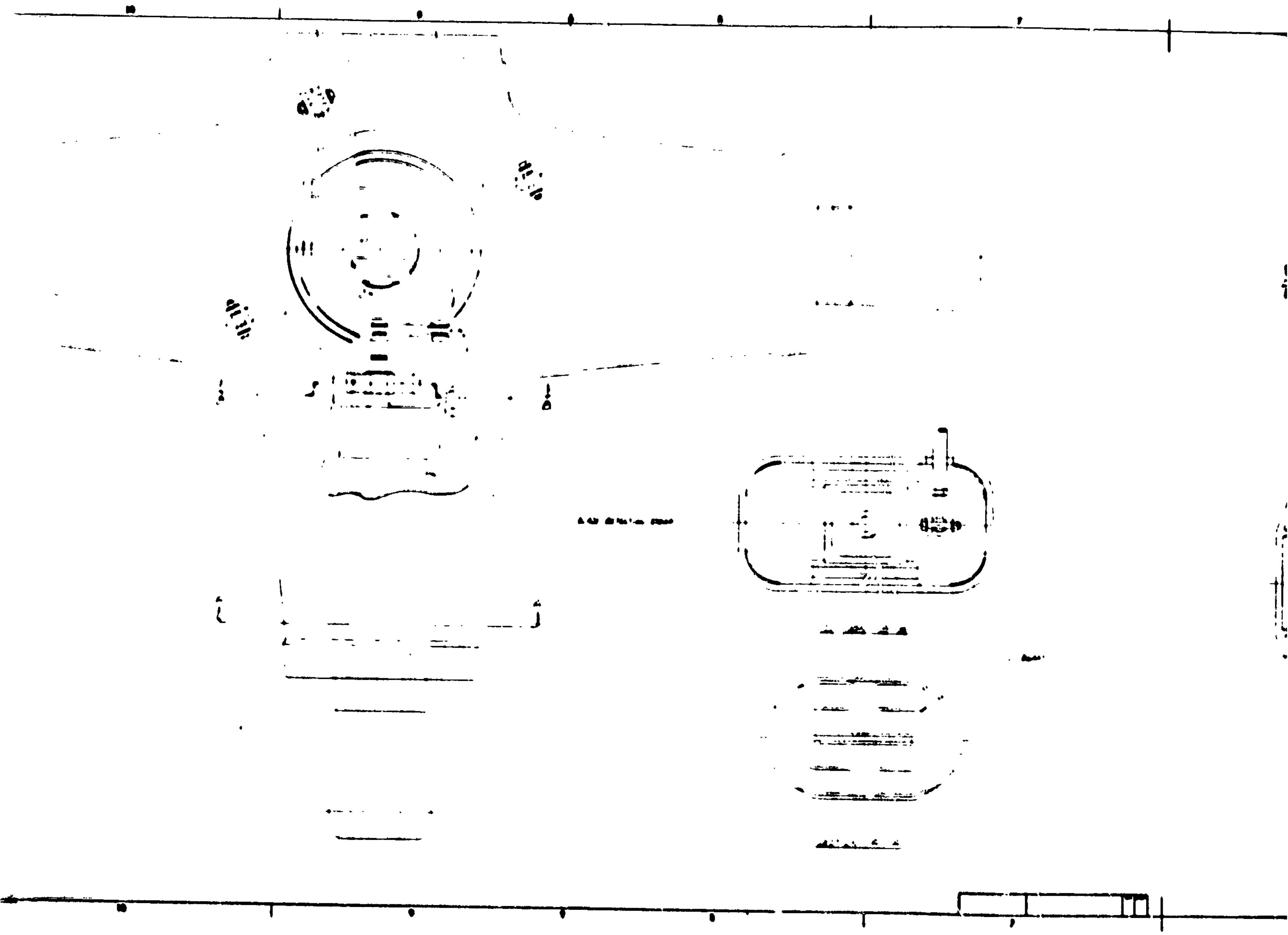


Figure 17. Hub System Integration, S-Beam Flexure.

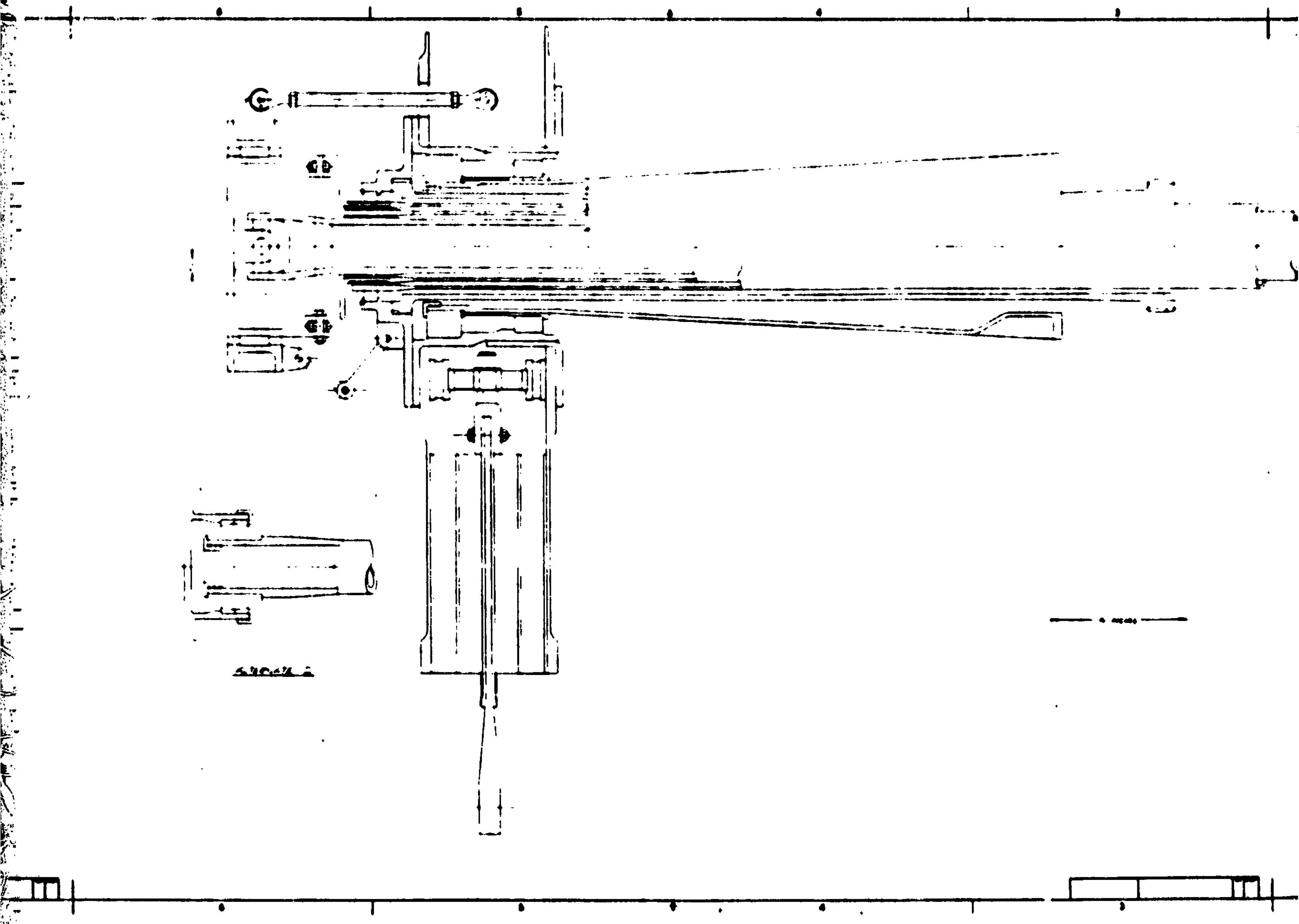


PRECEDING PAGE BLANK NOT FILMED

FOLDOUT FRAME

Figure 18. Hub and Control System with S-Beam Flexure

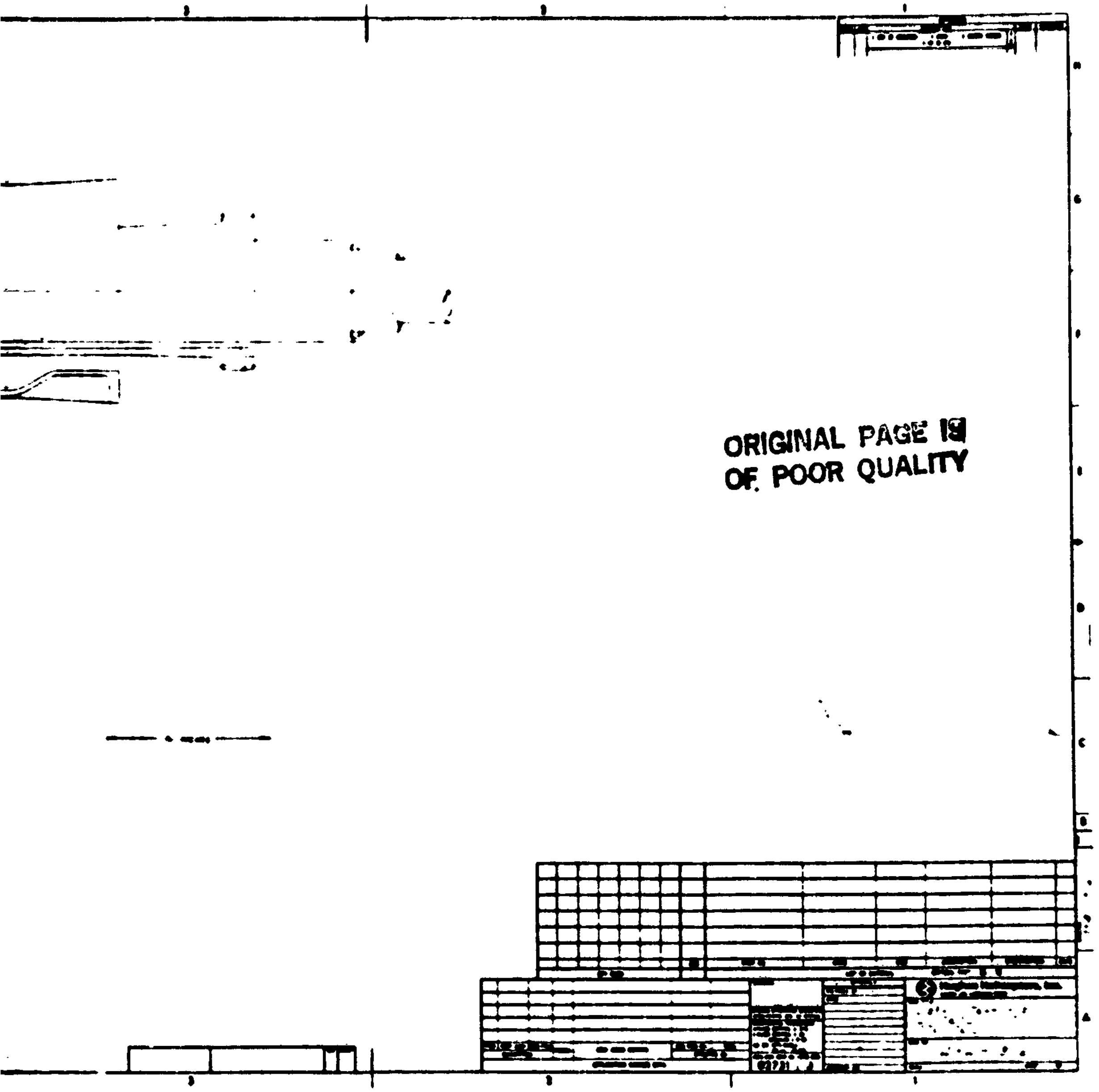
ORIGINAL PAGE IS
OF POOR QUALITY



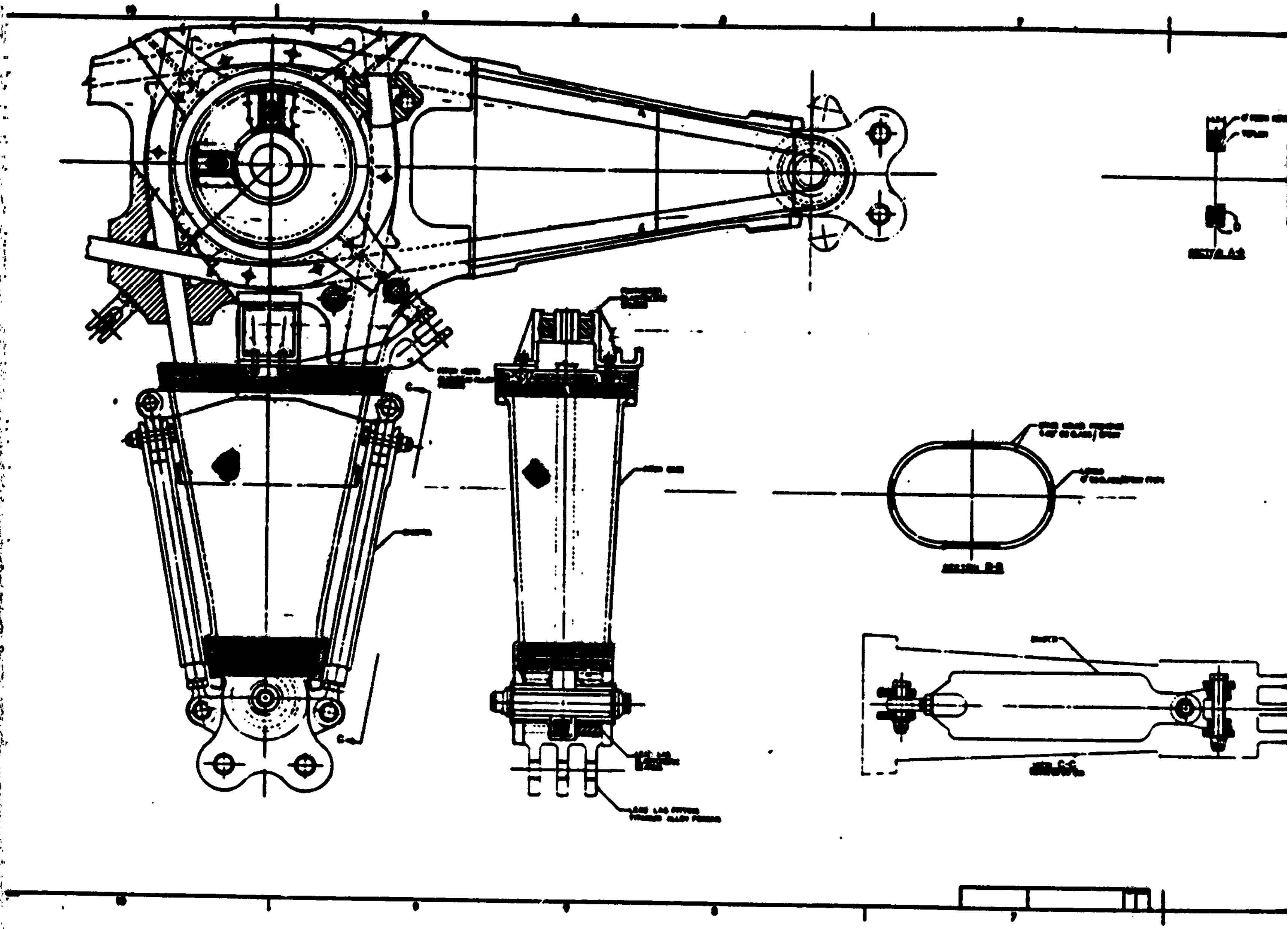
ORIGINAL PAGE IS
OF POOR QUALITY

2 FOLDOUT FRAME

C-2



3 FOLDOUT FRAME

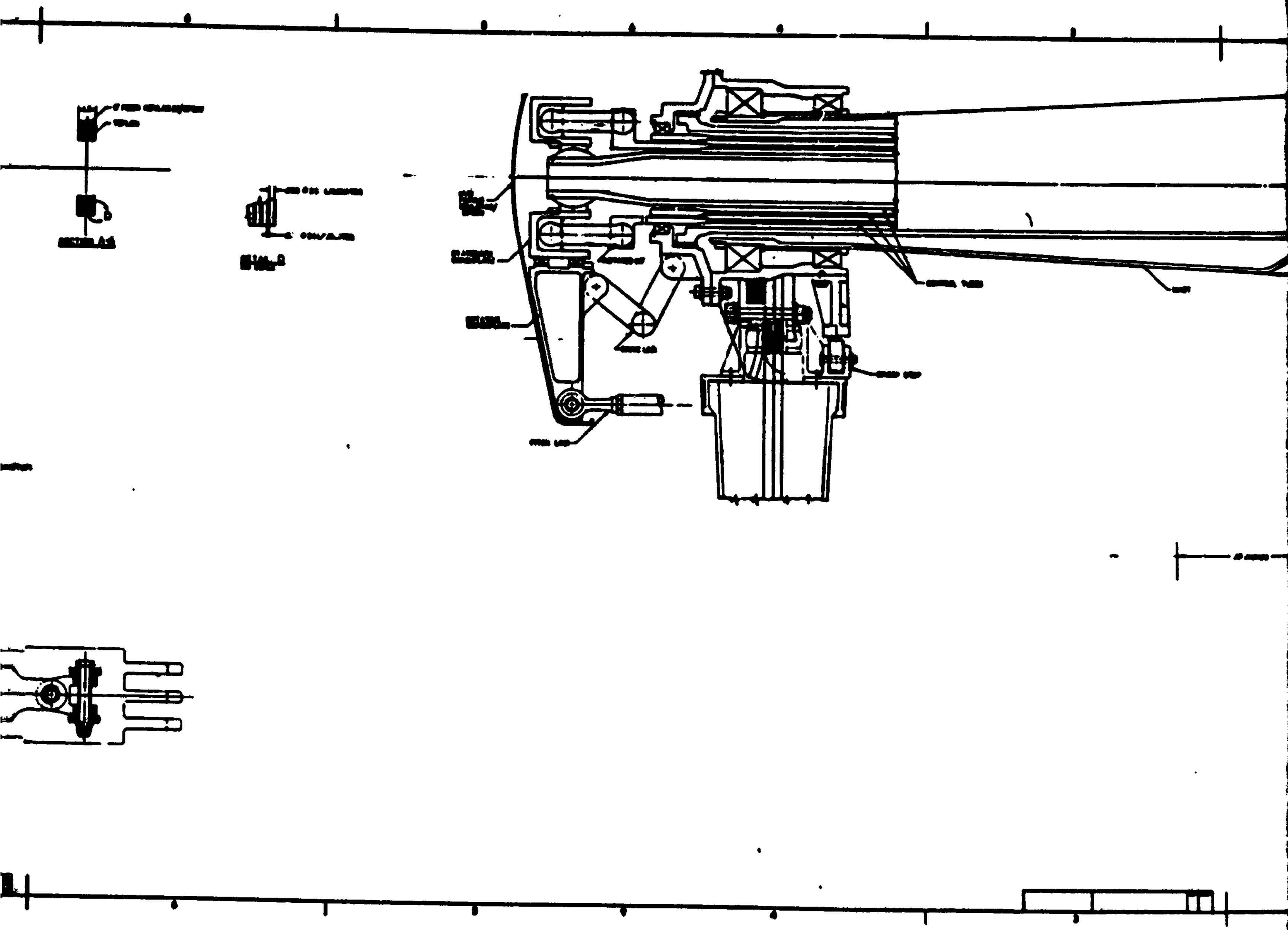


PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE IS
OF POOR QUALITY

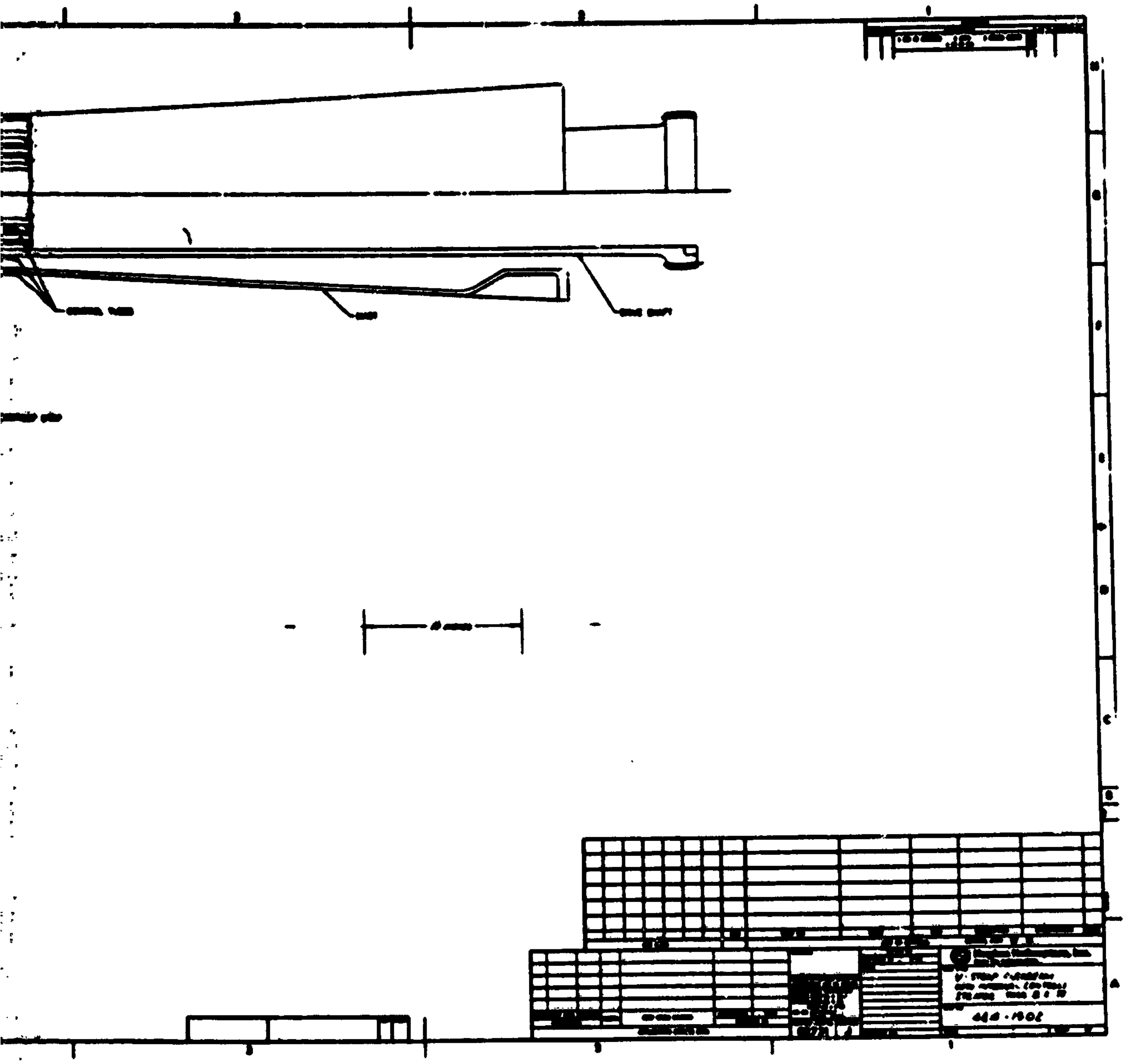
Figure 19. Hub System with V-Strap Flexure

