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HELICOPTER PAYLOAD POSITION SENSOR INVESTIGATION

H. Knoer

AiResearch Manufacturing Company

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This final report documents the Helicopter Payload Position Sensors Program. This program was an 8-mo investigation of techniques for determining position and motion of helicopter slung loads.

Initial program tasks included a review of slung load dynamics due to: (1) aerodynamic instabilities in the higher speed range, and (2)

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Many new payload position sensor concepts were identified in this program, some of which appear promising for use with load stabilization systems currently under development. Should current methods of sensing payload position prove to be inadequate as load stabilization development progresses, further consideration should be given to the use of one of the new sensor concepts investigated herein.

Richard E. Lane, Military Operations Technology Division, was the technical monitor for this contractual program.

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vehicle-load interactions during low-speed maneuvers and hover. This review and an analysis of current and projected load stabilization concepts, provided the basic performance requirements for the payload position sensor. The investigation included the influence of suspension systems configurations and load types.

Many sensing techniques were investigated; these ranged from simple cable angle measurement techniques to relatively sophisticated tracking techniques. As the more promising were identified, they were investigated in greater depth. Five of the most promising sensing techniques were subjected to a detailed comparative evaluation. The results of this evaluation form the basis of recommendations as to the best technical approaches. Design requirements, design disclosure, and qualification test requirements for the recommended concepts are supplied.

PREFACE

This report presents the final results of a program conducted by the AiResearch Manufacturing Company for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, under contract DAAJ02-73-C-0064. Richard E. Lane, Military Operations Technology Division, was the technical monitor for this contractual program.

The following AiResearch personnel contributed to the program:

R. E. Vesque
W. J. Harris
H. Knoer
J. E. Cook
J. E. Minnear
R. Morison
R. Critchfield
G. Prewitt
W. H. McCormack
W. Fidler
D. Nicholls
Dr. A. Saur
Dr. J. D. Chang

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J. B. Sinacori, Northrop Corporation, Hawthorne, California

W. Huebner, Sikorsky Aircraft Division--United Aircraft Corporation, Stratford, Connecticut

T. A. Dukes, Princeton University, Princeton, New Jersey

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INTRODUCTION

Helicopters with slung loads have serious stability problems due to the aerodynamic instability of most slung loads. In addition, current load suspension systems provide very little damping. The results of these problems are:

1. False motion cues, which can result in pilot-induced oscillation (PIO) and generally degraded handling qualities

2. Severely restricted operating speeds

3. Excessive hover time at delivery points

A number of passive measures have been investigated, and some have been implemented, to improve the aerodynamic stability of slung loads. Measures such as changing the shape of the load so that the aerodynamic center of pressure is significantly aft of the center of gravity will improve stability. Loads with a significant flat area on top, such as the MILVAN, are often carried with the front lower than the rear, thus generating a downward aerodynamic force. This measure is only partially successful; the increased downward force increases the apparent weight, but the load inertia is not affected.

Passive measures for improving slung payload stability all have significant limitations. Each type of load geometry requires its own scheme. Attaching stabilizing appendages such as drogues or fins to the load is usually unacceptable; in any case, the passive device increases the load carried, thus decreasing the power-limited speed of the helicopter and payload.

Because of the seriousness of the stability problem and the limited success of passive stabilization approaches, recent efforts have been directed toward development of active stabilization. Two basic approaches have been considered. Both approaches require accurate, continuous determination of the position and motion of the slung load with respect to the helicopter. These two approaches are:

1. The position and motion information is used as input to the helicopter flight control system, which controls the helicopter so as to damp instabilities.

2. The position and motion information is used as input to a mechanism that controls the location of the load suspension points on the helicopter so as to damp instabilities.

Typical of the first approach is HLH development work. Typical of the second approach are Active Arm External Load Stabilization System programs (AAELSS I and II).

These programs show that active stabilization system require accurate, high resolution, low hysteresis payload position sensors. AAELSS I experienced degraded precision hover performance and small amplitude limit cycling of load position due to sensor hysteresis*. As a result, an analysis of load position sensor requirements was performed during the AAELSS II program.** The need for accurate payload position information was also recognized during the simulation studies at Northrup with a system similar to the infrared approach described in this report being suggested***.

The current program was designed to survey the available technology to determine those approaches and techniques applicable to the helicopter externally slung payload position measurement problem.

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* DESIGN, FABRICATION, AND FLIGHT TEST OF THE ACTIVE ARM EXTERNAL LOAD STABILIZATION SYSTEM FOR CARGO HANDLING HELICOPTERS, USAAMRDL Technical Report 73-73, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, September 1973.

** Boeing-Vertol Company, DESIGN AND OPTIMIZATION STUDY OF THE ACTIVE ARM EXTERNAL LOAD STABILIZATION SYSTEM (AAELSS) FOR HELICOPTERS. Final report under Contract No. DAAJ02-73-C-0100.

*** IN-FLIGHT STABILIZATION OF EXTERNALLY SLUNG HELICOPTER LOADS, USAAMRDL Technical Report 73-5, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1973.