FOLDOUT FRAME



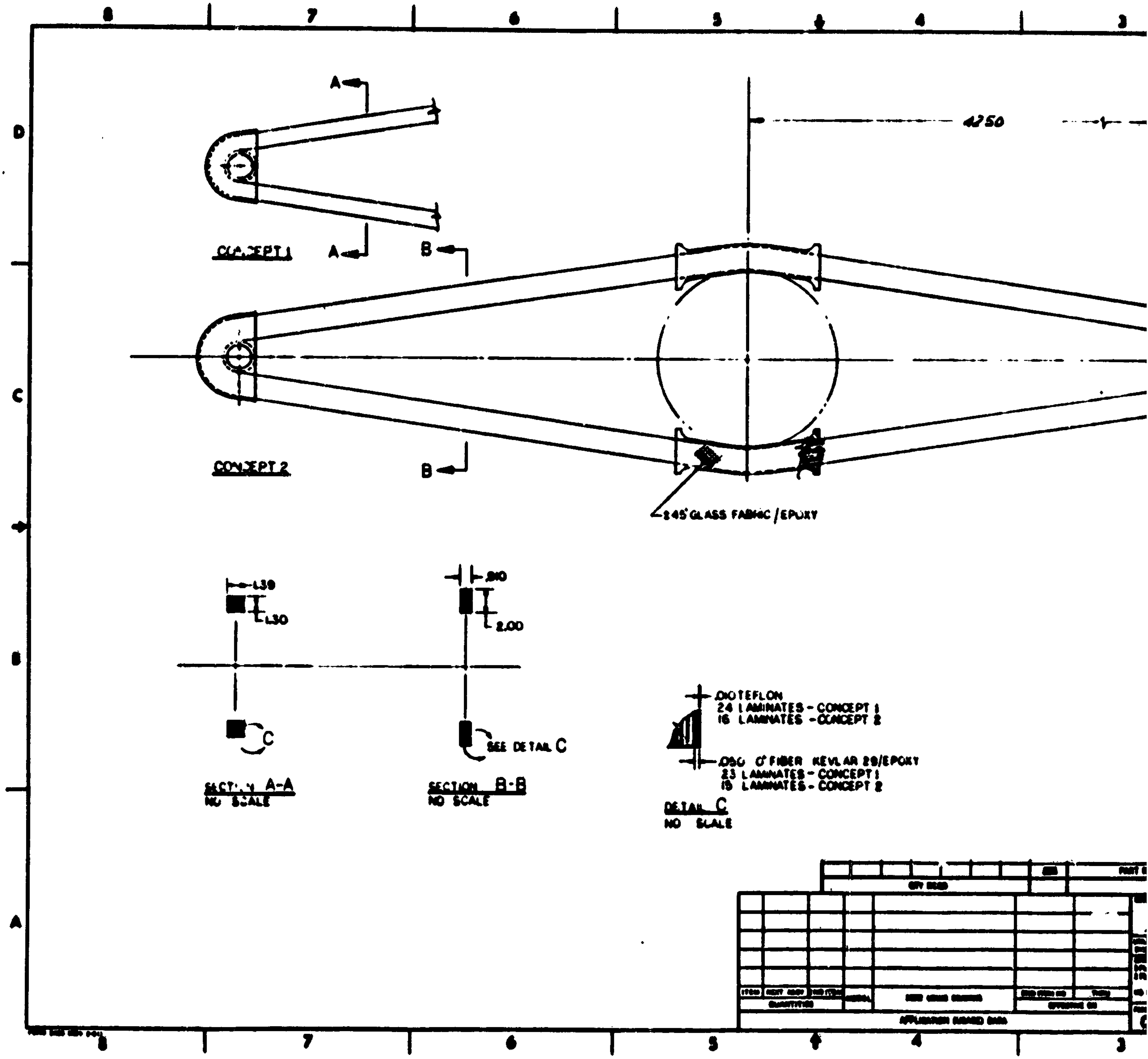
ORIGINAL PAGE IS
OF POOR QUALITY

2



ORIGINAL PAGE IS
OF POOR QUALITY

3 FOLDOUT FRAME



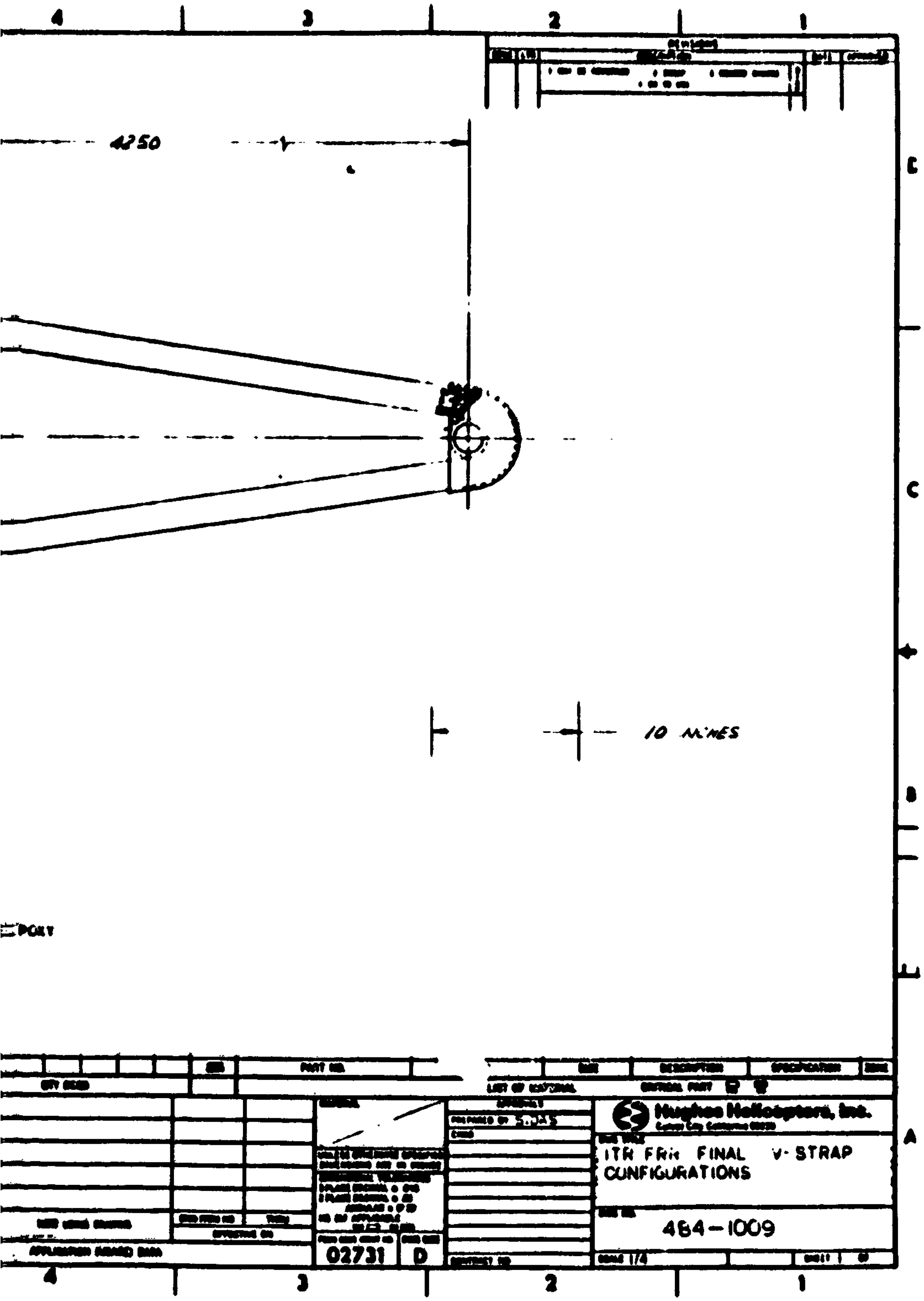
PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 20. V-Strap Flexures, Final Configurations

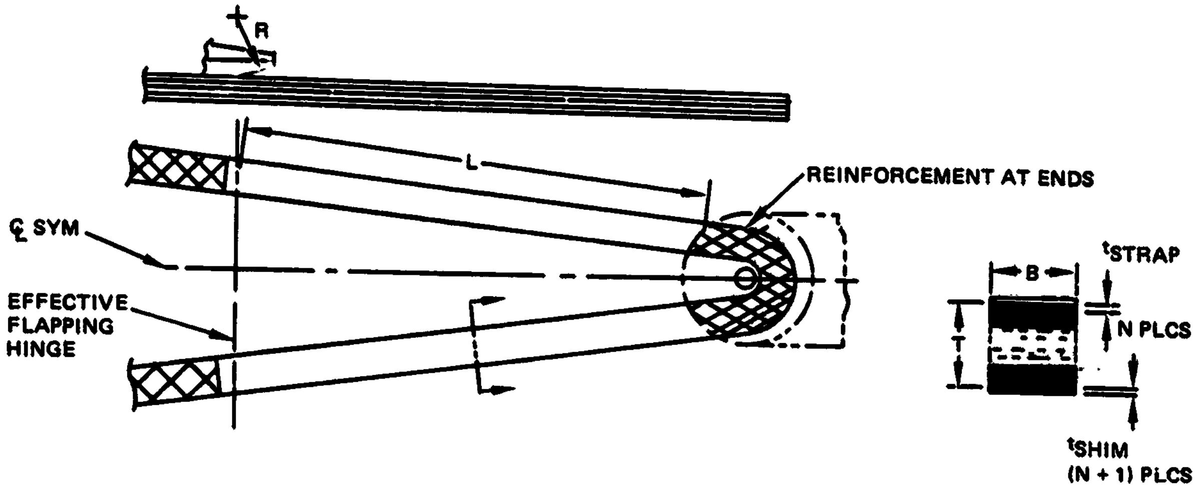
ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

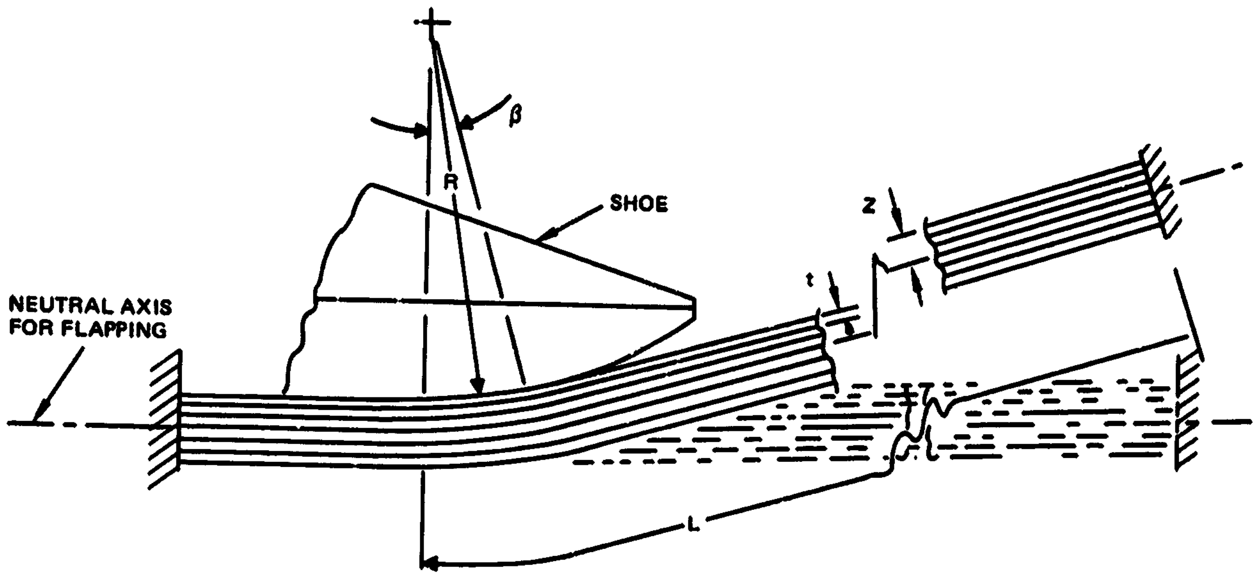
2 FOLDOUT FRAME



GEOMETRY	CONCEPT NO. 1	CONCEPT NO. 2
L	29 IN.	29 IN.
R	16 IN.	16 IN.
B	1.3 IN.	2.0 IN.
t_{STRAP}	0.050 IN.	0.050 IN.
t_{SHIM}	0.010 IN.	0.010 IN.
N	23 LAMINATES	15 LAMINATES
T	1.370 IN.	0.890 IN.

Figure 21. V-Strap Geometry

PRECEDING PAGE BLANK NOT FILMED



SHOE BENDING: $F_{SB} = \frac{Et}{2R}$, PSI

PACK BENDING: $F_{PB} = \frac{EZ\beta}{57.3L}$, PSI

WHERE

E – MATERIAL MODULUS
L – FLEXURE LENGTH
R – HUB SHOE RADIUS
t – LAMINATE THICKNESS
Z – DISTANCE FROM NEUTRAL AXIS
β – FLAPPING ANGLE

Figure 22. Flapping Stress Equations

ORIGINAL PAGE IS
OF POOR QUALITY

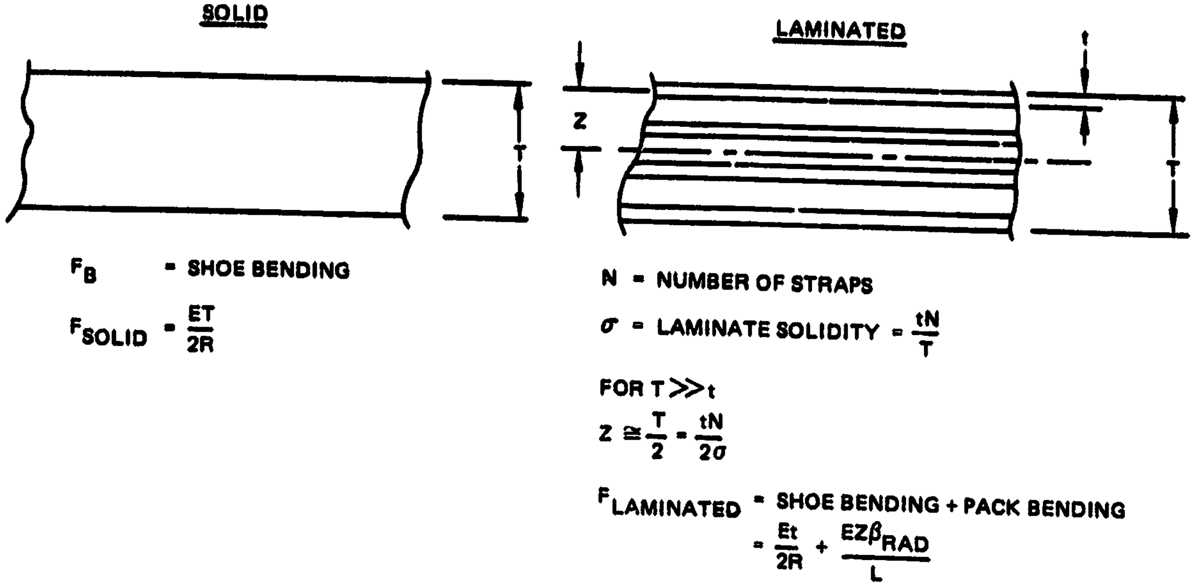


Figure 23. Stresses in a Solid vs Laminated Flexure Due to Flapping

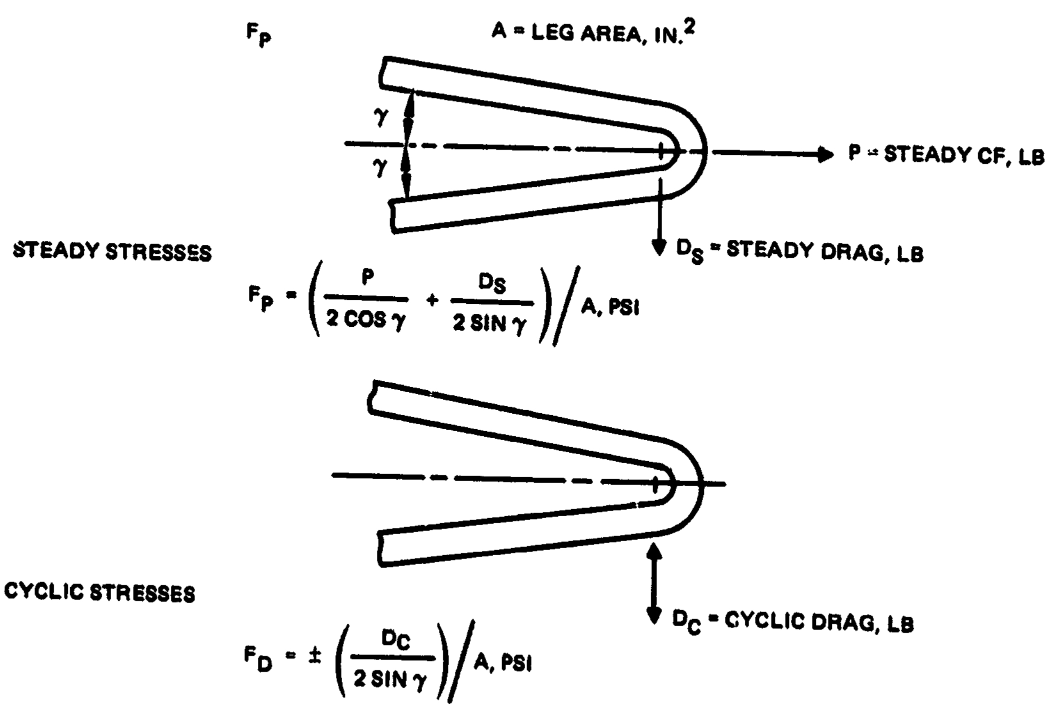


Figure 24. V-Strap Stresses Due to Drag and Centrifugal Force

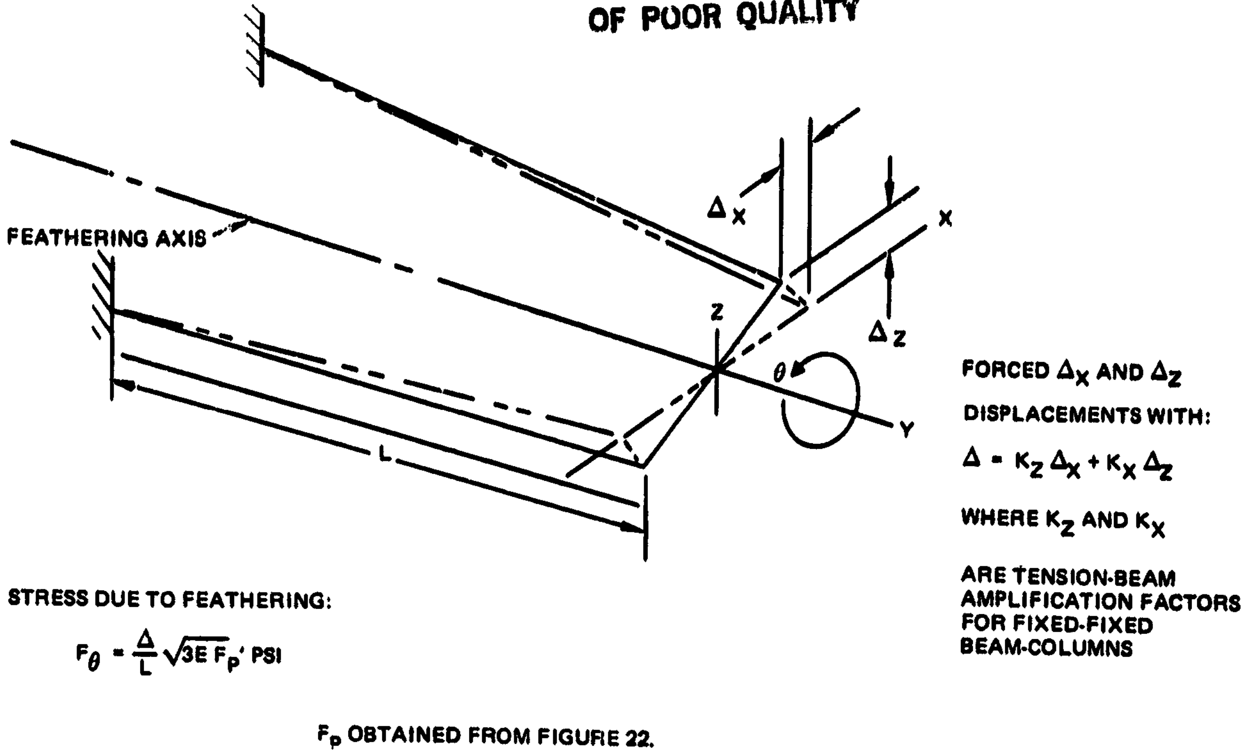
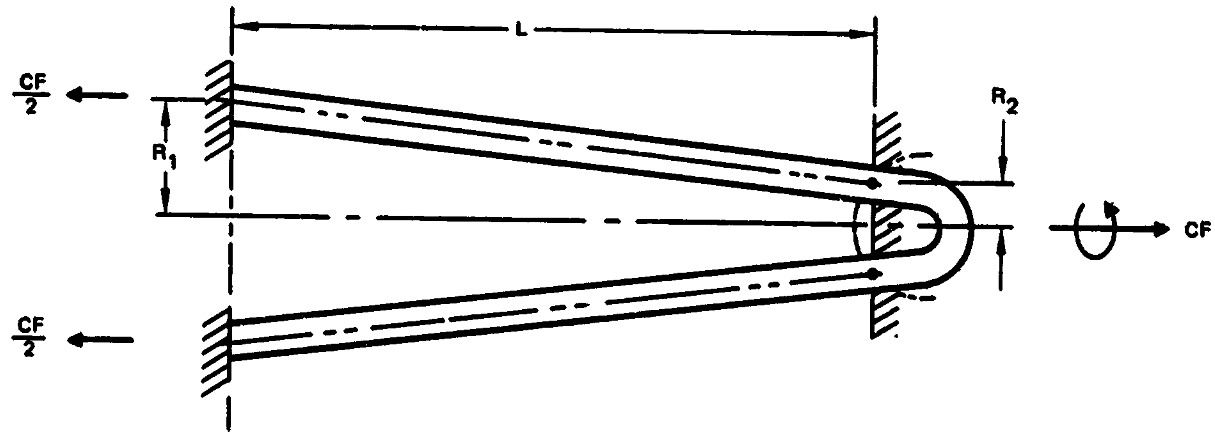


Figure 25. Stresses Due to Feathering Motion



TORSIONAL STIFFNESS EQUATION = $\frac{(CF)\,(R_1 - R_2)\,R_2}{57.3L}$, IN.-LB/DEG

	CONCEPT NO. 1	CONCEPT NO. 2
CF	68,000 LB	68,000 LB
R_1	6.00 IN.	6.35 IN.
R_2	2.20 IN.	2.75 IN.
L	29.00 IN.	29.00 IN.
TORSIONAL STIFFNESS =	342 IN.-LB/DEG	405 IN.-LB/DEG

Figure 26. V-Strap Torsional Stiffness

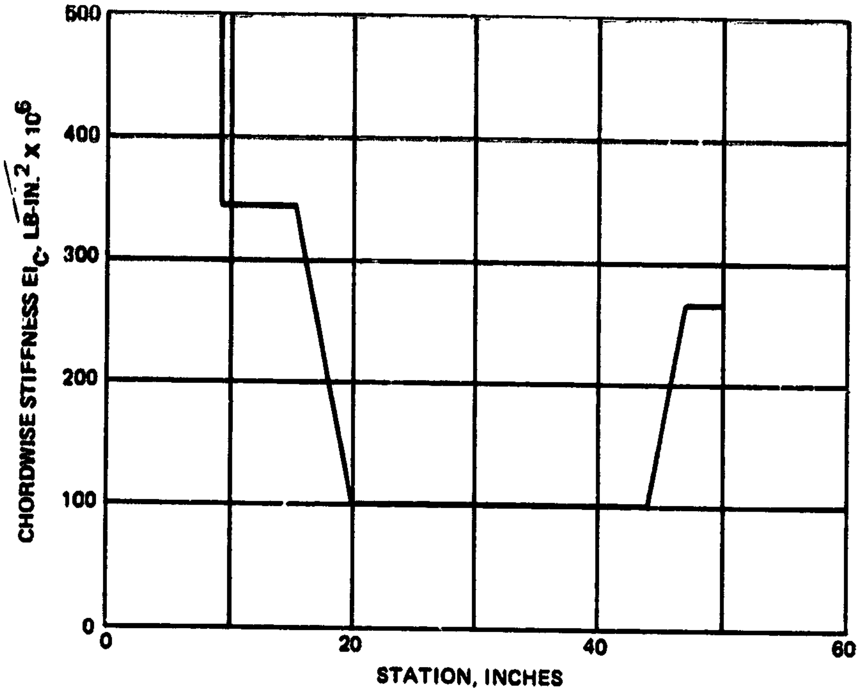


Figure 27. Flat-Strap Cruciform, Flexure Chordwise Stiffness

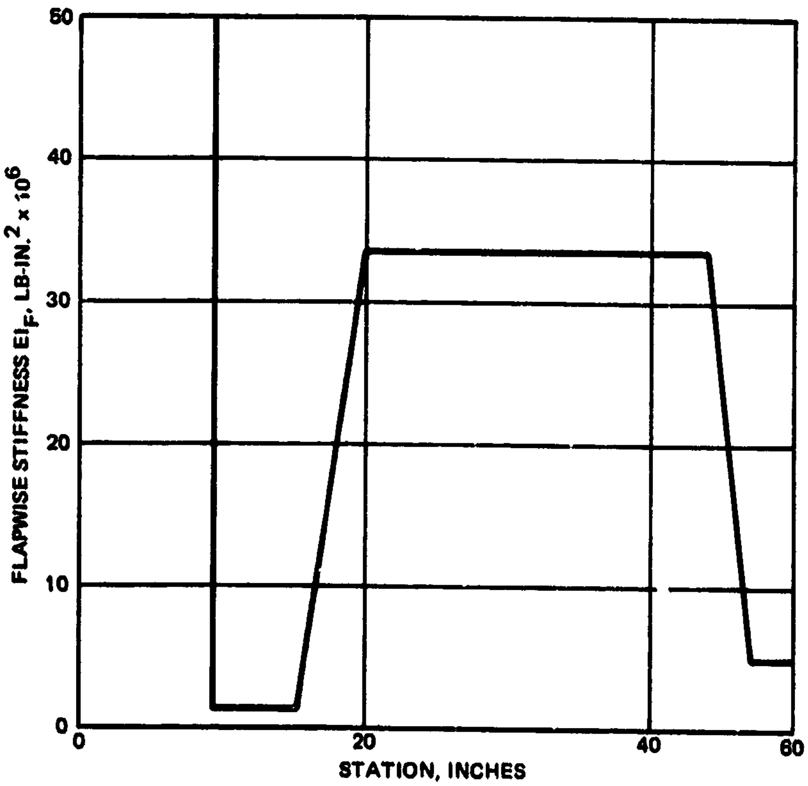


Figure 28. Flat-Strap Cruciform, Flexure Flapwise Stiffness

ORIGINAL PAGE IS
OF POOR QUALITY

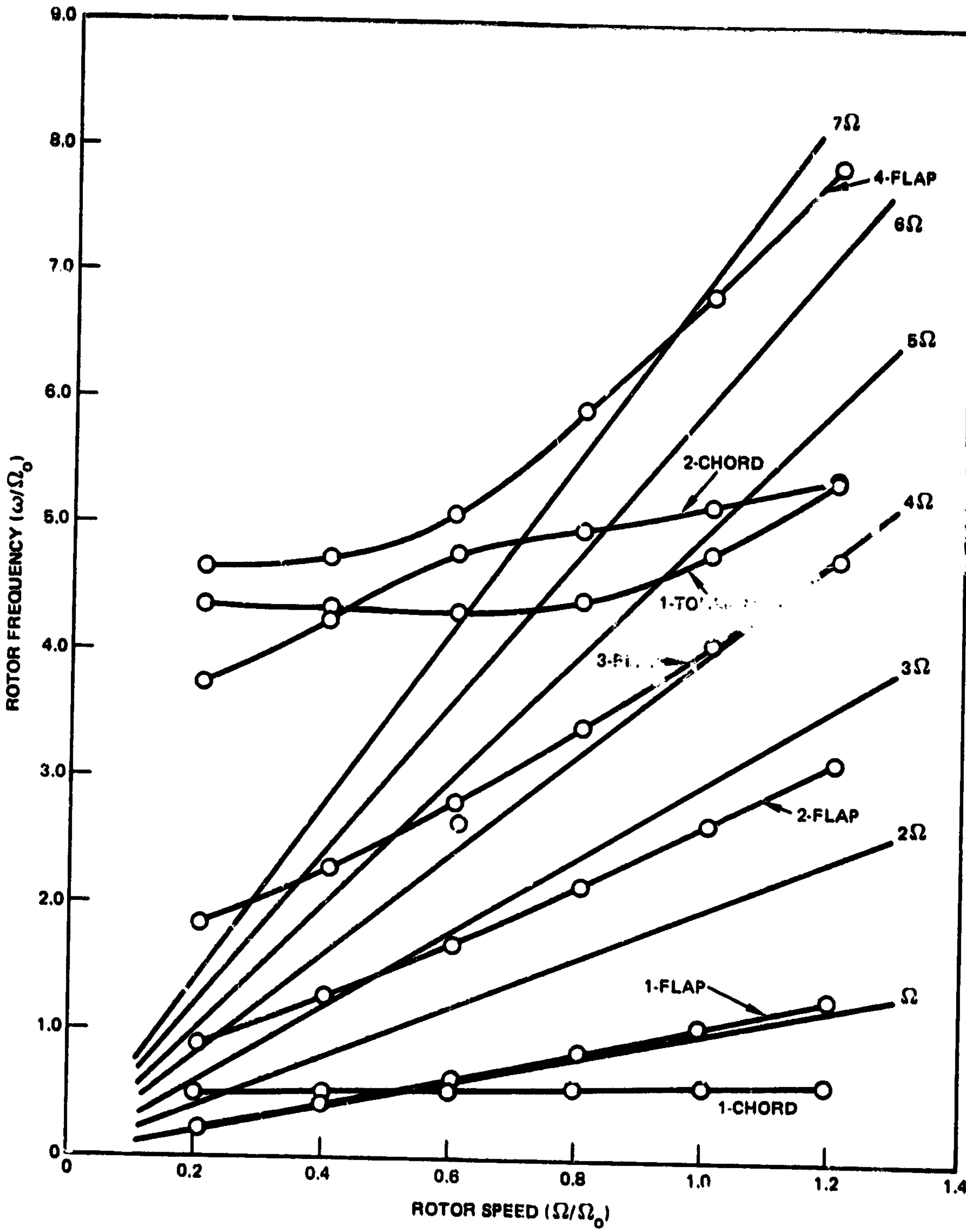


Figure 29. Flat Strap Cruciform Resonance Diagram

ORIGINAL PAGE IS
OF POOR QUALITY

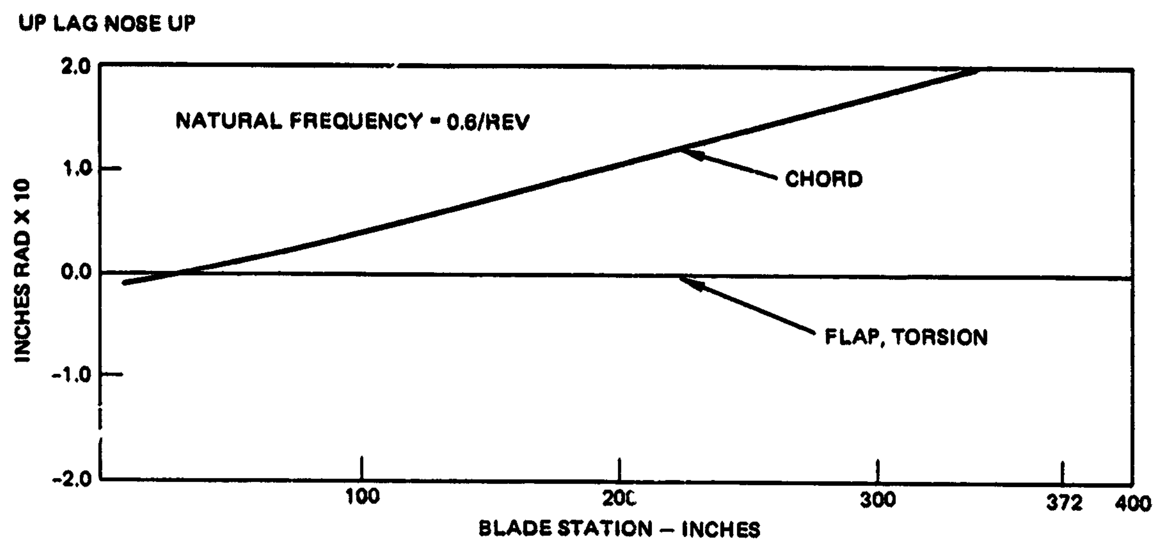


Figure 30. Flat-Strap Cruciform First Inplane Mode

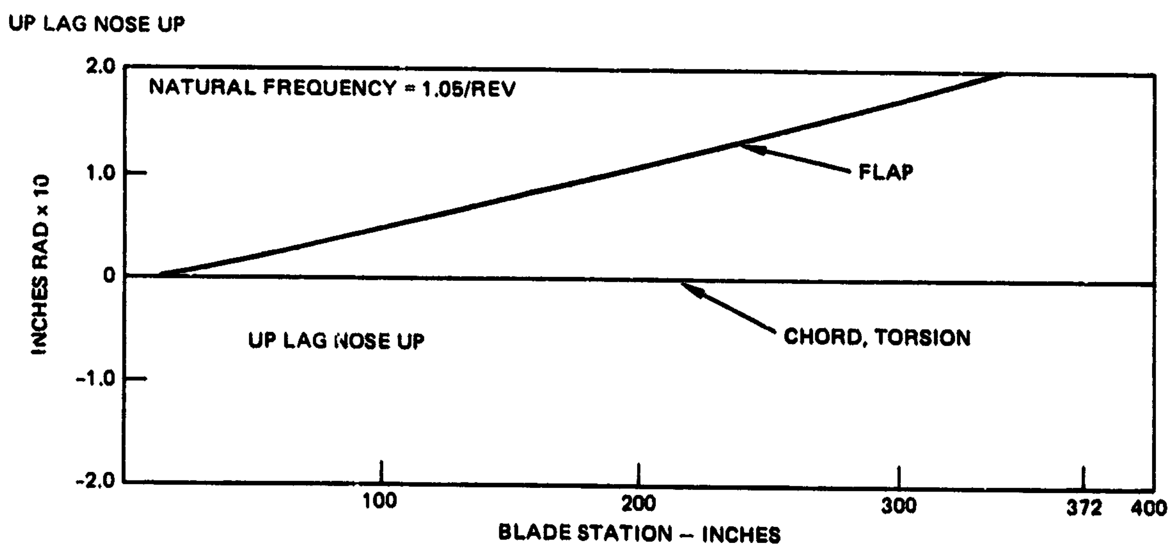
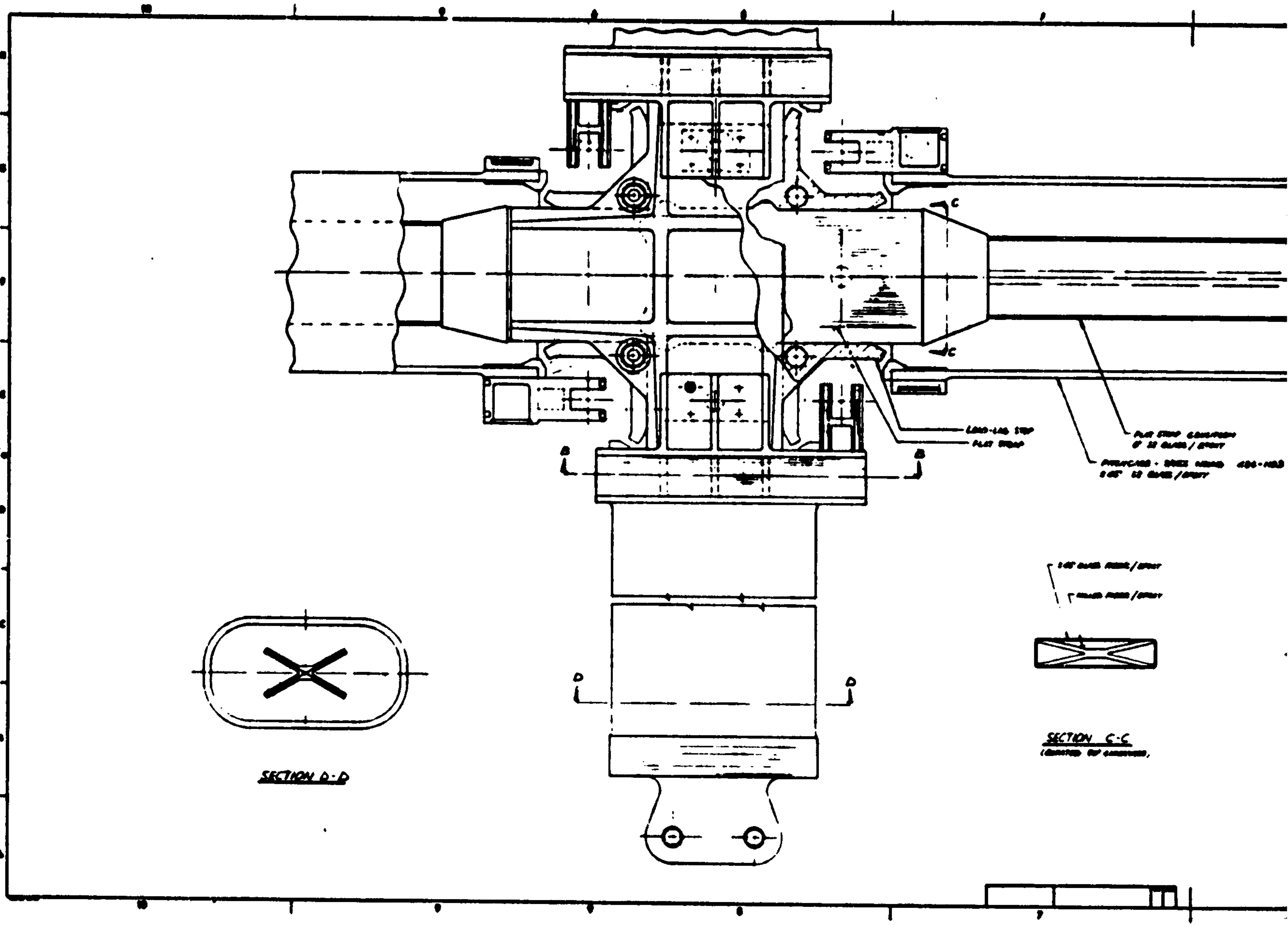