TECHNICAL APPROACH

Key elements of the technical approach are (1) definition of requirements for payload-position sensing, (2) definition and review of a broad spectrum of candidate sensing techniques, (3) detailed comparative evaluation of the most promising of those techniques, and (4) development of design details for the technique that appears optimum.

Initial program tasks included a review of slung load dynamics arising from aerodynamic instabilities in the higher speed range and from vehicle-load interactions during low-speed maneuvers and hover. Review of this area, and an analysis of current and projected load stabilization concepts were the prime determinants of basic performance requirements for the payload-position sensor. This determination included the influence of suspension system configurations and load types.

A variety of sensing techniques have been investigated for their applicability to payload-position sensing. These range from simple cable angle measurement techniques to relatively sophisticated tracking techniques. The intent was to provide relatively complete coverage of all possible techniques, furnishing successively greater depth of analysis for the most promising techniques.

The most promising sensing techniques were identified and recommended for detailed comparative evaluation. The methodology for conducting this evaluation was also constructed.

The above tasks and results constituted the first phase of the payload-position sensor study. The next phase of the program was a detailed, comparative evaluation of the recommended sensing concepts. The results of this evaluation form the basis of recommendations as to the best technical approach. Finally, design requirements, design disclosure, and qualification test requirements are supplied for the concept selected.

The functional flow of the various steps of the program is shown in Figure 1.

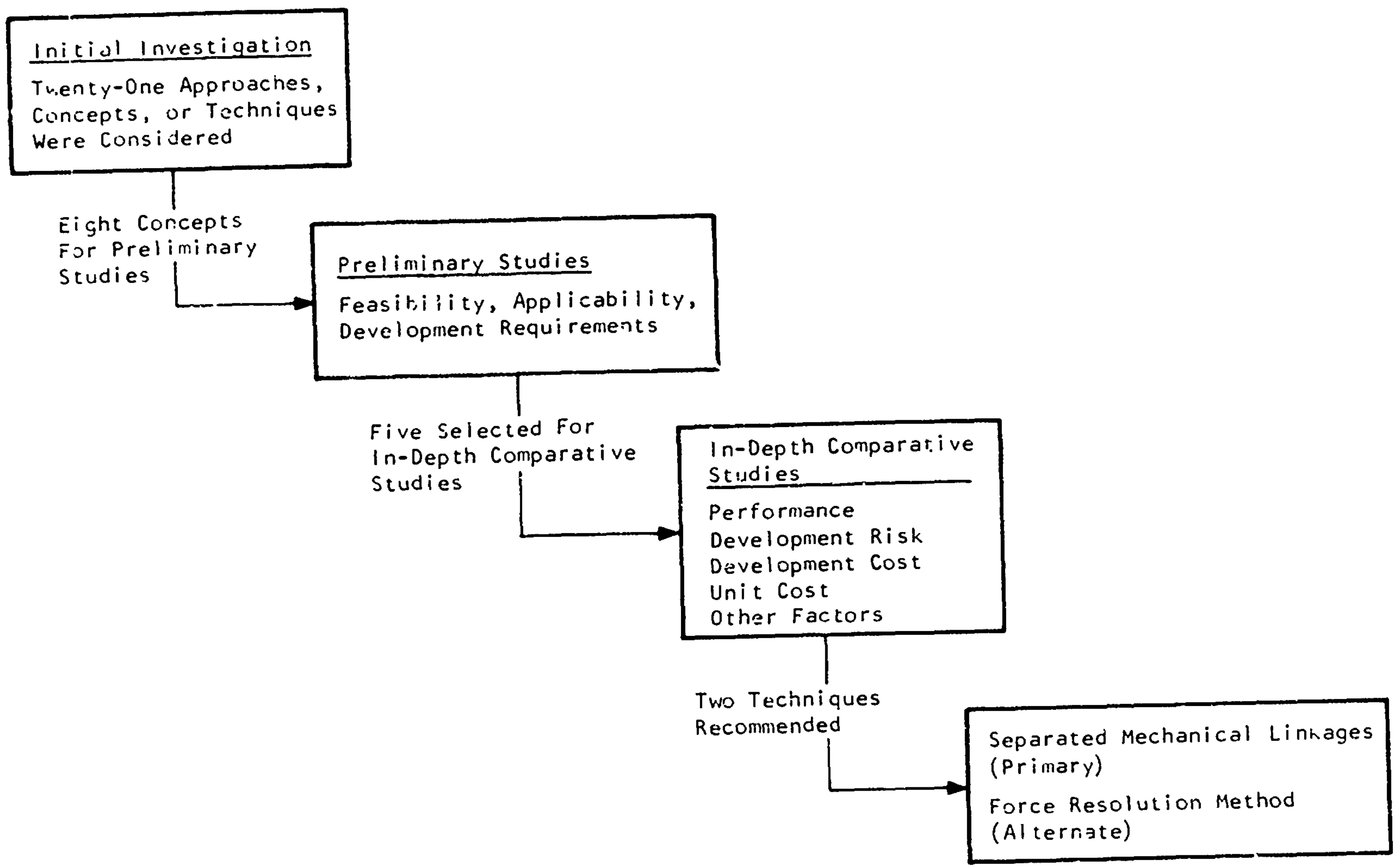


Figure 1. Position Sensor Evaluation Process.