Figure 31. Flat-Strap Cruciform First Flapping Mode

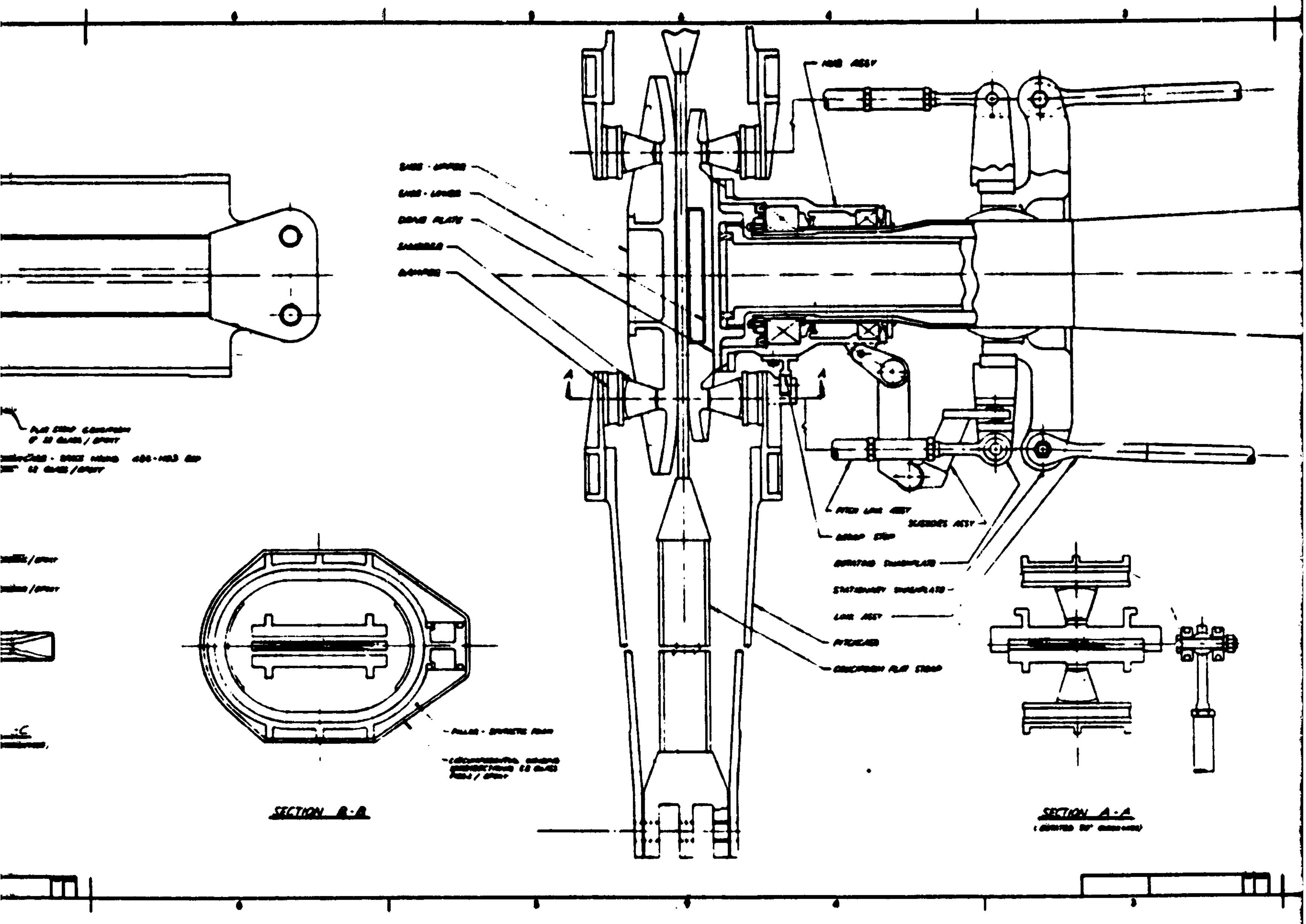


PRECEDING PAGE BLANK NOT FILMED

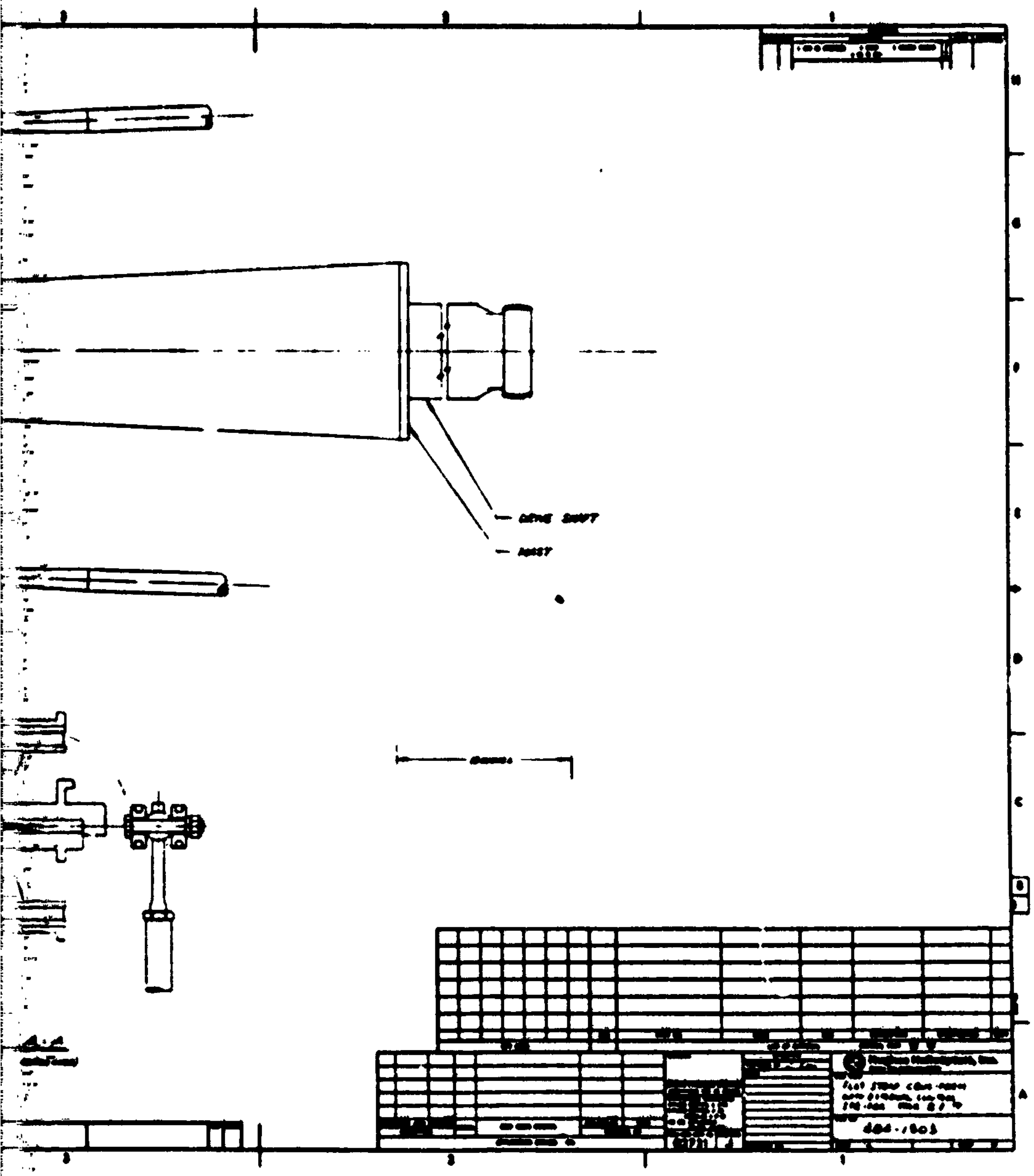
FOLDOUT FRAME

ORIGINAL PAGE IS OF POOR QUALITY

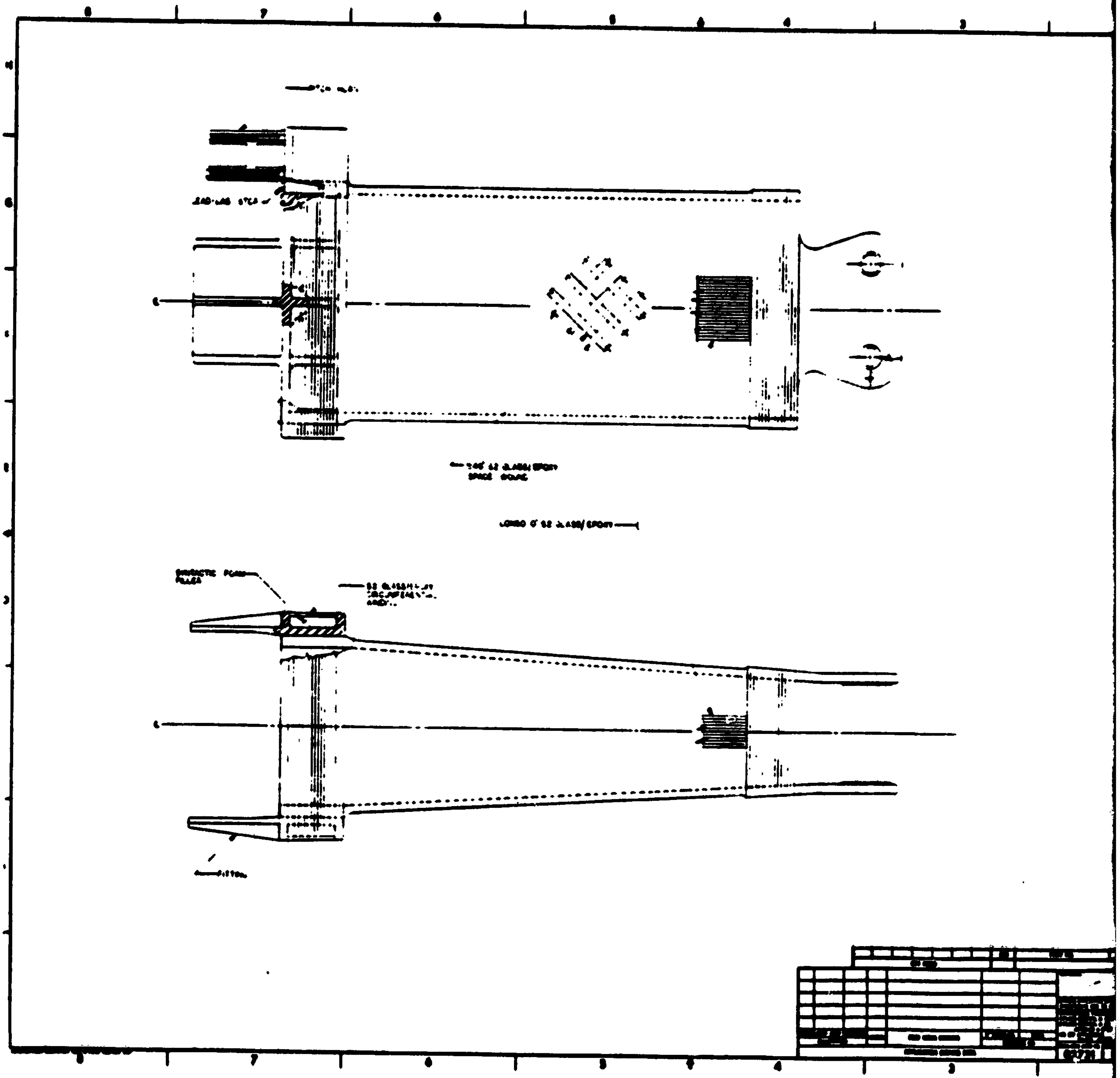
Figure 32. Hub System with Flat-Strap Cruciform Flexure



2 FOLDOUT FRAME



FOLDOUT FRAME



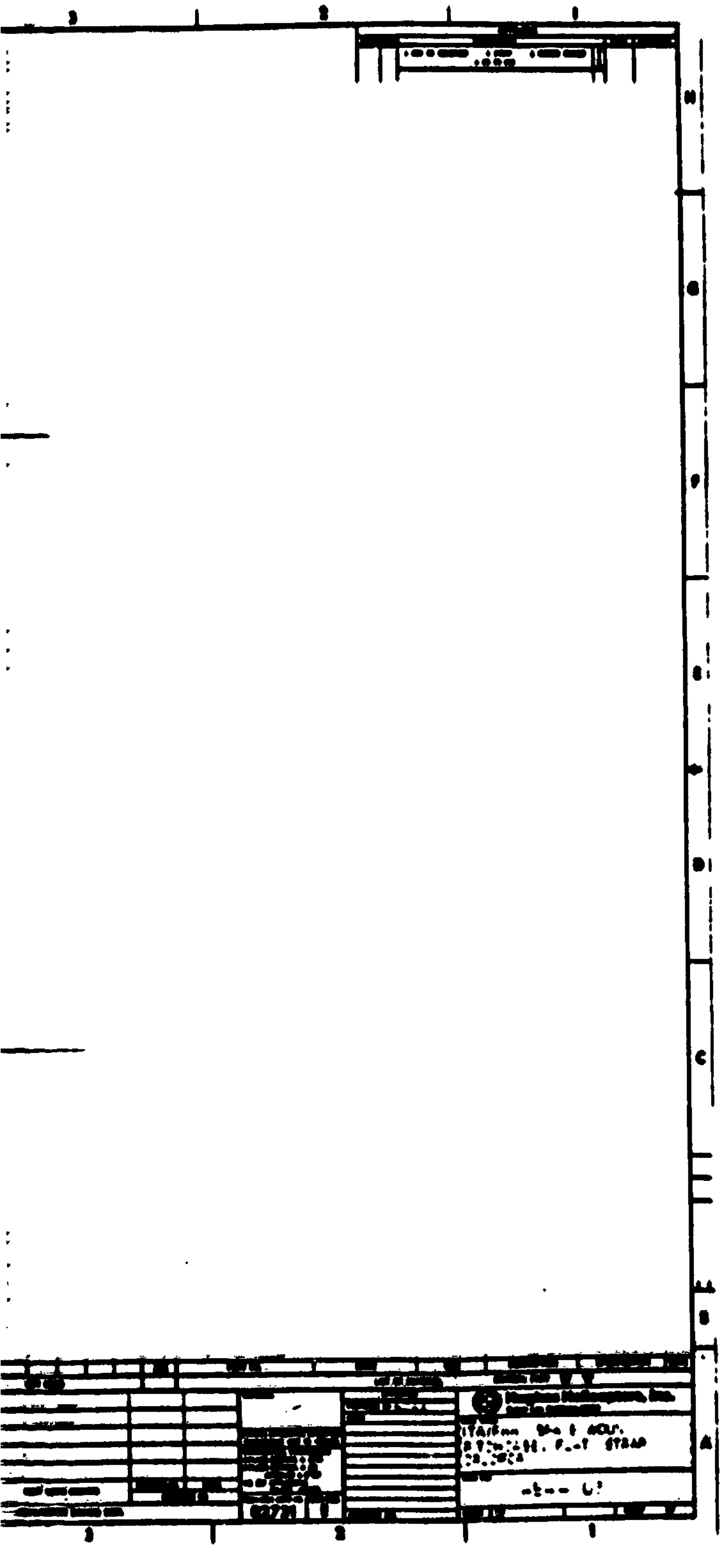
PRECEDING PAGE BLANK NOT FILMED

Figure 33. Space Wound Pitchcase

ORIGINAL PAGE IS
OF POOR QUALITY

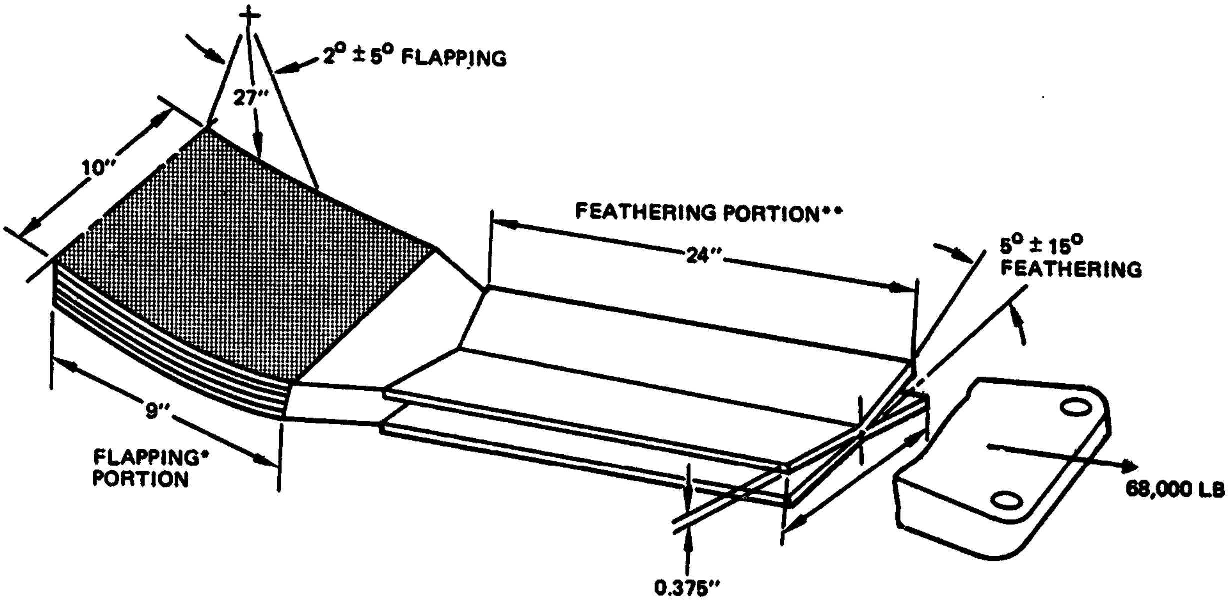
FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY



2 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY



*LAMINATED TO REDUCE FLAPPING STRESS
**CRUCIFORM SECTION PRODUCES MINIMUM SHEAR STRAIN

Figure 34. Flat-Strap Cruciform Flexure Geometry and Loads.

PRECEDING PAGE BLANK NOT FILMED

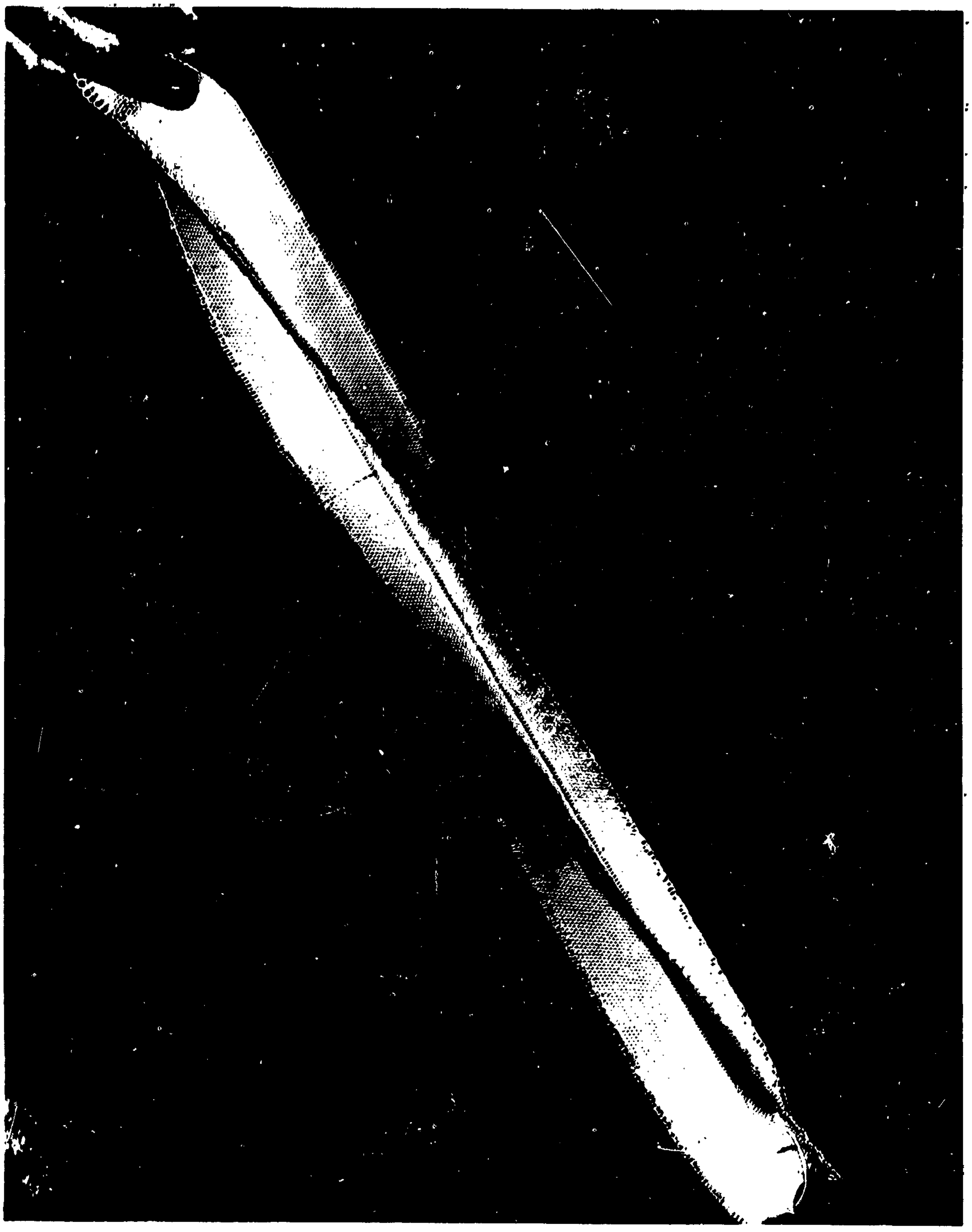
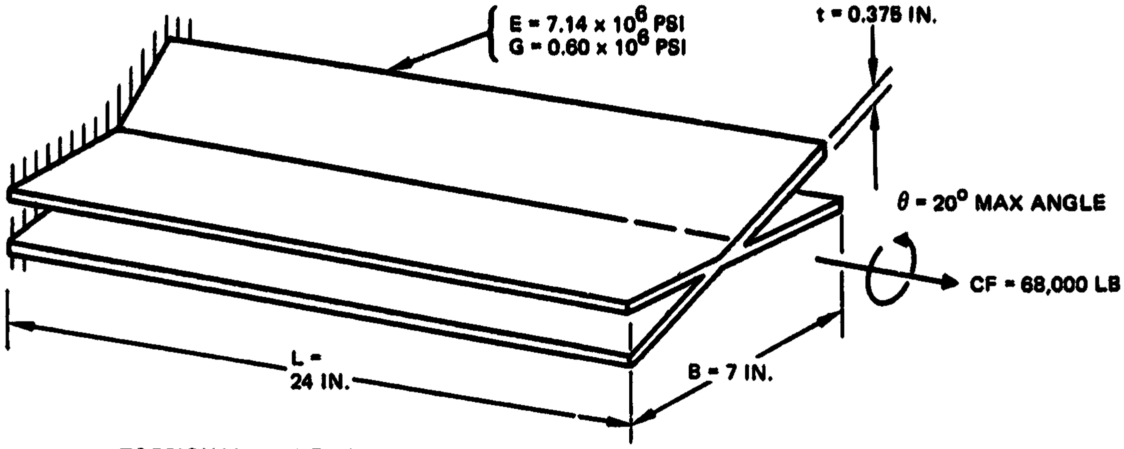


Figure 35. Woven Fiberglass Center of the Cruciform.



TORSIONAL STIFFNESS	=	DUE TO TORSIONAL RIGIDITY	+	DUE TO INDUCED AXIAL STRESS IN WIDE, THIN BAR	+	STIFFENING EFFECT DUE TO CF
	=	$\frac{2(Bt^3G)}{3(57.3L)}$	+	$\frac{2(EB^5t\theta^2)}{3(57.3)^3\,(120L^3)}$	+	$\frac{2(C.F.\ B^2)}{24(57.3L)}$
	=	108	+	38	+	202

TORSIONAL STIFFNESS = 348 IN.-LB/DEG

Figure 36. Flat-Strap Cruciform Torsional Stiffness

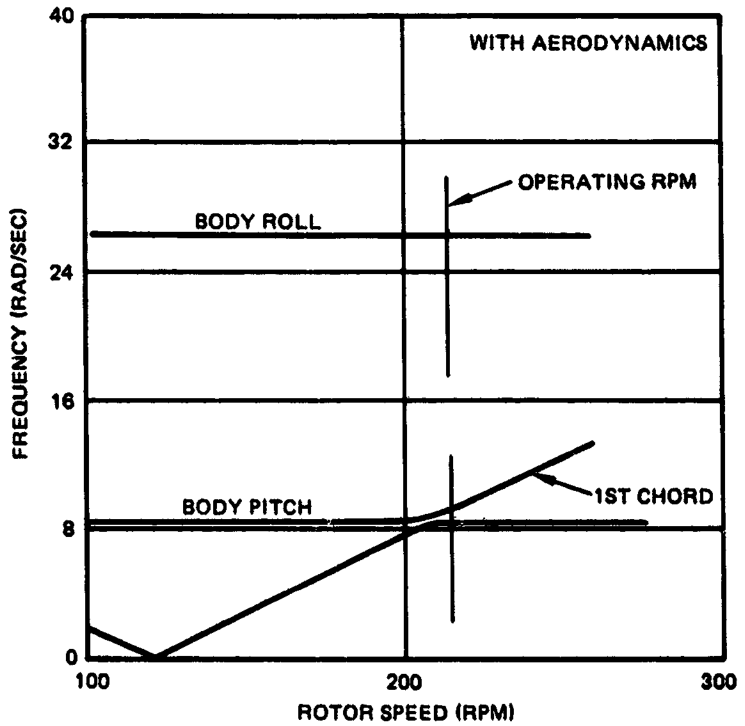


Figure 37. Flat-Strap Cruciform Installed on the RSRA, Natural Frequencies in the Fixed System

ORIGINAL PAGE IS
OF POOR QUALITY

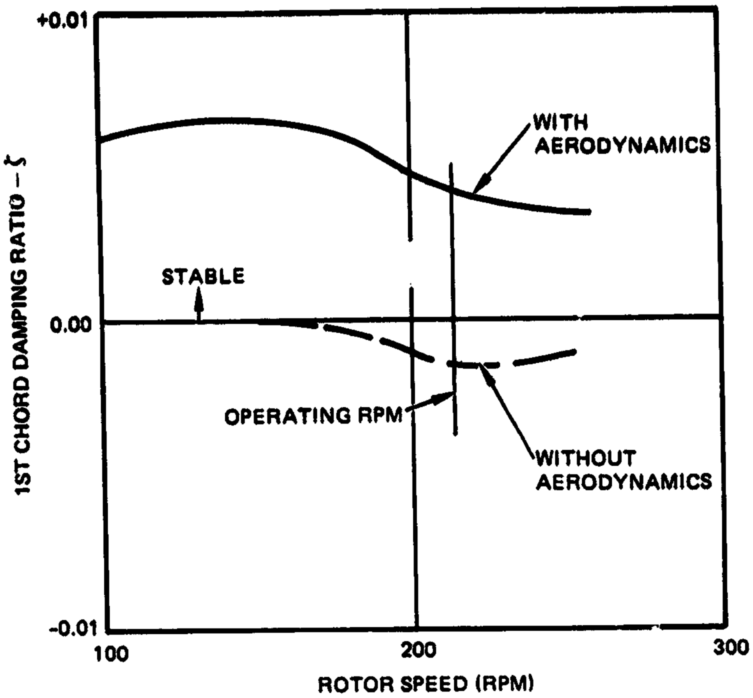


Figure 38. Inplane Damping Ratio, Flat-Strap Cruciform Installed on the RSRA

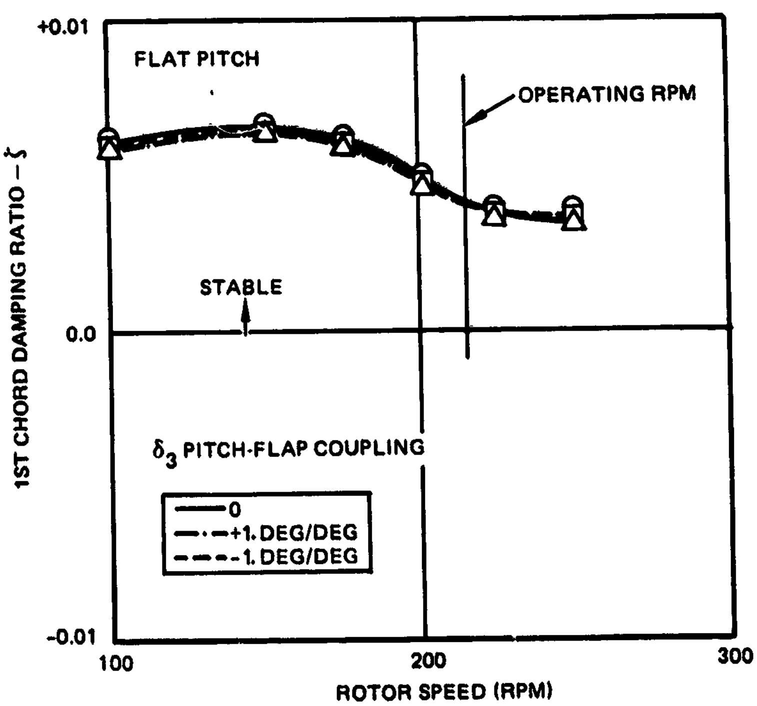


Figure 39. Effects of Pitch-Flap Couplings on Rotor Stability, Ground Resonance

ORIGINAL PAGE IS
OF POOR QUALITY

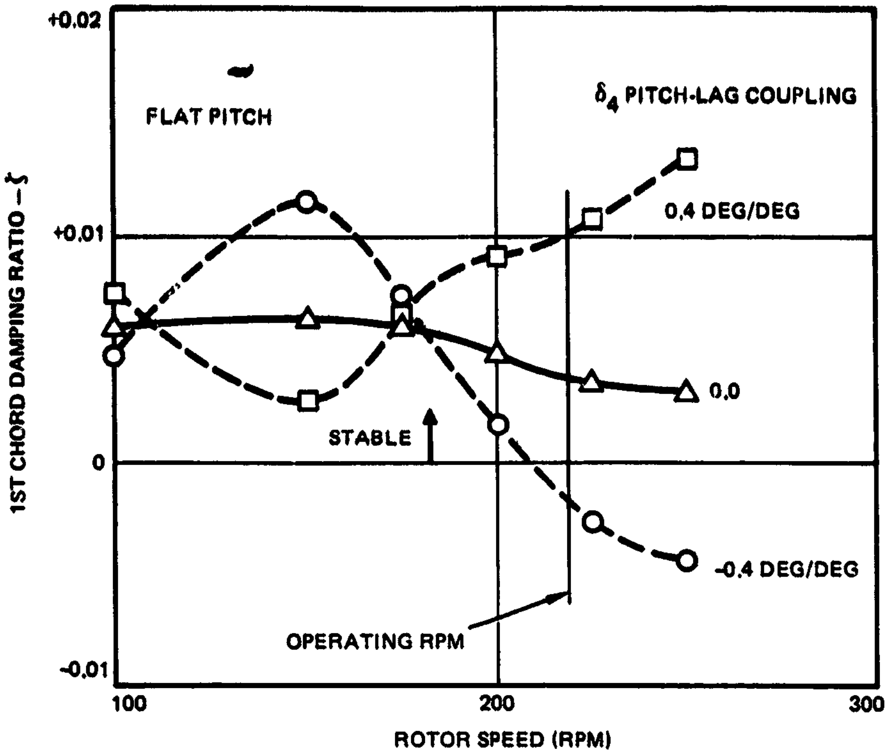


Figure 40. Effects of Pitch-Lag Couplings on Rotor Stability, Ground Resonance

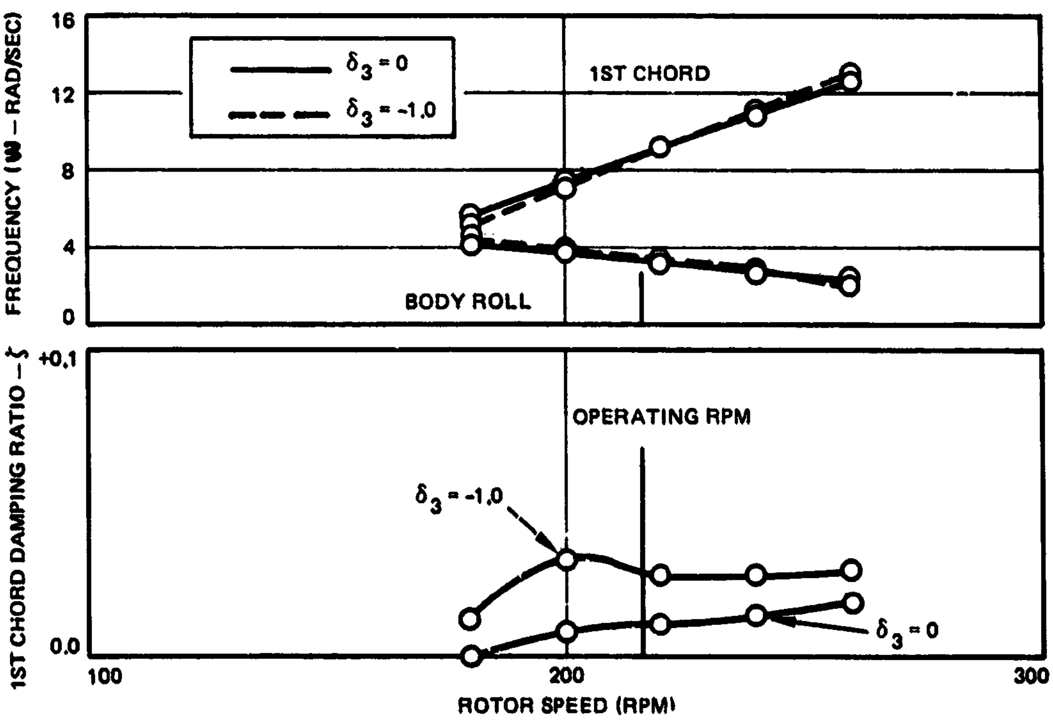


Figure 41. Effects of Pitch-Flap Couplings on Rotor Stability, Air Resonance

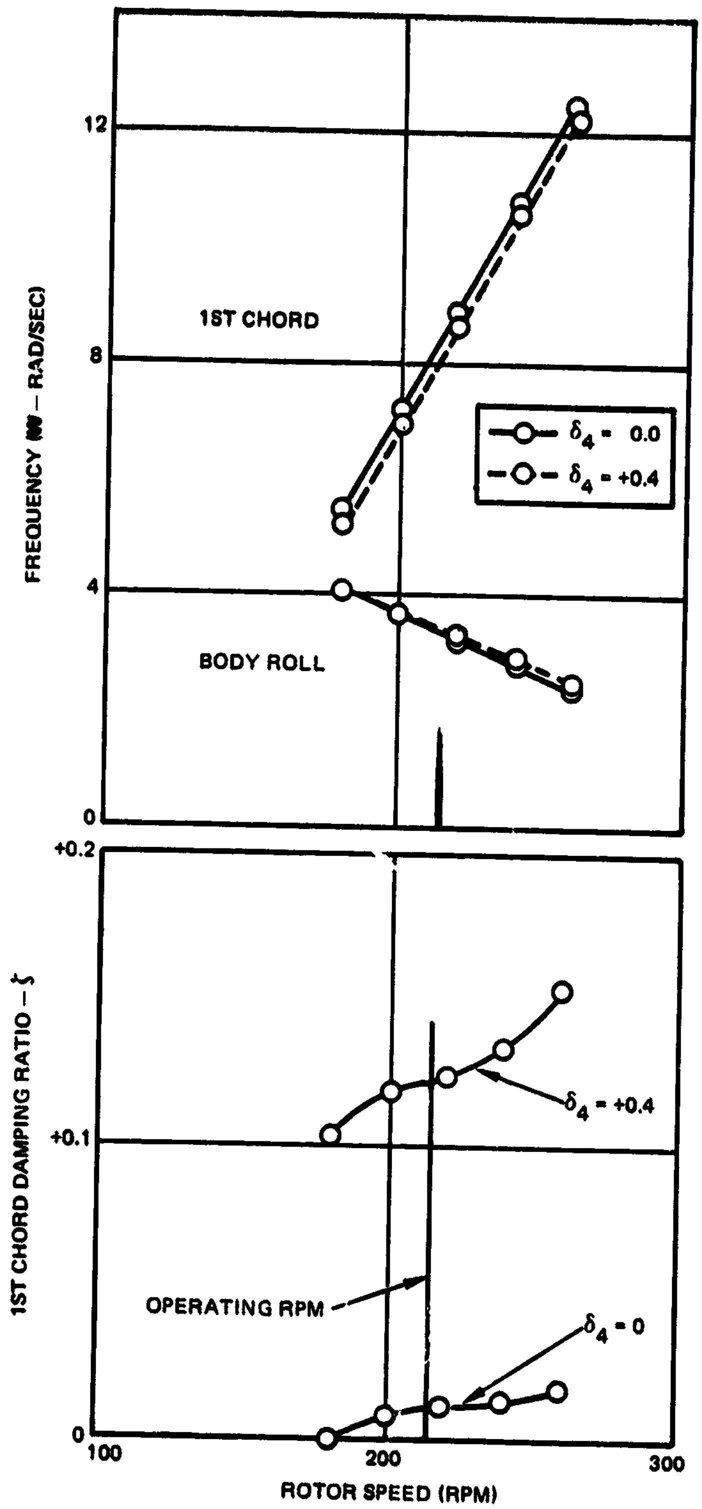
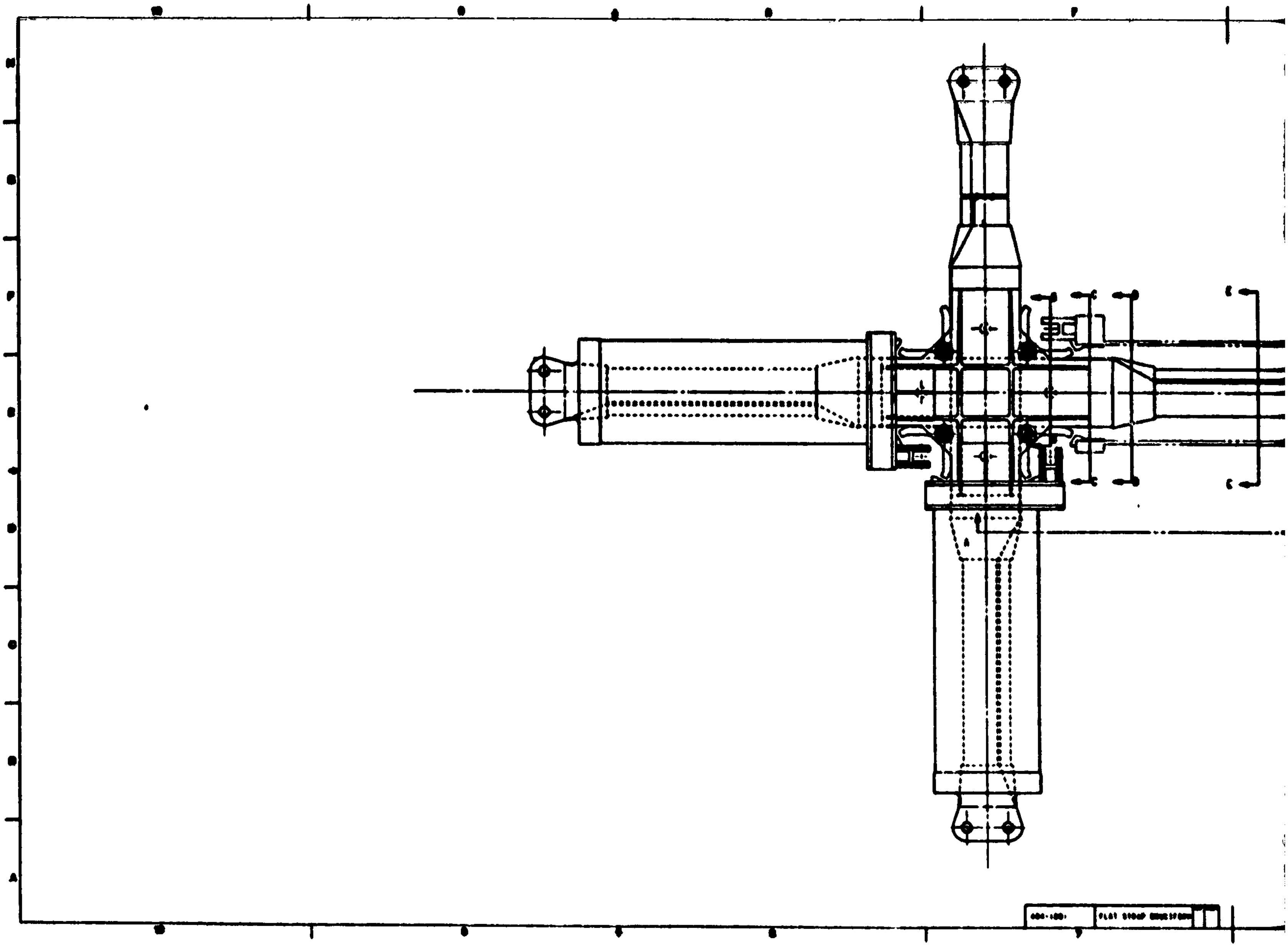


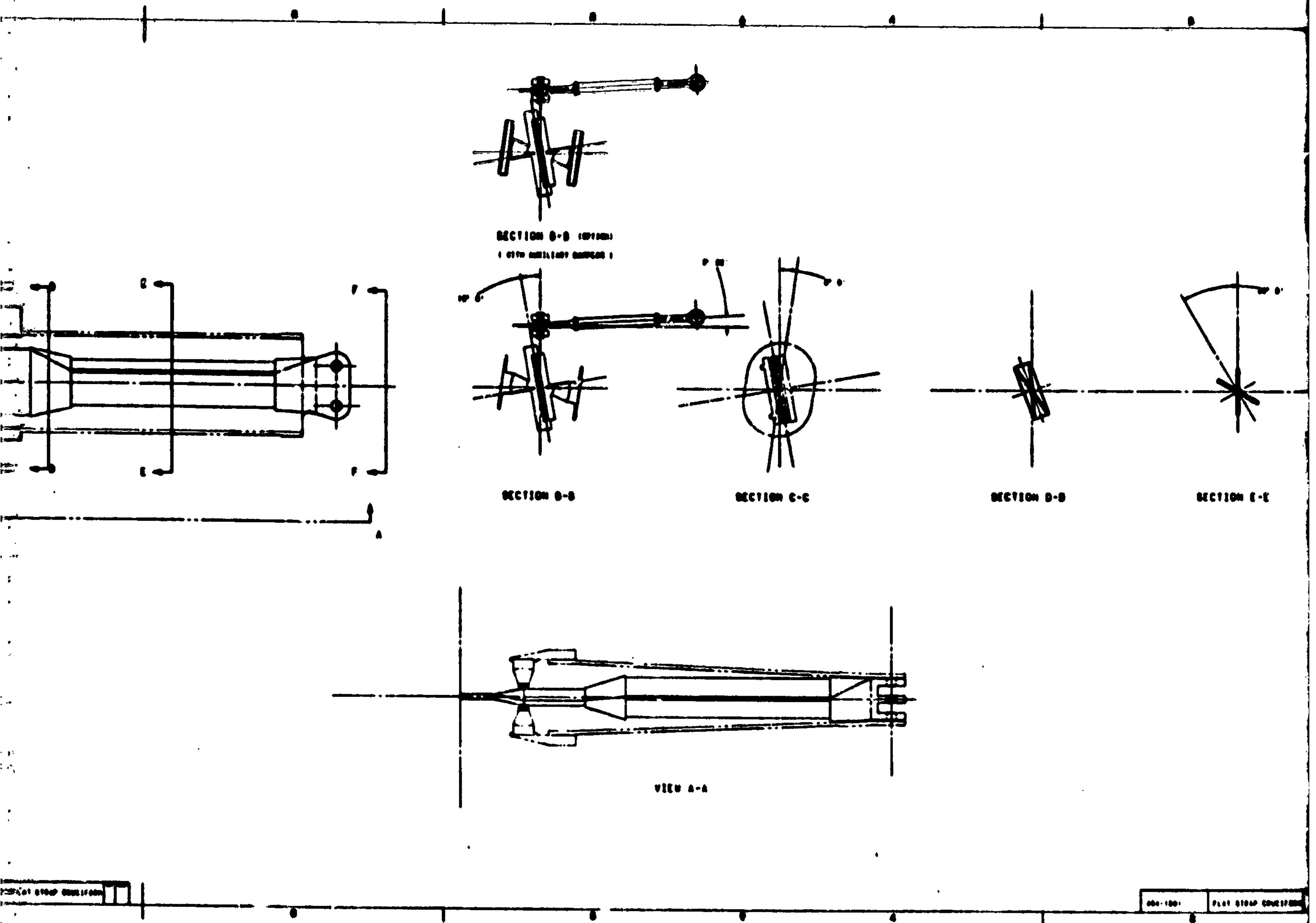
Figure 42. Effects of Pitch-Lag Couplings on Rotor Stability, Air Resonance