SENSOR REQUIREMENTS

VISIBILITY OF REQUIREMENTS

To establish sensor performance requirements, operational environment parameters were assumed for next-generation cargo carrying helicopters. The assumed operational conditions were:

Power-limited airspeed	≈150 knots
Maximum cable length	≈250 ft
Precision hover capability	≈±4.0 in. with 45-knot wind
Load weights	≈5,000-40,000 lb

These conditions, in conjunction with the active stabilization systems under investigation at Northrop and Boeing-Vertol, provided the basis for development of sensor requirements as outlined in the following paragraphs.

LOAD CHARACTERISTICS

Essentially any type of load can be carried slung beneath a helicopter, limited only by weight. In broad terms, the various types of loads fall into two categories: (1) dense objects, e.g., howitzers, self-propelled mortars, and tanks, and (2) aerodynamically bluff, and relatively less dense, objects, e.g., trucks and MILVAN containers. The rationale for this division is that loads in the second category exhibit high-speed yaw (directional) instability (ignoring erratic types of behavior such as "dancing", "flying", etc.), whereas loads in the first do not. The second category, therefore, presents the more difficult stabilization (and position measurement) problem, and for that reason is taken as the design case.

Among the loads in the second category, the MILVAN container has been selected as the worst-case load for purposes of this study; however, constraints imposed by the requirement to handle all load types are still considered. The primary constraint is that there is no standard load geometry, and therefore any concept that would require integral use of load geometry is not allowed.

Load weight, assuming heavy lift helicopters, has been taken as 5000 lb min. (the approximate weight of an empty 8- by 8- by 20-ft MILVAN container) and 40,000 lb max. Load weight is a relatively unimportant consideration in evaluating sensing techniques except in the case of the force vector resolution technique. Extremely light loads could, of course, give rise to erratic nonpendulous behavior, but the automatic stabilization approaches cannot handle that case; therefore, the question of the ability to sense such erratic motions is only of academic interest.

The MILVAN container is both a rational and convenient choice of a representative load. It represents the worst-case load both aerodynamically and from the point of view of possible precise load positioning requirements, e.g., containership loading and unloading. The aerodynamic characteristics of this load and its stabilization also have been well researched; its dynamic characteristics are provided later in this section.

BASIC STABILIZATION APPROACHES

The two basic stabilization approaches currently being pursued, the automatic flight control system (AFCS) approach, associated with HLH development work and the movable suspension point approach as exemplified by the Active Arm External Load Stabilization System (AAELSS), both appear viable. In terms of position sensing, either approach requires essentially the same sensor characteristics. The movable suspension point approach, however, may impose certain constraints on a cable-angle sensing approach, and therefore requires specific consideration of the suspension-active arm configuration in the case of cable-angle sensing approaches. Both of these active stabilization approaches require accurate load position information.

SUSPENSION CONFIGURATIONS

Both single- and multiple-point load suspension configurations warrant consideration with respect to position sensing. The pure single-point system offers no means of handling yaw instabilities, but that is only one of several uses of the load stabilization system, and therefore does not rule out its use for single-point systems. Moreover, yaw instability is not common to all loads, and there is a possibility of employing passive measures (improving load aerodynamics) to overcome the yaw problem. Load modification for aerodynamic stability, however, creates problems of load preparation, ground crew activity, and logistics. The most common load for military helicopters, the MILVAN, is not amenable to aerodynamic modification. For these reasons, passive devices were not considered in this investigation.

In the case of multiple-point suspension systems, it appears that the two-point suspension system may be representative of all such systems. For sensor concept design purposes, the two-point (tandem) suspension system has been assumed, since it represents the most general case. This assumption affects basic sensing requirements (load yaw must be sensed), and in the case of cable-angle sensing approaches, requires two sets of sensors, at least for lateral angles. The assumption is not restrictive, however, because any approach that is acceptable for the bifilar suspension system will also be acceptable for monofilar suspension. An 18-ft separation between the suspension points is also assumed.

The longitudinal axis of the load is, in general, not parallel with the longitudinal axis of the helicopter. It has been found that the stability of a MILVAN container is enhanced with a -10-deg (nose-down) pitch orientation.

AVAILABLE AUXILIARY MEASURES

Review of existing and planned hoist systems shows that these systems include measurements of load weight, accurate to within about 1 percent.

and cable length, probably accurate to within 1 percent or better. Lateral cable payout position with respect to the helicopter either is held constant or linearly related to cable length.

ELECTRICAL POWER AND SIGNAL CONDUCTOR AVAILABILITY AT THE LOAD

All current and planned hoist systems for large helicopters include provision for electrical control of the cargo hook. Thus, it may reasonably be assumed that both electrical power and signal conductors are available at each cargo hook for use by a contemplated position-sensing approach. The cargo hooks could also be modified so that electrical power and signal conductors could be routed to the load; however, it is undesirable to add these provisions because of increased complexity and vulnerability to human errors and damage from a variety of sources.

DEGREES OF FREEDOM

Figures 2 and 3 illustrate the degrees of freedom of the helicopter and slung load. With reference to Figure 3, the pitch angle and vertical position of the load relative to the helicopter are controlled by the cable lengths, assuming well-behaved (i.e., only pendulous) load motions. Cable length measurements are available, if necessary, to any position-sensing concept. Similarly, load roll relative to the plane containing the cables remains constant, given typical sling rigging and well-behaved load motions. Thus, in sensing load position relative to the helicopter body axes, it is necessary to sense only swing (longitudinal translation, or cable pitch), sway (lateral translation, or cable roll), and yaw (differential sway in terms of cable angles).

MEASUREMENT REFERENCE

For the AFCS approach, measurements should be made with respect to the helicopter body axes. In the case of an active arm approach, measurements with respect to the arms appear as an acceptable alternative; the position of the arms would be combined with the measurements to yield resultants in terms of the helicopter body axes.

LOAD STABILIZATION AND CONTROL MODES*

Three modes must be considered in arriving at performance requirements for the sensing approach: (1) load-helicopter offsets, (2) inflight instabilities, and (3) precise load positioning. To illustrate the functional

* Harris, W.J., Minutes of Meeting with Boeing-Vertol Flight Dynamics Group on June 21, 1973. Subjects: 347 Flight Test, HLH Load Position Stabilization and Load Position Sensing.

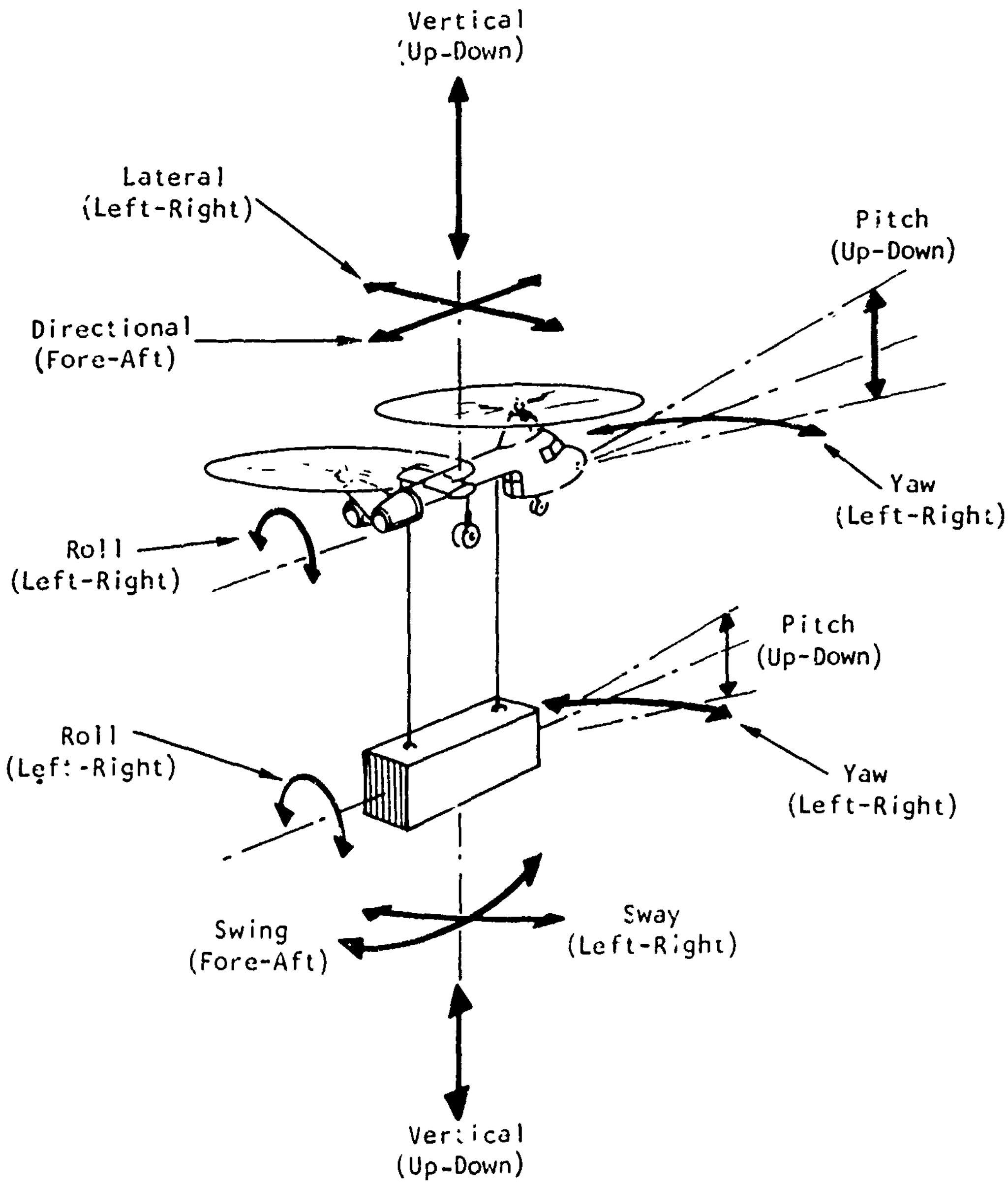


Figure 2. Degrees of Freedom of Helicopter and Slung Load.