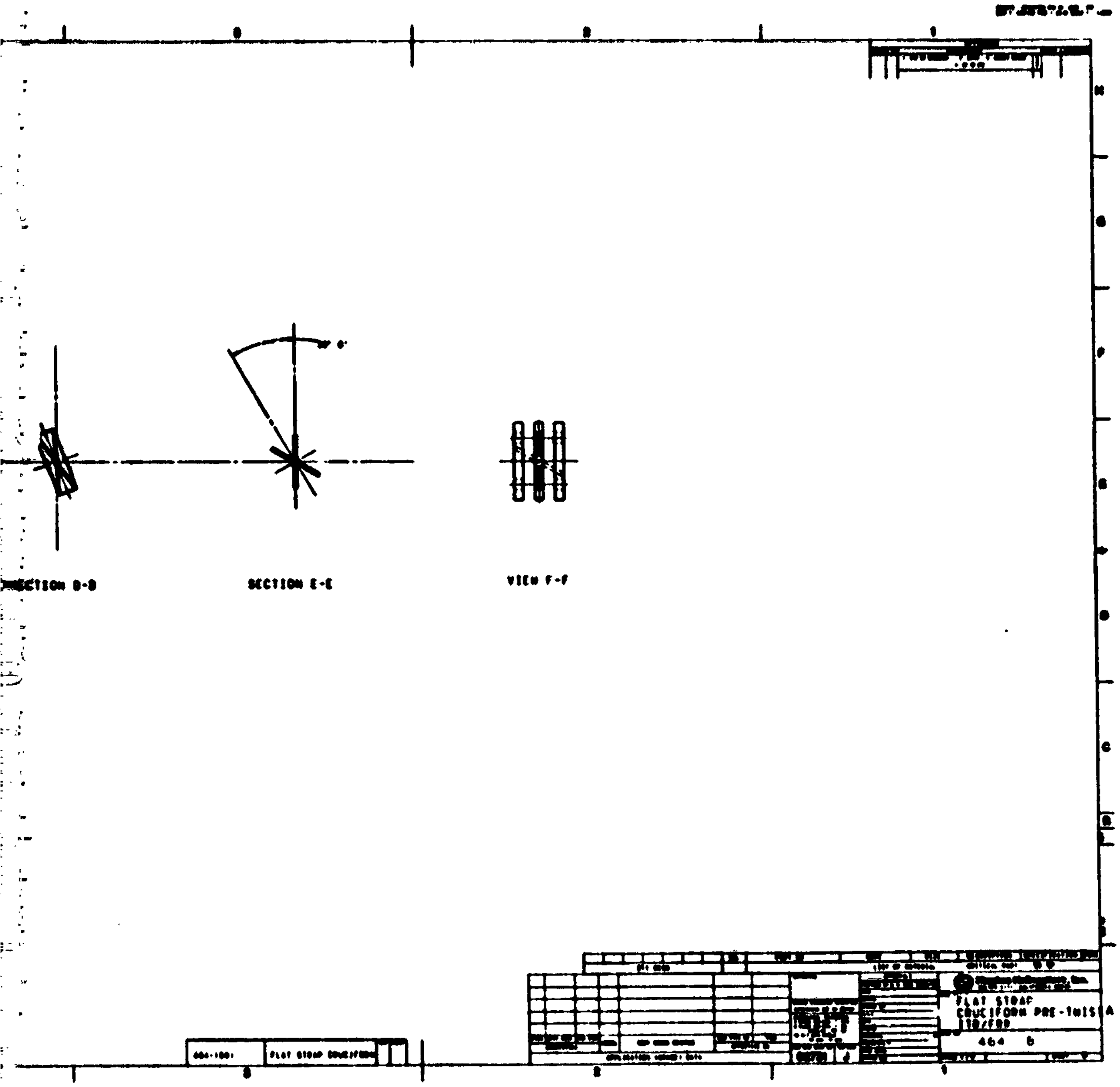
ORIGINAL PAGE IS
OF POOR QUALITY

PRECEDING PAGE BLANK NOT FILMED

Figure 43. Flat-Strap Cruciform with 30° Pre-Twist for Flap-Lag Couplings



2 FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

3 FOLDOUT FRAME

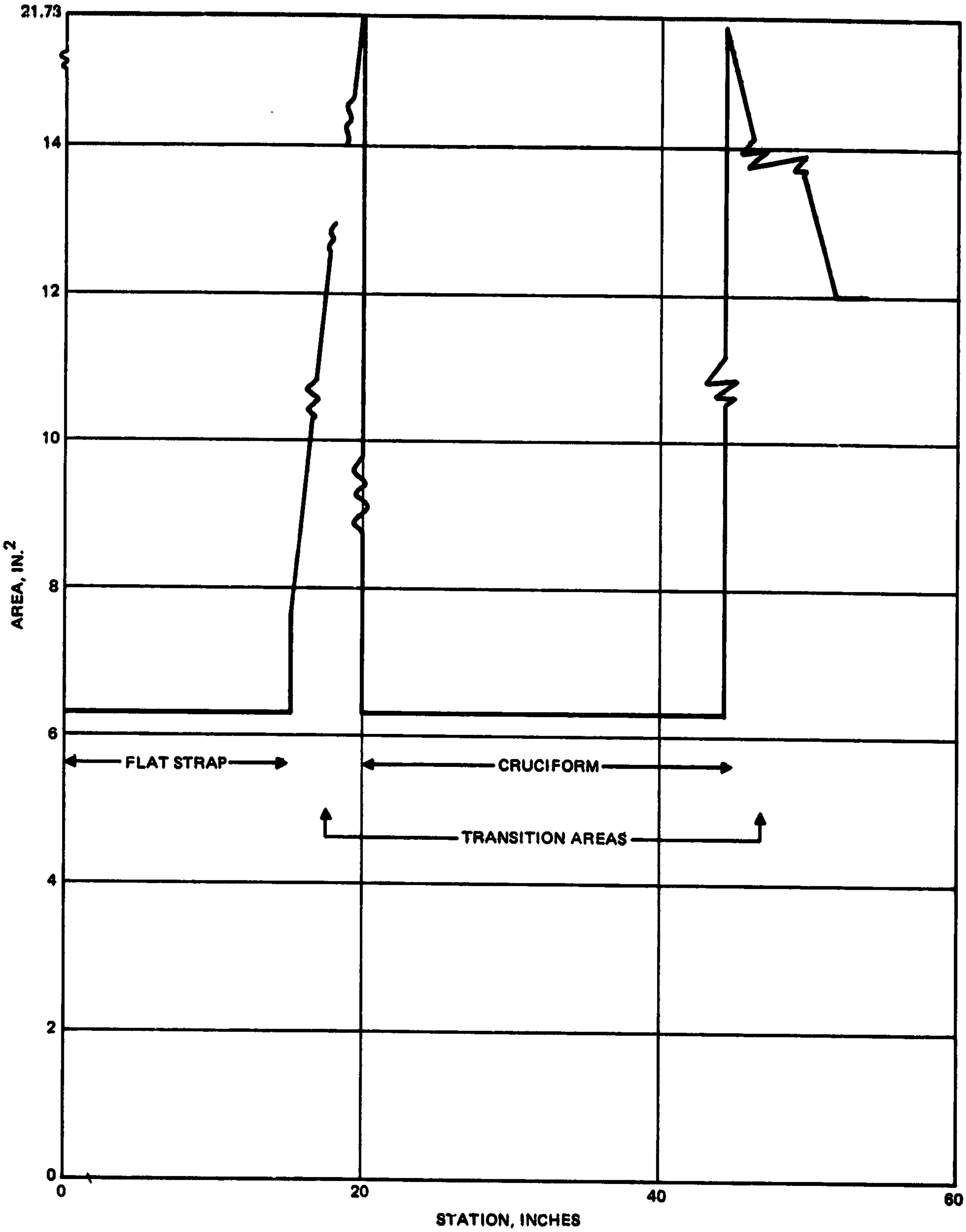


Figure 44. Cross Sectional Area of Flat-Strap Cruciform Flexure

ORIGINAL PAGE IS
OF POOR QUALITY

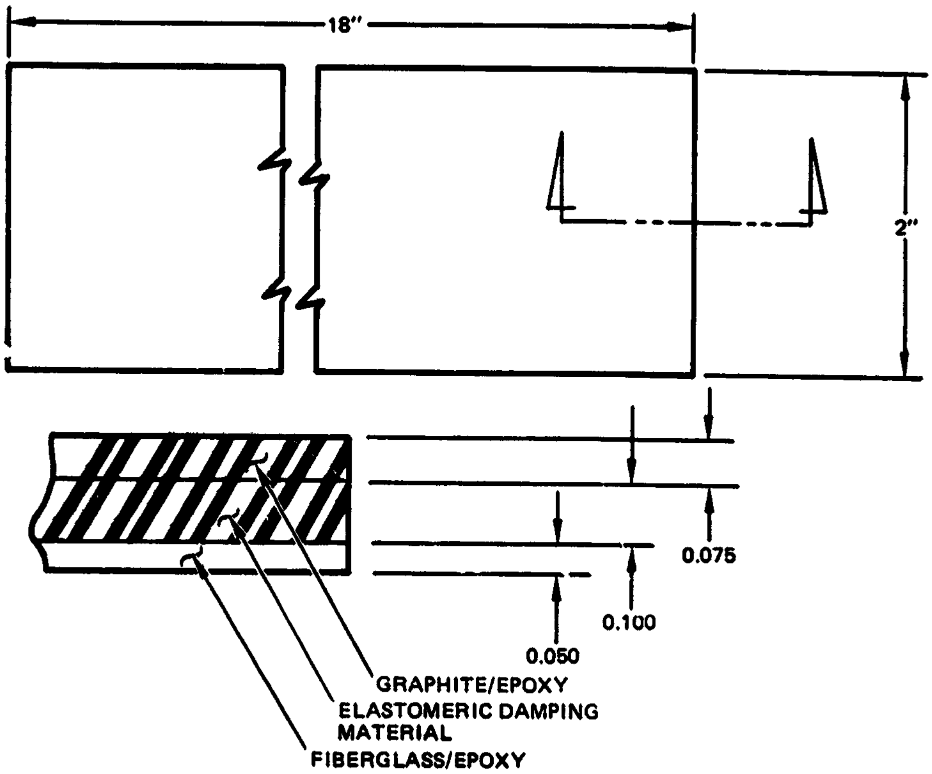
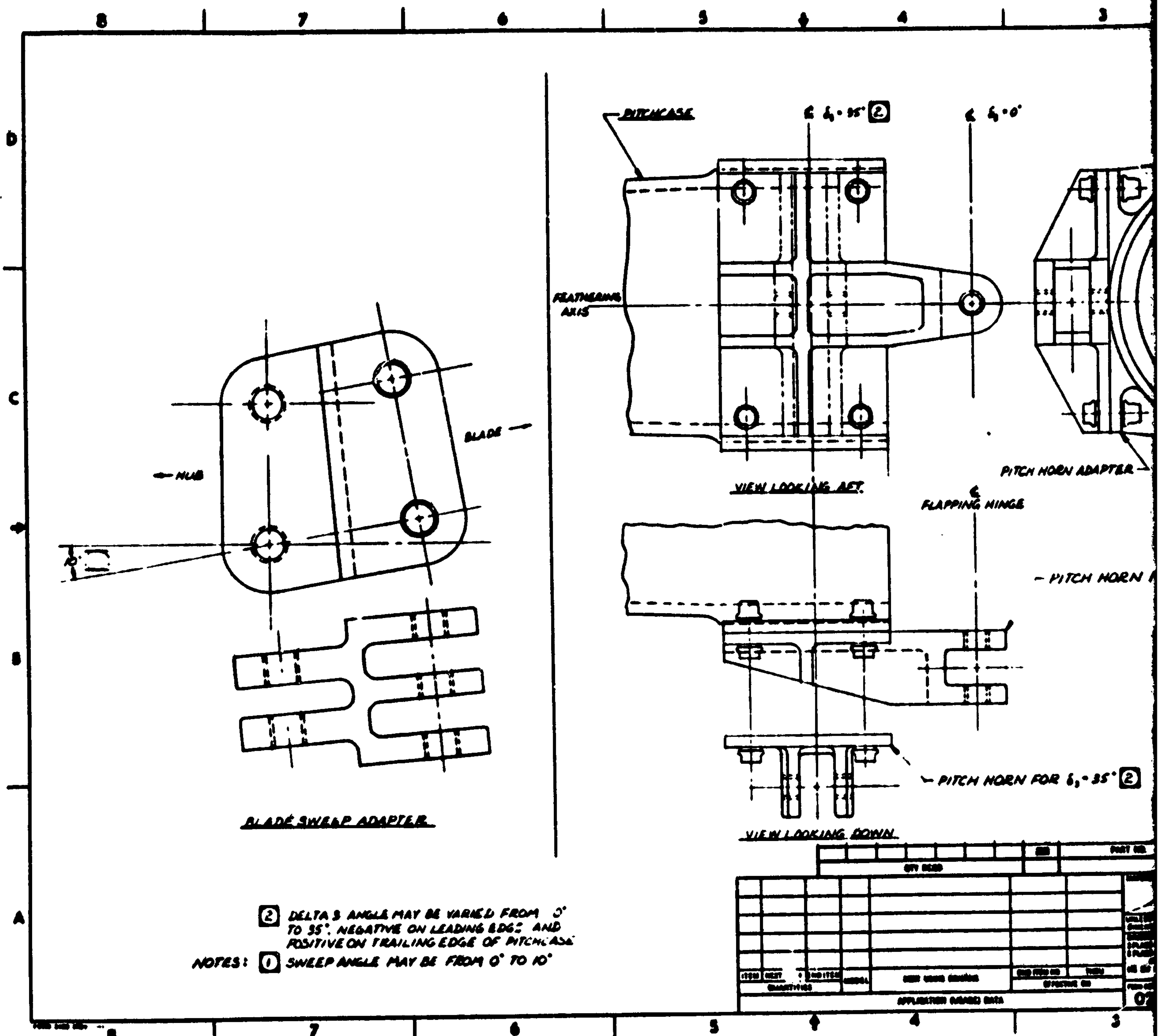


Figure 45. Auxiliary Damper Pads

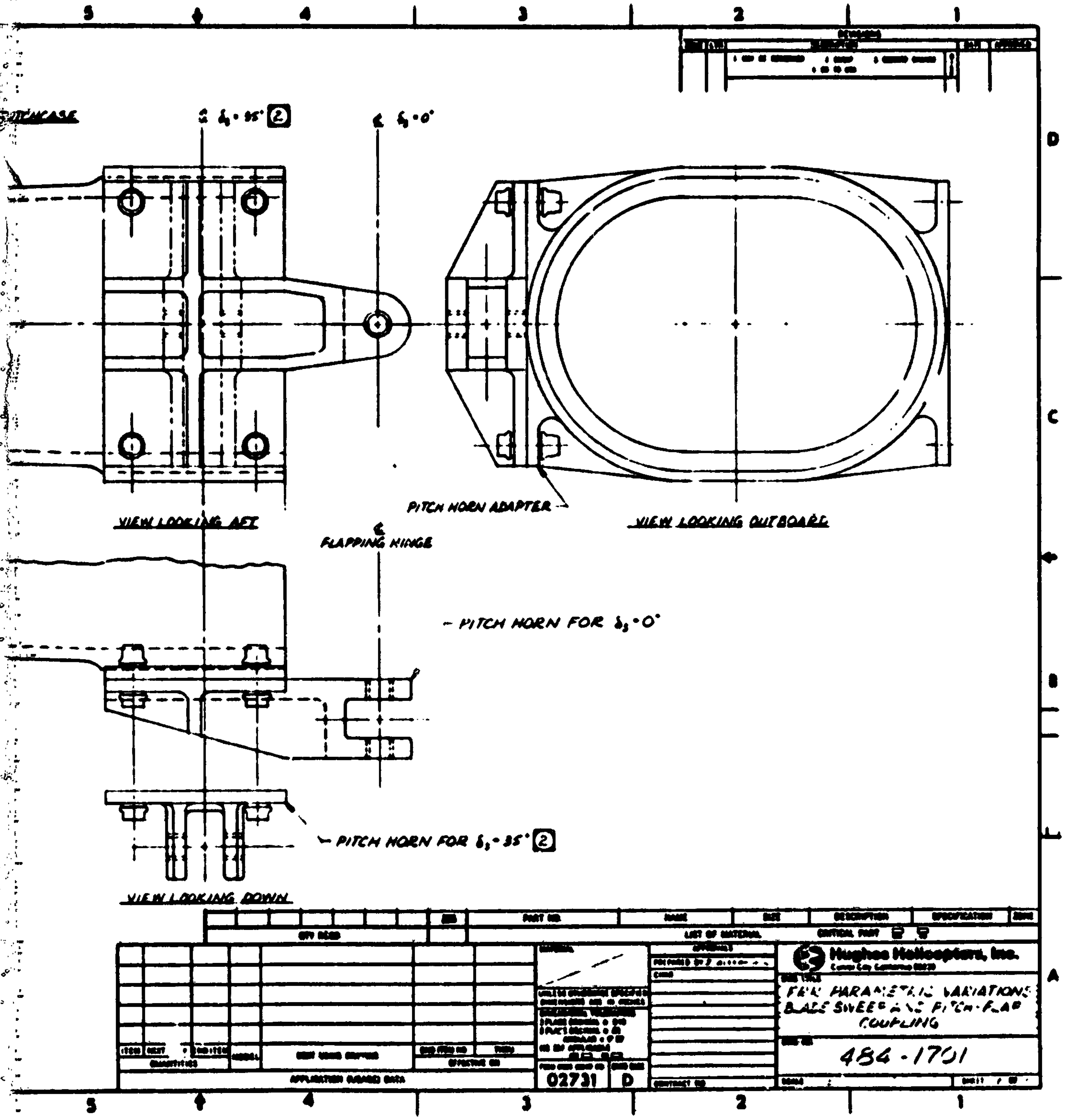


~~PRECEDING PAGE BLANK NOT FILMED~~

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 46. FRR Variations, Pitch-Flap Couplings and Blade Sweep

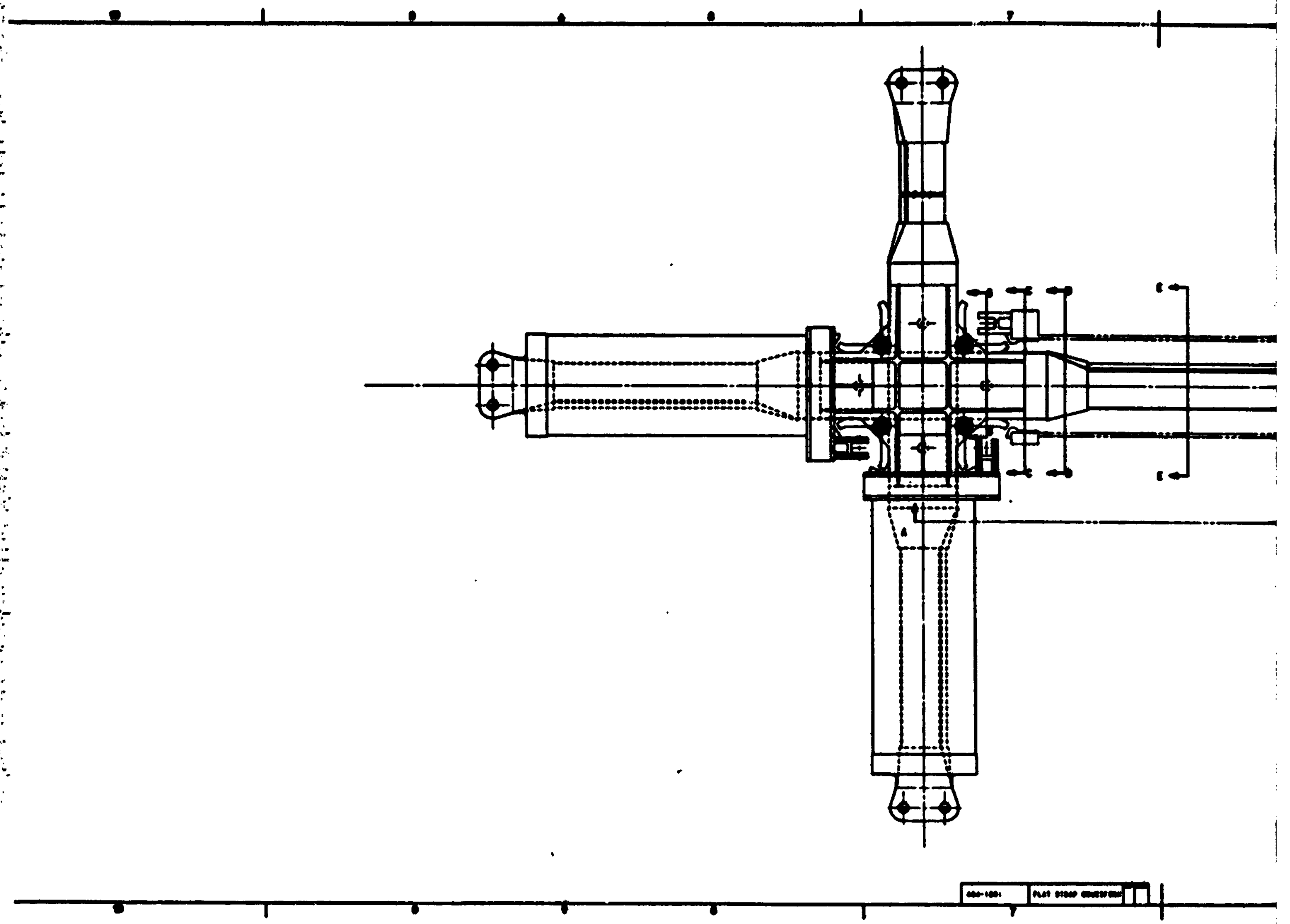
FOLDOUT FRAME



ORIGINAL PAGE IS
OF POOR QUALITY

nd Blade Sweep

2 FOLDOUT FRAME

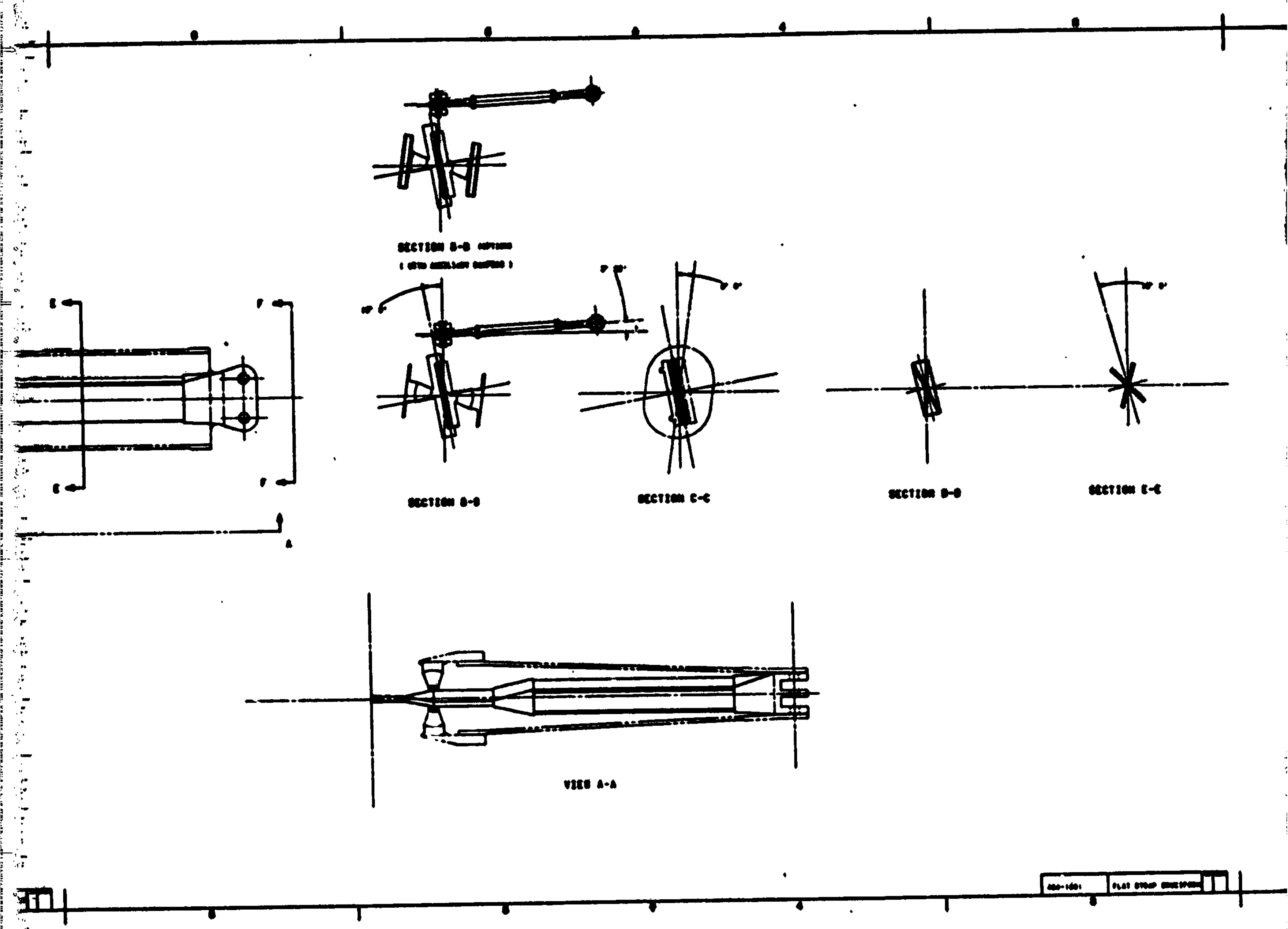


PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE IS
OF POOR QUALITY

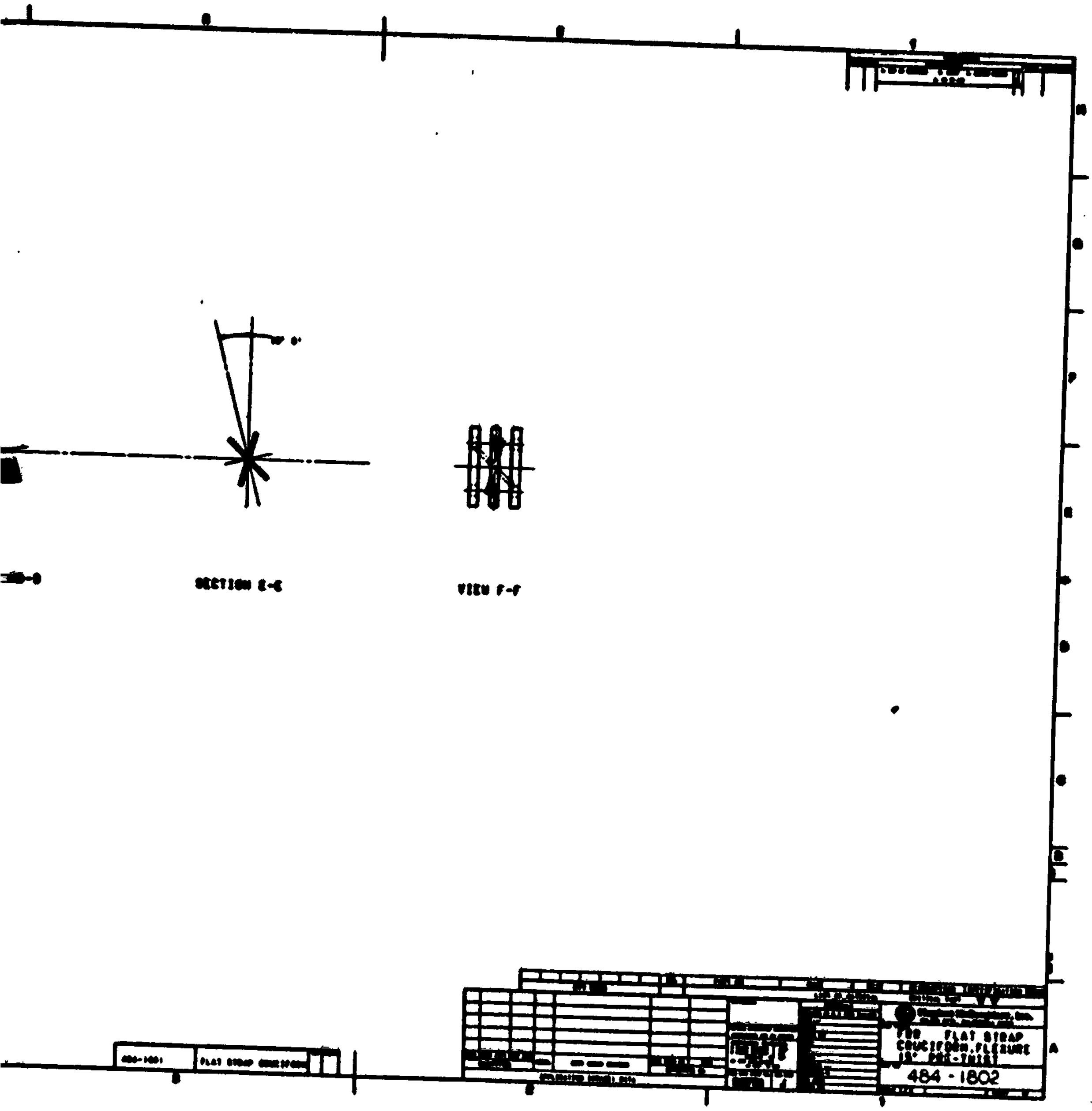
Figure 47. FRR Variation of the Flat-Strap Cruciform Concept
15° Flexure Pre-Twist