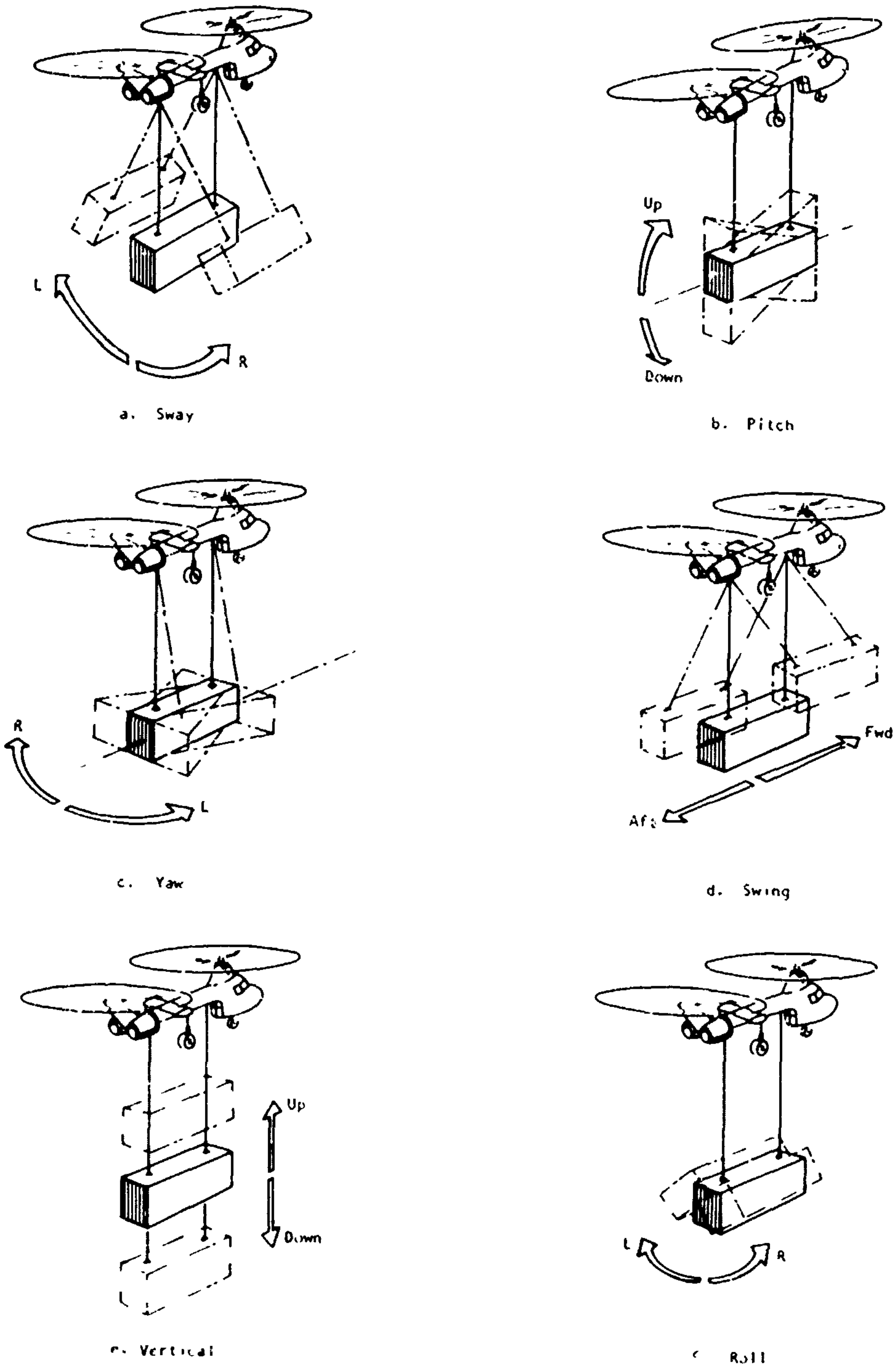


Figure 3. Degrees of Freedom of a Slung Load.

objectives and corresponding requirements for position sensing, the current plans for the HLH with respect to load stabilization and control as seen by Boeing-Vertol are briefly described below.

Positioning Helicopter Over Load During IFR Conditions

After the load has been hooked up, as the helicopter begins to lift off, cable tension will increase. Surpassing a certain minimum cable tension will enable the automatic positioning system, which will then sense cable angles and act to bring the helicopter directly over the load. Inputs required are cable tensions and lateral and longitudinal cable angles. The objective is to prevent load oscillations during initial lift-off Considering this objective, accuracy requirements would not appear stringent, except where the additional problem of easing the load through a window (e.g., cargo hold) exists.

Damping Pendulous Oscillations During IFR Cruise Flight

Slung loads are lightly damped (0.04 to 0.08). Damping will be achieved by feeding cable-angle inputs into the AFCS. Thus, only cable-angle measurements will be required during cruise.

Precision Hover

The HLH precision hover system is expected to be a sophisticated system that will act to maintain the helicopter (hands off) over a known location. The implication is that load position sensing must be commensurate so that both the load and the helicopter can be precisely maintained over the position. The system will be operable between 25 to 125 ft helicopter altitude and at speeds of 10 ft/sec or less. It will maintain the helicopter over the known location at wind velocities of up to 45 knots with less than a 2-deg heading change and with less than 4-in. x-y deviation.

MAXIMUM POSITIONAL ACCURACY

Extreme positional accuracy is not required for stabilizing the load during flight. For example, at stabilized high speed cruise, a MILVAN container will trail at an angle of approximately 30 deg and at a somewhat unpredictable yaw angle of several degrees. These angles need not be controlled; it is necessary only to damp any oscillations. Thus, sensitivity, resolution, and hysteresis are important in this mode, but an accuracy of perhaps ±5 deg for longitudinal (pitch) and ±3 deg for lateral (roll) would be sufficient.

Considering the effects of load-helicopter offsets and load oscillation damping provisions, it appears that this mode does not require extreme positional accuracy. Initial offsets should be kept within a limiting range so that only small motions of the helicopter or movable suspension point are required to stabilize any initial oscillation caused by offsets. Considering ±5 ft. lateral or longitudinal, as an allowable offset range, then the required accuracy in terms of cable angles is ±5.8 deg for a 50-ft cable length and 2.9 deg for a 100-ft cable length. Thus, an accuracy of about ±3 deg appears reasonable for this mode.

Finally, considering precision load placement (e.g., precision load control during unloading or loading of a container ship), required accuracy is dependent on which of two approaches is adopted.

In the first approach, the load stabilization system acts as an assist for this operation; that is, it acts to stabilize the load (damp oscillations) rather than control the position of the load with respect to a ground reference grid. Control of load position is then manually performed by the pilot, load control officer, ground control, or a combination of these.

In the second approach, a precision load control system performs these functions. This approach requires that the position of the load with respect to a ground reference grid, such as a cargo hatch of a ship, be sensed and fed back to the system.

There are two ways that the position of the load with respect to a ground reference can be sensed. First, the position of the load can be measured from a ground-located device. This would obviate the need for a sensor on the helicopter.

The second alternative is to combine a measurement of the load with respect to helicopter body axes with a measurement of the position of the helicopter relative to a ground reference. This alternative leads to the most stringent accuracy requirement possible for the payload position sensor. In this case, the accuracy required is approximately equivalent to the translational tolerance of this mode of operation. To illustrate, Figure 4 shows the cable-angle accuracy required to obtain positional accuracy at various suspension lengths. Although ±4 in. has been adopted as a tentative requirement for the HLH, opinions regarding required tolerances range up to ±2 ft. Considering maximum cable lengths ranging between 50 and 250 ft, this leads to a range of possible acceptable angular errors of 0.076 to 2.3 deg.

Considering what appears to be a reasonable maximum suspension length (75 to 100 ft), the maximum acceptable error is about ±1 deg and the minimum is about ±0.2 deg.

PARAMETER RANGES

Figure 5 shows the pendulum frequencies vs cable length for the bifilar suspension on an average weight MILVAN. Cable vibration modes are also shown. The curves shown are applicable to low-speed flight. At high speeds, the frequencies for the yaw mode are somewhat higher than predicted by Figure 5 due to aerodynamic effects. Figure 5 also shows the frequency predicted for lateral cable vibrations (vibrating string formula). If the frequency of this vibration approaches that of the yaw mode (as might happen with very light loads and very long cable lengths), a cable-angle