FOLDOUT FRAME



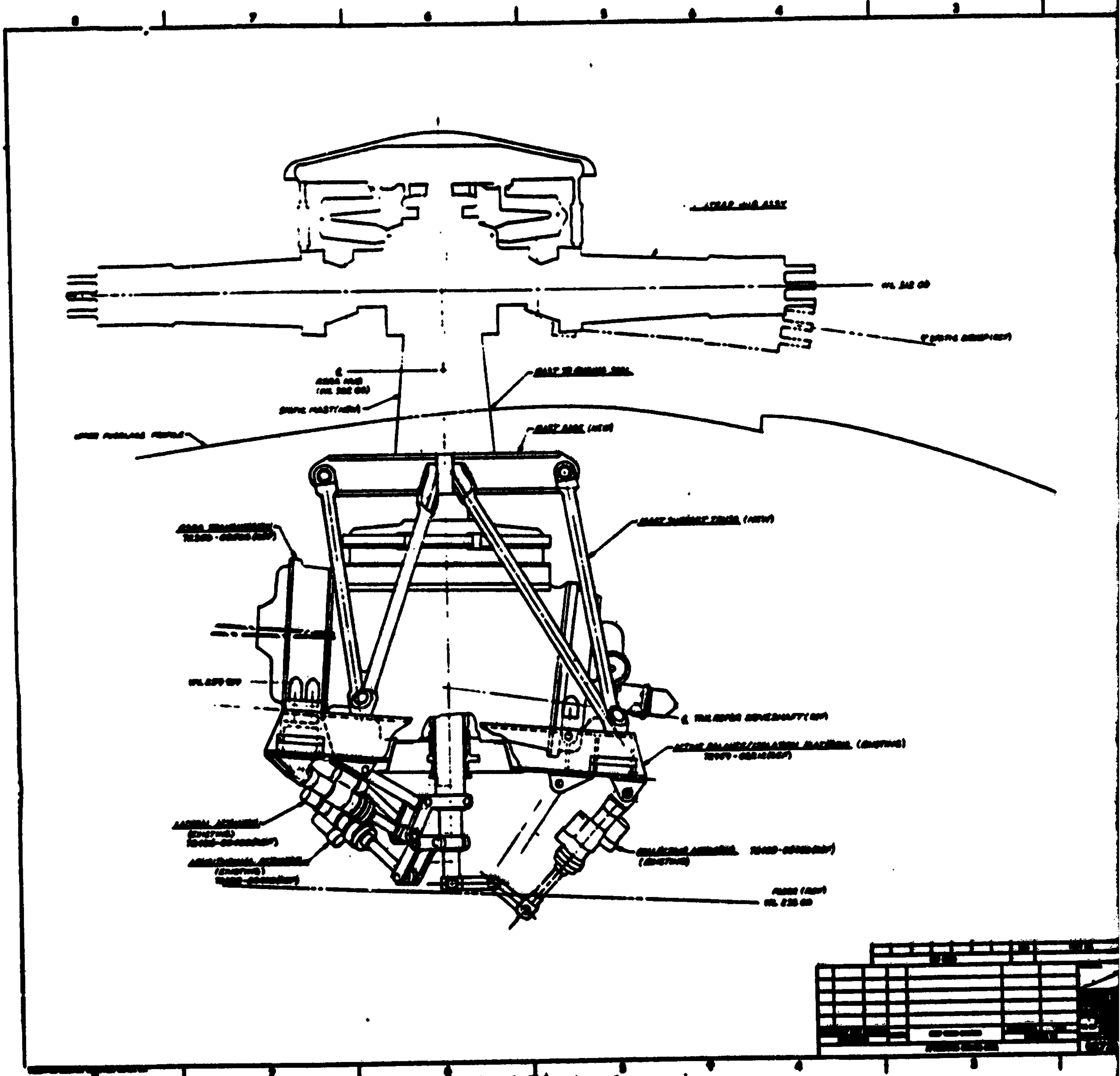
ORIGINAL PAGE IS
OF POOR QUALITY

2 FOLDOUT FRAME



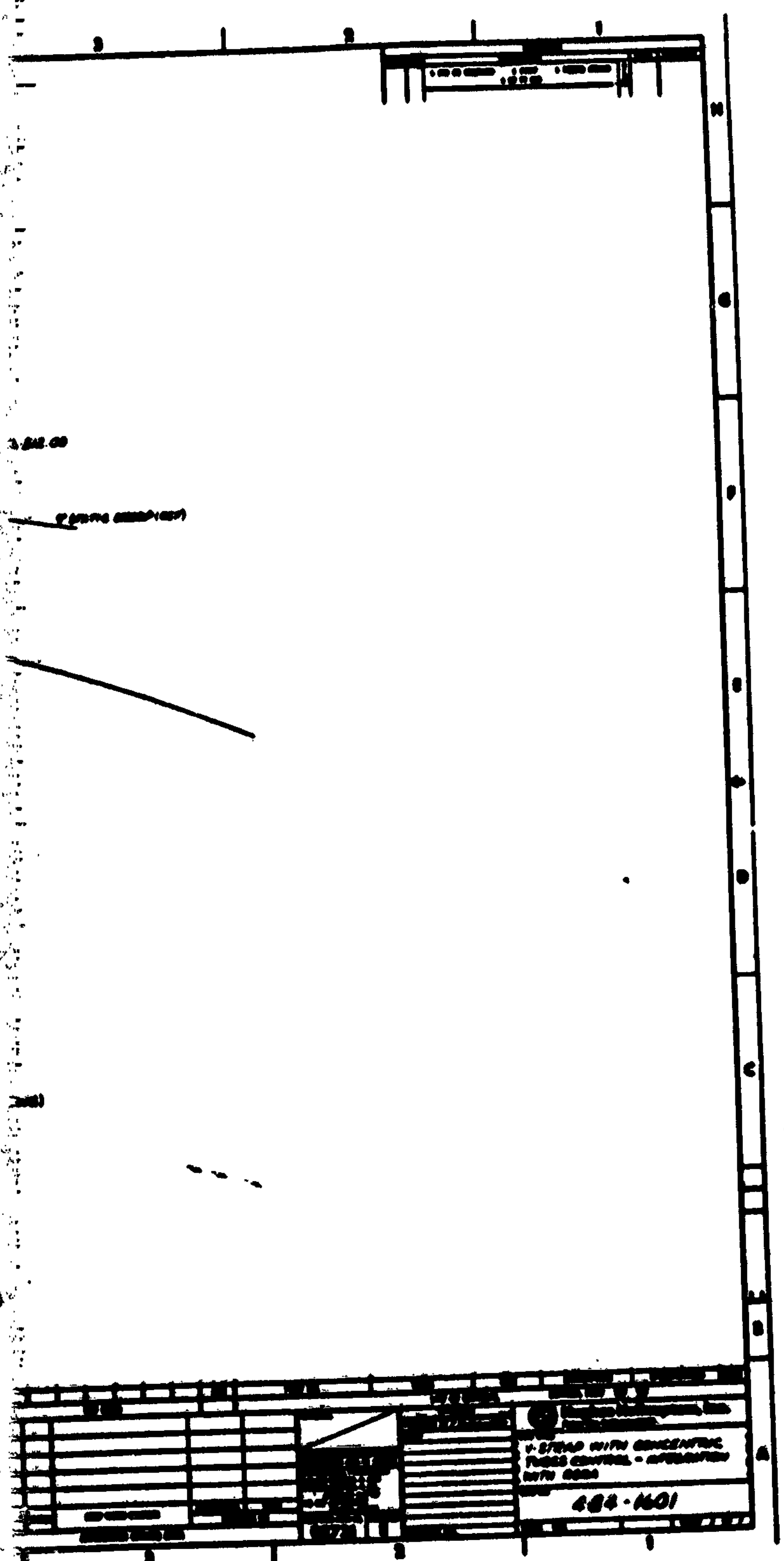
ORIGINAL PAGE IS
OF POOR QUALITY

3 FOLDOUT FRAME



PRECEDING PAGE BLANK NOT FILMED

Figure 48. ITR Integration with the RSRA, V-Strap Concept



2 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX A
ARMY/NASA — ITR/FRR PROJECT PLAN SUMMARY

The Integrated Technology Rotor/Flight Research Rotor (ITR/FRR) Project is a joint effort of the US Army Research and Technology Laboratories (USARTL) and the National Aeronautics and Space Administration (NASA). The project is for the design, construction, and flight test of three rotors employing advanced technology in their design. Two ITRs will be developed by integrating advances in the disciplines of aerodynamics, structures, materials, acoustics and dynamics to provide improvements over a wide spectrum of parameters from rotor performance, fuel economy, noise and vibration to reliability, maintainability, and cost. The FRR will be a modified version of one of the ITRs and will be designed to provide configuration versatility and comprehensive instrumentation so that technology enhancements for increasing capabilities beyond that of the ITR technology can be investigated on the Rotor Systems Research Aircraft (RSRA).

The project is composed of four phases: (1) Predesign Studies, (2) Preliminary Design, (3) Detail Design and Fabrication, and (4) Demonstration and Test. The Predesign Studies Phase includes contracted studies relative to critical technologies for ITR and FRR design, and will conclude with competitive Concept Definition Studies of candidate ITR/FRR hub designs. Following Concept Definition, competitive contracts for the Preliminary Design Phase will be awarded. For the Detail Design and Fabrication Phase one contract will be awarded for a single ITR and another contract will be awarded for an ITR and a comparison FRR rotor. The Demonstration and Test Phase will include an airworthiness and flight envelope demonstration for the three rotors, a demonstration phase for the two ITR designs to determine the degree to which the technical objectives are met, and an evaluation phase of the FRR design.

ITR/FRR OBJECTIVES

The overall objectives of the Army/NASA ITR/FRR Project are as follows:

- To demonstrate a significant advance in rotor systems technology through the integration of the disciplines of rotor design, aerodynamics, structures and materials, dynamics and acoustics. The demonstration will show the potential for reduced life cycle costs;

~~PRECEDING PAGE BLANK NOT FILMED~~

Preceding page Blank not Filmed

that reliability, maintainability, and survivability will be improved, that performance characteristics such as rotor L/D, fuel consumption, high speed maneuverability, agility and handling qualities are improved; and rotor weight, rotor noise and vibratory loads are reduced.

b. To demonstrate the improved technology to the extent that the major risks are removed, and to transfer this technology to industry for use in engineering development or product improvement programs.

c. To provide an advanced technology rotor, fully instrumented, having the capability for significant variation in rotor properties. This rotor will provide the capability to generate an expanded data base, and investigate further advances in rotor technology.

ITR TECHNICAL GOALS

One of the purposes of the ITR/FRR program is to stimulate the advance of rotor system technology to the maximum possible extent. While it is not appropriate to specify the degree of advancement as a requirement, reasonable technology goals can be defined to help stimulate and guide the technical thrust of the design. In what follows, where mention is made of vehicle system parameters or operating conditions, they are based on a design gross weight of 16,000 pounds, a vehicle flat plate drag area of 15.0 ft^2, and 4,000 foot pressure altitude, 95° F conditions. Where technical goals are specified with respect to a baseline value, the baseline is taken to be the value corresponding to the UH-60 aircraft at 16,000 pounds gross weight.

a.	Maximum rotor equivalent lift-to-drag ratio, without hub drag, L/D_e, at V_{Cruise}.	10.5
b.	Maximum rotor figures of merit, rotor alone.	0.80
c.	Rotor hub flat plate drag area for a design gross weight of 16,000 pounds; for other values of the design gross weight, the goal for hub area is assumed to scale with the 2/3 power of the design gross weight.	2.8 ft^2

d. V_{Cruise} using MCP of the powerplants required to meet the VROC performance capability specified in the System Design Specifications. For design gross weights different from 16,000 pounds the flat plate drag area is assumed to scale with the 2/3 power of the design gross weight.	170 KTAS
e. V_{Dash} using IRP of the powerplants required to meet the VROC performance capability specified in the System Design Specifications. For design gross weights different from 16,000 pounds the flat plate drag area is assumed to scale with the 2/3 power of the design gross weight.	185 KTAS
f. Reduction in low frequency impulsive noise from baseline (0 to 1000 Hz) when measured directly ahead of the helicopter in the plane of the rotor and when operating at an advancing tip Mach number of 0.9.	6 dB
g. Rotor weight as a percentage of design gross weight.	7.0
h. Rotor system parts count.	75
i. Rotor system fatigue life.	10,000 hours
j. Mean-time-between-removal (MTBR)	1,500 hours
k. A vibration acceleration level based on a hypothetical estimate obtained by applying 4P hub vibratory forces and moments to a rigid body fuselage without anti-vibration devices. This vibration goal is defined within a volume extending to one-half the rotor radius in front and behind the center of the rotor, one-quarter of the rotor radius below the plane of the rotor, and one-quarter of the rotor radius	0.1g

laterally on either side of the rotor. The mass and inertia of the assumed rigid fuselage are to be taken equal to the baseline aircraft values or scaled appropriate if the design gross weight differs from 16, 000 pounds.

l. The ITR rotor system will be designed to provide the lowest possible procurement cost for future production rotors based on ITR technology, without unduly compromising other cost factors that impact optimum life cycle costs.

ITR SYSTEM DESIGN SPECIFICATIONS

The following system design specifications are intended to establish a minimum set of operating conditions and other design constraints to be used to guide the design of the ITR.

a. Design Gross Weight

The ITR design gross weight shall be not less than 16, 000 pounds and not more than 23, 000 pounds. The specification requires that the ITR rotor be designed to have the thrust capability to permit the vehicle to hover OGE at 4, 000 ft pressure altitude and 95° F with a total vehicle weight equal to the design gross weight plus a 10 percent fuselage download penalty.

b. Design Envelopes

For the purposes of the rotor design, the structural design envelope is +3.50g and -0.5g. The envelopes are shown in Figure A-1. Slope landing conditions up to and including 12 degrees shall be accommodated.

c. Rotor System Instability

The rotor and test aircraft shall be free of critical aeroelastic instability and mechanical instability at all operating conditions and throughout a typical range of gross weights. For the purpose of air/ground resonance instability, the rotor hub design requirements shall be consistent with fuselage and blade mass and inertia characteristics typical of the design gross weight.

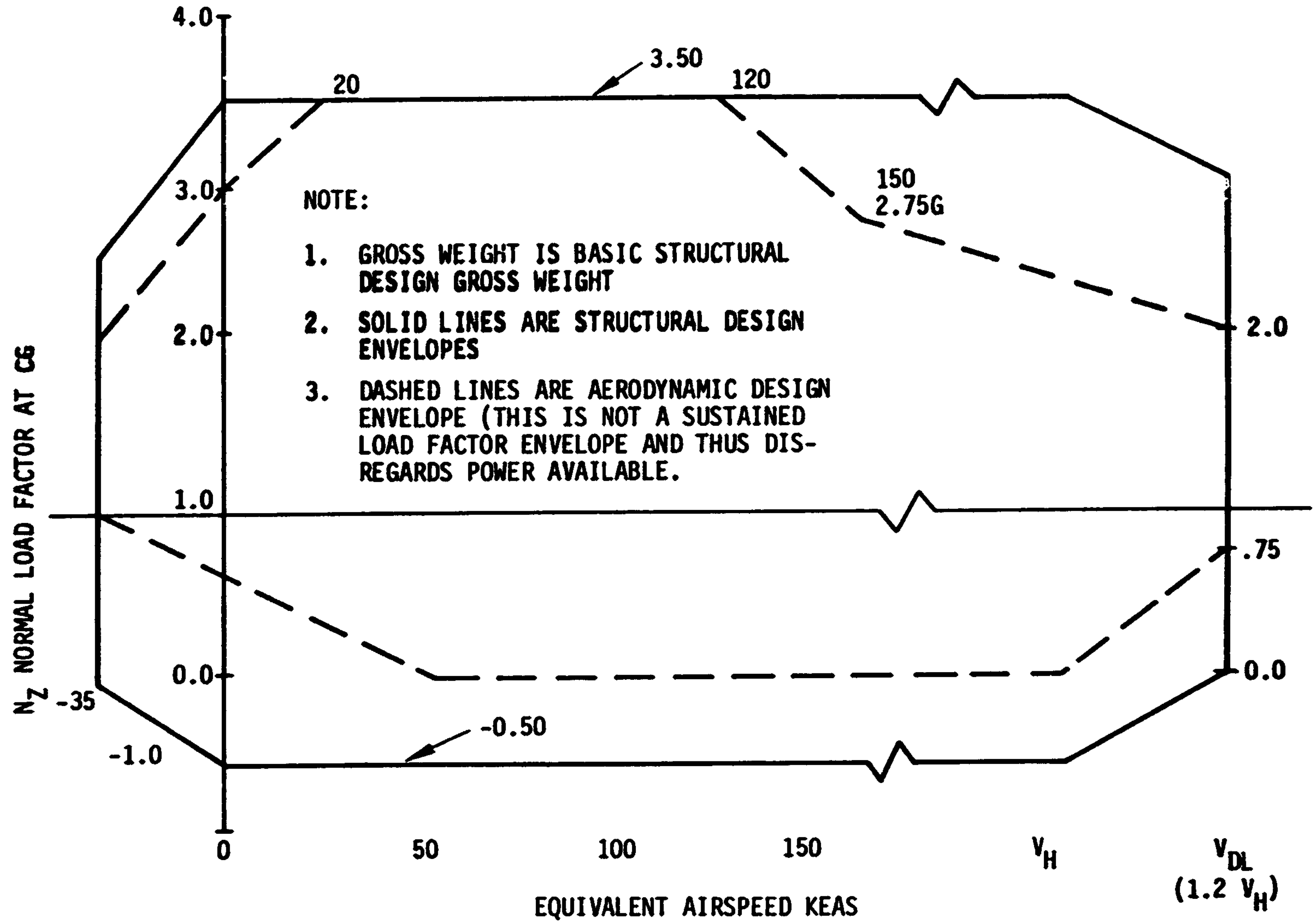


Figure A-1. Design Envelopes

d. Rotor Configuration

It is desired that the rotor be a four-bladed system. The hub design shall not preclude the incorporation of normal operational requirements for simple and quick manual blade folding and blade removal or replacement which does not require retracking or rebalancing. The blade design concept shall not be so restrictive or unconventional that it would be incompatible with the incorporation of provisions for meeting normal operational requirements including rain, ice, dust, and sand erosion, and lightning protection. Furthermore, the blade design concept shall not be incompatible with provisions for surviving limited tree strikes (one-inch pine branches), wire strikes (0.25-inch copper nonshielded wires), and combat damage (minimum probability of catastrophic failure following hit by a small HEI projectile).

e. Maneuverability

The aircraft shall provide the following capabilities at 4,000 feet pressure altitude, 95° F temperature, and at the design gross weight. From a level, unaccelerated flight condition at 170 KTAS, it shall be possible to attain, within 1.0 second from the initial control input, a sustained load factor of 1.75g in a symmetrical pullup. Following this load factor buildup, it shall be possible to maintain a minimum load factor of 1.75g for 3.0 seconds after the initial attainment of 1.75g. Airspeed at the end of the 1.75g, 3.0 seconds duration segment of the maneuver shall not be less than 140 KTAS. It shall be possible to attain, within 1.0 second from the initial control input, a sustained load factor of -0.25g in a pushover. Following the attainment of this load factor, it shall be possible to maintain a load factor of -0.25g for 2.0 seconds. At no time during either the pullup or pushover maneuvers described above shall angular deviations in roll and yaw greater than +10° from the initial unaccelerated level flight conditions be permitted.

f. Flight Test Aircraft

The ITR/FRR will be demonstrated in flight on a Contractor furnished aircraft, a Government bailed aircraft, or the RSRA. The Contractor will be free to propose the option of his choice. In the event the RSRA is not used for the demonstration testing, the Army may choose to carry out additional testing of the ITR on the RSRA. In any event, the Army and NASA intend to do research testing of the ITR and FRR on the RSRA.

APPENDIX B
ARMY/NASA – ROTOR HUB DESIGN SPECIFICATIONS

The following rotor hub design specifications establish minimum requirements to be used to guide the design of the rotor hub. The hub design specifications have been derived from the ITR System Design Specifications, specialized as appropriate for the development of hub components within the scope of the Concept Definition work.

DESIGN GROSS WEIGHT

The ITR design gross weight shall be not less than 16,000 pounds and not more than 23,000 pounds. The specification requires that the ITR rotor be designed to have the thrust capability to permit the vehicle to hover OGE at 4,000 feet pressure altitude and 95° F with a total vehicle weight equal to the design gross weight plus a 10 percent fuselage download penalty.

DESIGN ENVELOPE

For the purposes of the rotor hub design, the structural design envelope is +3.50g and -0.5g. Slope landing conditions up to and including 12 degrees shall be accommodated.

ROTOR SYSTEM INSTABILITY

The rotor and test aircraft shall be free of critical aeroelastic instability mechanical instability at all operating conditions and throughout a typical range of gross weights. For the purpose of air/ground resonance instability, the rotor hub design requirements shall be consistent with fuselage and blade mass and inertia characteristics typical of the design gross weight.

ROTOR HUB CONFIGURATION

It is desired that the rotor be a four-bladed system. The hub design shall not preclude the incorporation of normal operational requirements for simple and quick manual blade folding and blade removal or replacement which does not require retracking or rebalancing. The hub design concept shall not be so restrictive or unconventional that it would be incompatible with the incorporation of provisions for surviving limited wire strikes (0.25-inch copper nonshielded wires), and combat damage (minimum probability of catastrophic failure following hit by a small HEI projectile).