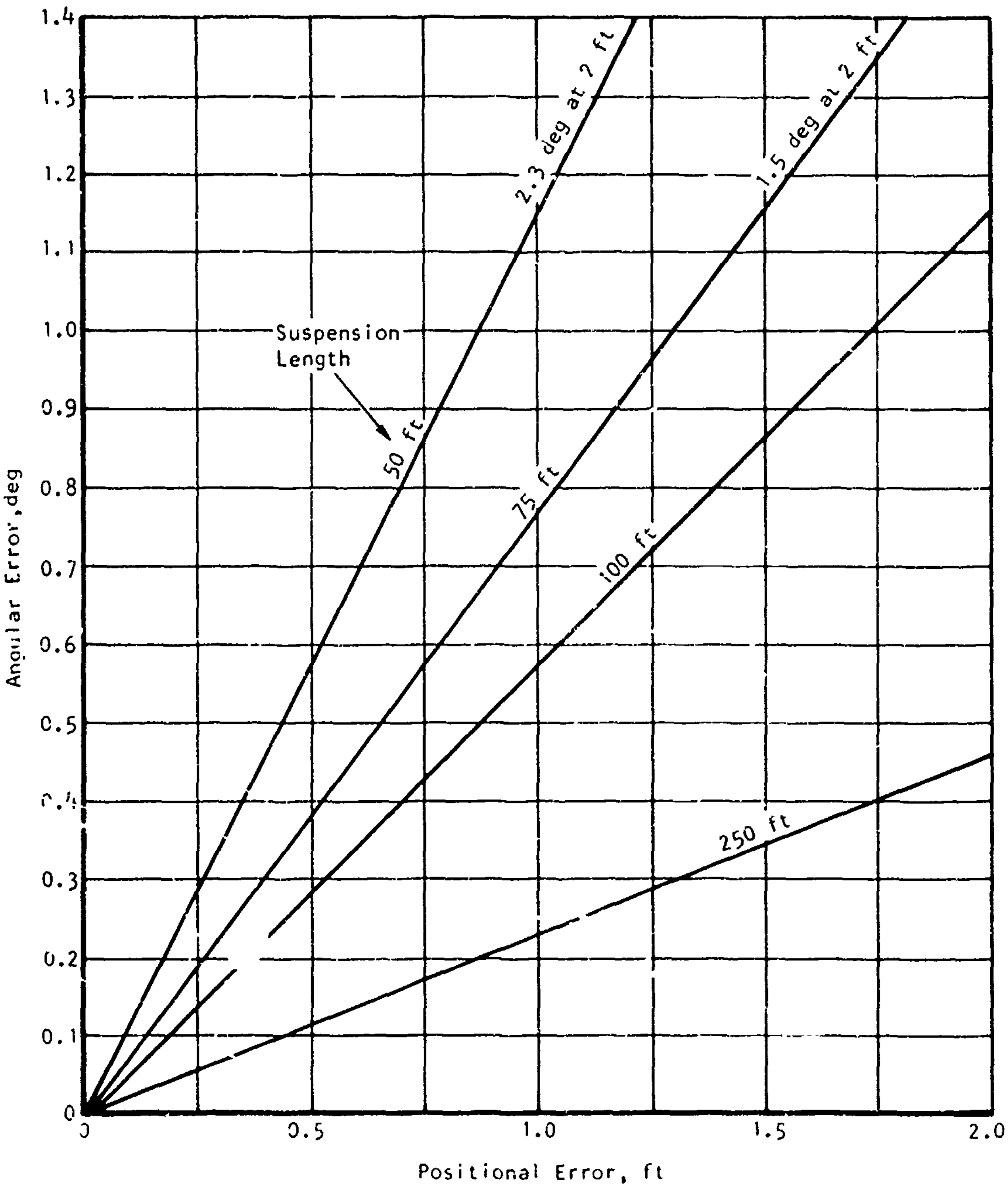


Figure 4. Angular Accuracy Required to Obtain Positional Accuracy at Various Suspension Lengths (Distance Between Slung Load and Helicopter).