One of the purposes of the ITR/FRR Program is to stimulate the advance of rotor system technology to the maximum possible extent. While it is not intended to specify the degree of advancement as a requirement, reasonable technical goals can be defined to stimulate and guide the technical thrust of the Concept Definition work. Where the following properties are dependent on rotor vehicle system parameters they are based on a design gross weight of 16,000 pounds.

a.	Rotor hub flat plate drag area for a design gross weight of 16,000 pounds; for other values of the design gross weight, the goal for hub area is assumed to scale with the 2/3 power of the design gross weight.	2.8 ft^2
b.	Rotor hub weight as a percentage of design gross weight.	2.5 percent
c.	Rotor hub system parts count, exclusive of standard fasteners.	50
d.	Rotor hub moment stiffness. Defined by the moment in foot-pounds, acting at the center of the hub, per unit angular rotation in radians of the rotor disc about an axis perpendicular to the rotor shaft axis. The rotor disc is defined by the circle inscribed by hypothetical rigid blade tips. The goal is specified for a design gross weight of 16,000 pounds; for other values of the design gross weight, the rotor hub moment stiffness goal is scaled in direct proportion to the design gross weight.	100,00 ft-lb/radian
e.	Minimum rotor hub moment. The minimum rotor hub moment in ft-lb, acting at the center of the rotor hub, below which fatigue damage will not be incurred by the hub; for a design	10,000 ft-lb

gross weight of 16,000 pounds. For other values of the design gross weight, the minimum rotor hub moment goal is scaled in direct proportion to the design gross weight.

f.	Minimum rotor hub tilt angle. The minimum rotor disc angle defined in paragraph (d) above, below which fatigue damage will not be incurred by the rotor hub.	5 degrees
g.	Auxiliary lead-lag damping. The goal of the ITR is to develop a rotor system that does not require auxiliary hydraulic or elastomeric damper components incorporated in the hub. It is desirable to have the potential of incorporating some form of additional damping, if at some later stage in the development process it appears prudent to do so in order to solve an emerging stability problem.	–
h.	Torsional stiffness. The technical goal is to develop a rotor hub system that does not require substantially more blade pitch control actuator force than required by current rotor systems.	–
i.	Rotor hub system fatigue life.	10,000 hours
j.	Reliability. Mean-time-between-removal (MTBR) for the hub.	3000 hours
k.	Manufacturing cost. The ITR rotor system will be designed to provide the lowest possible procurement cost for future production rotors based on ITR technology, without unduly compromising other cost factors that impact optimum life cycle costs.	–

APPENDIX C
ARMY/NASA – MERIT FACTORS/MERIT FUNCTION

	Parameter	Merit Factor
a.	Vulnerability to a small HEI projectile	K_v – probability of surviving hit
b.	Risk of aeromechanical instability	K_a – probability that rotor system will be free from air/ground resonance instability
c.	Hub drag area	K_d – % reduction from technical goal
d.	Hub weight	K_w – % reduction from technical goal
e.	Parts counts	K_p – % reduction from technical goal
f.	Rotor hub moment stiffness	K_e – equal to 5 if rotor hub moment stiffness is within ±20% of the technical goal. K_e is reduced from 5 by one-tenth of the percentage that the parameter exceeds a ±20% margin from the goal
g.	Minimum rotor hub moment	K_m – one half of the percentage by which the parameter exceeds the technical goal
h.	Minimum rotor hub tilt angle	K_b – one half of the percentage by which the parameter exceeds the technical goal

ORIGINAL PAGE IS OF POOR QUALITY

Parameter	Merit Factor
i. Reliability	K_r — ten times the probability of meeting or exceeding technical goal* for MTBF
j. Manufacturing cost	K_c — qualitative estimate from 1 to 10, varying inversely with expected cost
k. Fatigue life	K_f — ten times the probability of meeting or exceeding the technical goal*
l. Auxiliary lead-lag damping	K_z — 0 to 2, qualitative estimate of practicality of incorporating auxiliary damping
m. Torsional stiffness	K_s — if pitch control system forces exceeds of 1.5 times typical pitch bearing hub K_s = -2; if forces less than this level, K_s = 0

$$\text{Merit Function} = K_v \times K_a \times (K_d + K_w + K_p + K_e + K_m + K_b + K_r + K_c + K_f + K_z + K_s)$$

*Technical goals refer to values given in Appendix B, Army/NASA-Rotor Hub Design Specifications.

APPENDIX D
HHI ASSESSMENT OF ITR/FRR PROJECT PLAN SUMMARY, ROTOR HUB DESIGN SPECIFICATIONS AND MERIT FACTORS/MERIT FUNCTION

This appendix presents the work conducted by Hughes Helicopters, Inc. under Task I, Review Goals and Specifications, of the ITR/FRR Concept Definition Contract. HHI reviewed the ITR System Design Specifications in Appendix A (of the SOW), Technical Goals in Appendix B, and the Merit Factor/Merit Function of Appendix C. In addition, HHI determined a representative set of helicopter characteristics and operating conditions for estimating rotor hub design loads.

The operating conditions are shown in Table D-1. These conditions were based on the design criteria for the AH-64, but the conditions are representative of a high performance military helicopter. HHI chose the RSRA as the baseline helicopter for the hub design. The RSRA was selected because its design gross weight of 18,400 pounds met the design requirement (between 16,000 to 23,000 pounds). In addition, using the RSRA as the baseline helicopter for the hub design ensured that the rotor would be compatible with the RSRA both for Task VII (ITR Compatibility with the RSRA) of this study and for future phases of the Army/NASA's Advanced Rotor Program. Table D-2 lists the technical goals for an 18,400 pound design gross weight with original goals from Appendix B and goals that reflect suggested changes.

Appendixes A, B, and C were reviewed and comments, suggested changes, and additions are presented. These suggestions and remarks are parallel in form with the original appendices.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE D-1. OPERATING CONDITIONS FOR HUB DESIGN

Cond	Maneuver	Forward Speed	Main Rotor Speed	Limit Load Factor	Remarks
1	Pull up Entry Power-On	0.4 V_H to V_{DL}	Design Max and Design Min	2.5	
2	Max G Pull up Power-On	0.4 V_H to V_H	Design Max and Design Min	3.5	
3	Pull up at Limit Rotor Speed	0.4 V_H to V_H	Limit	3.5	
4	Pull up Entry Power-Off	0.4 V_H to V_{MA}	Design Max	2.5	
5	Max G Pull up Power-Off	0.4 V_{MA} to V_{MA}	Design Max	3.5	
6	Pull up at Limit Rotor Speed Power-Off	0.4 V_{MA} to V_{MA}	Limit	3.5	
7	Minimum Redline Autorotation	0.4 V_{MA} to V_{MA}	Design Min	3.3	
8	Rolling pull-out Power-On	0.4 V_H to V_H	Limit	2.8	
9	Rolling Pull-Out Power-On	0.4 V_H to V_H	Design Min	2.8	
10	50 fps Gust Power-On	V_H	Design Max	2.2	
			Limit	2.4	
11	Maximum Rotor Torque Power-On	0	0		Divide among n-1 blades
			90% Design Max		Divide among n-1 blades, equilibrium lag angle = full lag angle
			49% Design Max		
12	10% Blade Strike Power-On		Design Max		
13	Ground Flapping Power-On	45 kn Wind	25% Design Max		
14	Negative G Power-On	0.4 V_H to V_H	Design Max	-0.5	
15	Braking	0	0 to 50% Power-On Design Max		Slow to 50% RPM with Pitch, then apply brake. Total time 60 sec.
16	Failsafe		Ultimate Torque		
17	Vulnerability Power-On	0.9 V_H	Design Max	2.0	
18	Weighted Fatigue Power-On	V_H	Design Max	1.2	
19	Ground to Air Power-On	0	50% to 90% Design Max		3 cycles per hour
20			90% to 100% Design Max		
20	Reduced Load Factor Power-On	0.4 V_H to V_H	Design Max	0.5	
21	Zero Load Factor Power-On	0.4 V_H to V_H	Design Min	0	
			Limit	0	
22	Flutter Power-On	1.15 V_{DL}	Design Max		
23	Flutter Power-Off	V_{DL}	125% Limit		
	Power-On	V_{DL}	125% Limit		
24	Jump Takeoff Power-On	0	Limit	0 to 3.5	
25	Maximum Speed Forward Flight	V_{DL} V_{DL}	Design Min Limit	1.0 1.0	
26	Maximum Speed Rearward Flight	V_{AFT} V_{AFT}	Design Min Limit	1.0 1.0	
27	Maximum Speed Sideward Flight	V_{IAT} V_{IAT}	Design Min Limit	1.0 1.0	

TABLE D-2. DESIGN GOALS

Parameters (Dependent on Gross Weight)	Goals from Appendix B	
	Original	With Suggested Changes
Hub flat plate drag area	3.1	4.4
Rotor hub moment stiffness	115,000.0	323,725.0
Minimum rotor hub moment	11,500.0	28,175.0

ITR/FRR PROJECT PLAN SUMMARY (REFERENCE APPENDIX A)

ITR TECHNICAL GOALS

a. Maximum rotor equivalent lift-to-drag ratio - 10.5. No changes were recommended.

b. Maximum rotor figure of merit, rotor alone - 0.80. Since figure of merit depends on disc loading (induced power variations), the thrust coefficient should be specified or a power loading (pounds per horsepower) goal should be specified rather than figure of merit. For the given figure of merit of 0.8 and the UH-60 at sea level, standard day conditions the pounds per horsepower are 11.4.

c. Rotor hub flat plate drag area - 2.8 ft^2. See comments under Appendix B.

d. V_{Cruise} using MCP - 170 KTAS. VROC is not specified under the System Design Specifications. HHI suggested a VROC of 450 fpm at 4000 feet 95° day be specified. This is a typical specification for a military helicopter. No other changes were recommended.

e. V_{Dash} using IRP - 185 KTAS. See comments under d. above.

f. Reduction in low frequency impulsive noise - 6 dB. HHI recommended this reduction be specified at sea level standard day.

g. Rotor weight as percentage of design gross weight - 7.0. HHI recommended that this be changed to 6.5 percent. The design goal for hubs is very challenging at 2.5 percent of design gross weight and it was suggested the total rotor weight goal be 6.5 percent, not 7 percent of design gross weight. This change would have required the designer to consider blade innovations as well as hub improvements.

h. Rotor system parts count - 75. No changes were recommended.

i. Mean-time-between removal (MTBR) - 1,500 hours. No changes were recommended.

j. Vibration acceleration level - 0.1g. HHI recommended the 0.1g level be specified at V_{Cruise}. It was suggested that during the later phases of the Army/NASA ITR/FRR program, consideration should be given to refining this design criterion.

k. Rotor procurement cost. No changes were recommended.

ITR SYSTEM DESIGN

. <u>Design Gross Weight</u>

See comments under Appendix B.

b. <u>Design Envelopes</u>

It was recommended that the existing Design Envelopes shown in the SOW (Figure A-1) be replaced by the enclosed figure. The enclosed figure is the AH-64 design envelope which is thought to be more representative of the operational environment than the design envelopes presented in the SOW. Specific changes compared to the original envelopes follow:

1. Rearward Flight Capability. HHI suggested that the rearward flight capability be changed from 35 knots to at least 45 knots. This change would have reflected recent Army requirements which are more stringent than previous requirements.

2. "G" Envelope In Rearward Flight. The high and low G envelopes shown in the original figure were considered too extreme for rearward flight, and HHI recommended the new figure be adopted.

3. High Speed Negative "G" Capability. Negative "G" capability at high speed flight is needed for nap-of-the-earth flying. Thus, it was recommended the -0.5G design envelope at high speeds be accepted.

4. Low Speed High "G" Capability. HHI recommended that the high "G" envelope at hover and low forward flight speeds be modified to that shown in the new figure. The high aerodynamic "G" envelope at low forward flight speeds is not representative of the operational environment.

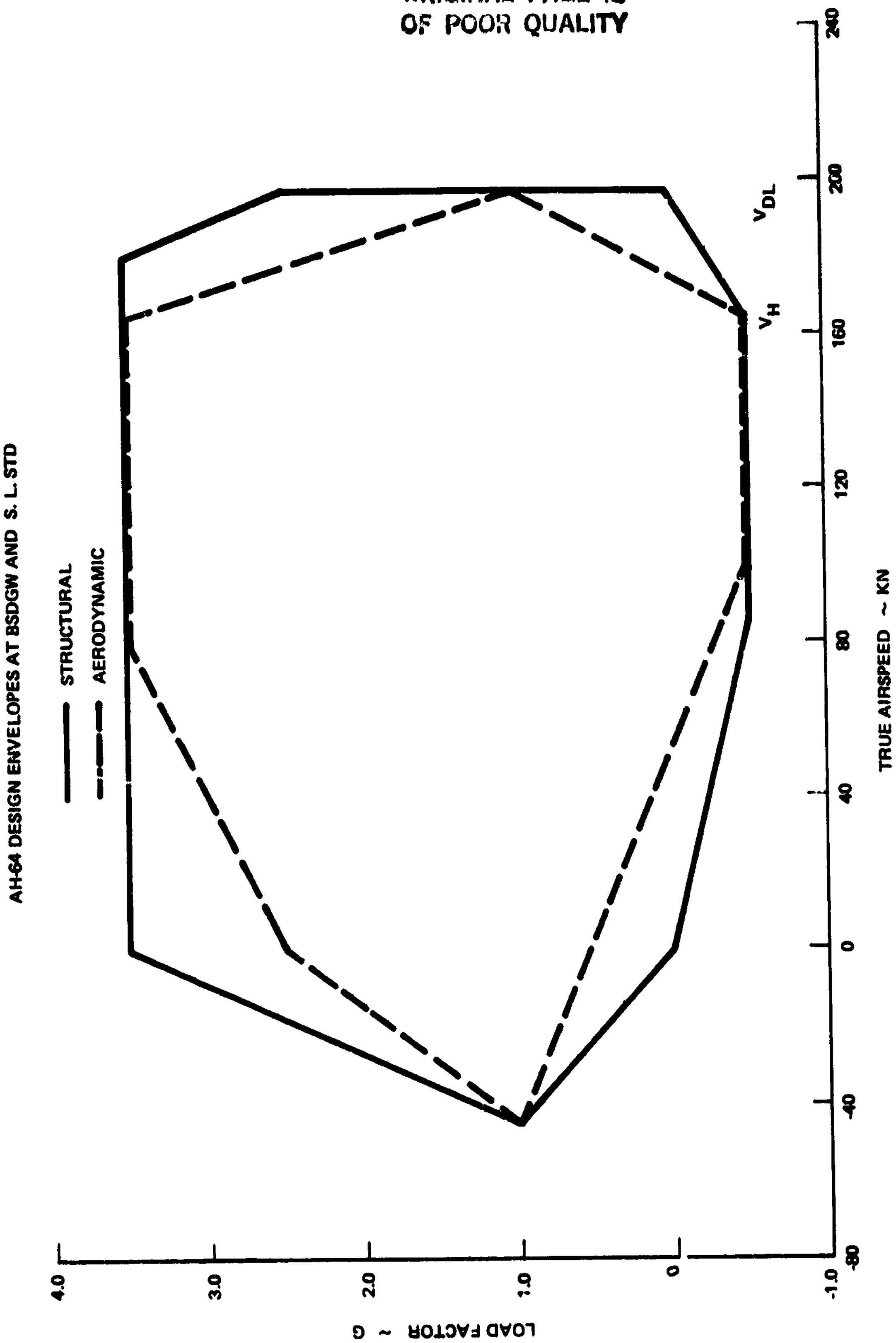


Figure D-1. Suggested Design Envelopes

5. V_H and V_{DL}. It was felt that actual forward flight speeds need not be as shown but kept at V_H and V_{DL}. V_H is level flight speed at the engine(s) 30 minute horsepower rating and V_{DL} is 1.2 times V_H.

c. Rotor System Instability

See commends under Appendix B.

d. Rotor Configuration

See comments under Appendix B, Rotor Hub Configuration.

e. Maneuverability

Changes were recommended for the pushover maneuver. The sentences dealing exclusively with the pushover maneuver were to be deleted and the following sentence added: It shall be possible to achieve a substained load factor of -0.5g for two seconds in a symmetrical pushover initiated at an airspeed of 120 KTAS.

f. Flight Test Aircraft

No changes were recommended.

g. Stability and Control

No changes were recommended for this study. HHI recommended a short stability and control section be added for the ITR/FRR Preliminary Design phase of the Advanced Rotors Program. The S&C section would, in that case, use only selected criteria from MIL-H-8501.

ROTOR HUB DESIGN SPECIFICATIONS (REFERENCE APPENDIX B)

DESIGN GROSS WEIGHT

It was suggested that the last sentence should be changed from "...95°F with a total vehicle weight equal to ..." to "...95°F with a total vehicle thrust equal to ..."

DESIGN ENVELOPE

No changes were recommended.

ROTOR SYSTEM INSTABILITY

It was suggested that overspeed criteria should be added to this section. Thus the first sentence would have been changed from "... at all operating conditions and..." to "at all operating conditions including 130 percent above normal operating rpm and..."

Additional Comments

HHI suggested that in order to obtain a consistent data base for comparison purposes the fuselage/fixed system properties should be specified. Also it was felt that the contracting agency should define a simplified fuselage model with either physical parameters (weights, inertias, landing gear damping) or analytical parameters such as mode shapes, generalized masses, and damping at the rotor hub. A common known data base facilitates comparisons and also precludes the possibility of a contractor using unrealistic fuselage parameters in order to obtain a stable hub/fuselage configuration.

As stated previously the HHI hubs shall be designed for the RSRA thus fulfilling the suggested criteria that the hubs be investigated on a known data base.

ROTOR HUB CONFIGURATION

It was recommended that the paragraph dealing with combat damage be changed. The phrase "... and combat damage... by 23mm HEI projectiles)." be deleted and following sentences added. "The hub vulnerable area for attrition plus forced landing shall be zero for a worse case single hit by, 23mm HEI or 12.7mm API projectiles. The hub shall be capable of flight for 30 minutes at 100 knots with a 2.0G transient maneuver after being hit, whether in hover or forward flight. The hub shall be invulnerable for a worse case single hit by a 7.62mm API projectile. The hub shall be able to complete the mission after being hit by a 7.62mm API projectile.

The specific technical goals are as follows:

a. Rotor hub flat plate drag area - 2.8 ft^2. HHI recommended this goal be changed to 4.0 ft^2. The AH-64 hub drag is 5.4 ft^2 and the S-61 rotor on the RSRA is estimated to have a hub drag of 8.9 ft^2. A hub drag goal of 2.8 ft^2 appears to be very difficult to achieve when compared to the drag of the aforementioned hubs. Vulnerability requirements also impact on the hub area and make large drag reductions difficult to achieve. Thus, a more achievable goal of 4.0 ft^2 for hub drag was proposed. This proposed goal is still very challenging.

b. Rotor hub weight as a percentage of design gross weight - 2.5 percent. No changes were recommended. This goal appeared obtainable, but the solution was again complicated by the vulnerability requirements.

c. Parts count - 50. No changes were recommended.

d. Rotor hub moment stiffness - 100,000 foot-pound/radian. HHI recommended this goal be changed to 281,500 foot-pound/radian. The 100,000 foot-pound/radian rotor hub moment for a flexbeam rotor is equivalent to an articulated rotor with a flapping hinge at 2.7 rotor radius (UH-60A radius of 26.83 feet and centrifugal force of 70,000 pounds). Existing flexbeam rotors such as the Bolkow 105 and the Army/Boeing BMR have equivalent flapping hinge locations of approximately 10-15 percent rotor radius. Thus, a more attainable goal of 7.5 percent rotor radius for an equivalent flapping hinge location was proposed for the hub for the ITR/FRR Concept Definition Studies. The 7.5 percent rotor radius equivalent flapping hinge location corresponds to approximately a 281,500 foot pound/radian hub moment.

e. Minimum rotor hub moment - 10,000 foot pounds. HHI recommended this be changed to 24,500 foot-pounds. This hub moment was obtained from the hub stiffness of 281,500 foot-pounds/radian (d) and 5° flapping (f).

f. Minimum rotor hub tilt angle - 5°. No changes were recommended.

g. Auxiliary lead-lag damping. No changes were recommended. Comments made regarding a consistent data base for stability analyses are contained under the section "Rotor System Instability". Those remarks also pertain to this section.

h. Torsional stiffness. No changes were recommended.

i. Rotor hub system fatigue life - 10,000 hours. No changes were recommended.

j. Reliability. MTBR - 3,000 hours. No changes were recommended.

k. Manufacturing cost. No changes were recommended.

MERIT FACTORS/MERIT FUNCTION (REFERENCE APPENDIX C)

a. Vulnerability

K_V is the probability of achieving a hub vulnerable area of zero. See Appendix B, Rotor Hub Configuration.

b. Aeromechanical instability

K_a. No changes were recommended.

c. Hub drag area - K_d

d. Hub weight - K_w

e. Parts Count - K_p

The following formula was suggested for drag, weight, and parts count. Merit Factor = 2- (Estimated Value/Technical Goal). If the technical goal is met exactly, a value of one is assigned to the merit factor. If the estimated value for a given hub is three times greater than the technical goal, a value of -1 is assigned to the merit factor. Values greater than one (approaching two) would be assigned for hubs that better the Technical goals.

f. Rotor hub moment stiffness

K_e would be assigned values according to the following table:

K_e	% Technical Goal
5	Within ±20%
3	±21 to ±50%
1	±51 to ±80%
0	Greater than ±81%

g. Minimum rotor hub moment - K_m — The following formula was suggested for moment and tilt angle:

h. Minimum rotor hub angle - K_b — Merit factor = 1.5 (Technical Goal/ Estimated Value). This formula is similar to c, d, and e, above except that it has half the weighting of hub drag, hub weight, and parts count. In addition higher values are beneficial for these parameters, thus the goals would be divided by the estimated values.

Reliability, cost, and fatigue life are weighted approximately ten times higher than the other parameters in the merit function (of those parameters which are additive). The cost, reliability and fatigue life are very important for this study yet the ten times weighting factor overpowers all the other parameters to such a degree that it was thought not worthwhile to consider the other parameters in the design. Thus a weighting factor of five was suggested.

a. Reliability - K_r — Five times (not ten) the probability of meeting or exceeding the technical goal for MTBF.

b. Manufacturing Cost - K_c — Qualitative estimate from one to five (not ten), varying inversely with expected cost.

c. Fatigue Life - K_f — Five times (not ten) the probability of meeting or exceeding the technical goal.

d. Auxiliary lead-lag damping - K_z — No changes were recommended.

e. Torsional stiffness - K_s — No changes were recommended.

Merit Function

The vulnerability criteria drives the original equation. The following equation was proposed which would have been used in addition to the original equation. The suggested Merit Function retains the importance of vulnerability but allows the consideration of other desirable parameters. Using both equations would ensure new, promising hub designs would be investigated even if they couldn't meet the vulnerability criteria. Additional Merit Function:

$$(1 + K_v)(K_a)(K_d + K_w + K_p + K_e + K_m + K_b + K_r + K_c + K_f + K_z + K_s)$$