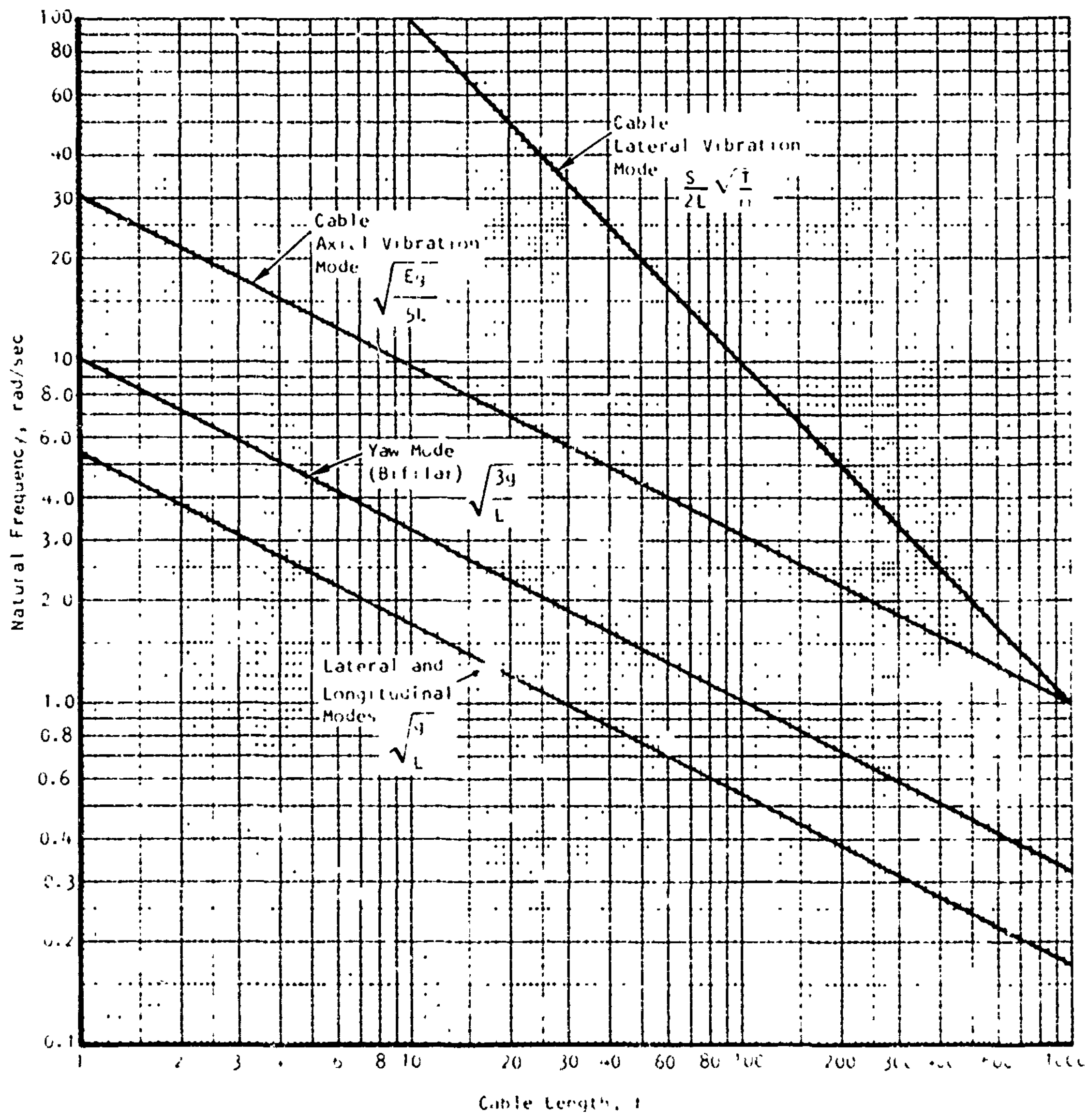


Figure 5. Pendulum and Vibration Mode Frequency vs Cable Length (Bifilar Suspension of MILVAN at Low Airspeeds).

measurement might be adversely affected. As indicated in the figure, under normal conditions, lateral vibration effects probably can be eliminated by filtering.

The following is a summary of the ranges of the position parameters in terms of cable-angle parameters measured with respect to the helicopter body axes:

1. Lateral: ±30 deg
2. Longitudinal: +30 deg, -60 deg (trail)
3. Yaw: ±20 deg (divergent beyond ±20 deg)
4. Maximum lateral and longitudinal rates: 2 rad/sec
5. Maximum yaw rate: 3 rad/sec (6 rad/sec extreme)
6. Maximum pilot-induced rate: 30 deg/sec (helicopter roll)

Cable length may be categorized as follows:

1.	20 to 50 ft	Normal range
2.	50 to 100 ft	Maximum (rare)
3.	100 to 250 ft	Extended range (very rare)

PERFORMANCE REQUIREMENTS

The following listing of performance requirements summarizes the foregoing discussion and presents a consensus gained from review of available literature and discussion with investigators in the area of load stabilization.

1. Positional accuracy:

   a. Precise load control mode: ±4 in. to ±2 ft (±0.2 to ±1 deg)

   b. Stabilization modes: ±3 to ±5 deg longitudinal; ±2 to ±3 deg lateral

2. Sensitivity and resolution: 0.1 to 1.0 deg
3. Hysteresis: 0.1 to 1.0 deg
4. Frequency response: flat to approximately 1 Hz
5. Rate threshold (sensitivity): ±1 to ±12 deg/sec
6. Angular rate accuracy: ±3 to ±1 dB

The positional accuracy requirements have been previously discussed. It should also be noted that the requirements for precision load control apply only to hover and near-hover operations and therefore apply to a limited range about the vertical, perhaps ± 5 deg lateral and ± 15 deg longitudinal, the larger longitudinal range due to static angles offset because of rigging of the load. With regard to sensitivity and resolution, 0.1 deg is based on the gain and sensitivity of a particular AFCS approach; 1.0 deg has been quoted based on simulation studies of a movable suspension point approach. Allowable hysteresis is estimated to be of the same order as sensitivity requirements. Frequency response follows from consideration of maximum load translation rates. The rate threshold estimate is based on simulation study results.

The ranges quoted for performance requirements may be interpreted as follows: the lower requirement (e.g., in the case of accuracy, the larger allowable error) may be considered an approximate minimum requirement; i.e., an approach not meeting the lower requirement is considered unacceptable in a prima facie sense. Similarly, an approach just meeting the lower requirement is marginally acceptable. The upper requirement (e.g., in the case of accuracy, the lower allowable error) may be considered an approximate maximum requirement; an approach which offers performance that is better than the upper requirement does not provide a significant improvement, all other things being equal.

With respect to environmental requirements, the approaches must operate satisfactorily in extreme conditions of dust, sand, rain, fog, snow, temperature, etc. Approaches that cannot operate in such conditions are unacceptable for consideration.

INITIAL SELECTION AND EVALUATION

GENERAL

More than twenty concepts, approaches, and techniques were considered in the quest for viable methods of determining the position of externally slung helicopter payloads. These concepts, approaches, and techniques were subjected to a preliminary evaluation of six criteria. Eight were thus selected for further evaluation.

The payload sensor approaches fall into three general classifications: 1) cable-angle determination, 2) direct measurement of load position with respect to the helicopter, and 3) inertial techniques. Each of these general classifications is then divided into subclassifications with one or more specific techniques or devices considered for each subclassification.

CABLE-ANGLE DETERMINATION

All of the approaches to the payload position sensing problem that fall under this classification depend upon the assumption that the payload position with respect to the helicopter frame is known if the angles between the cable(s) and the helicopter frame are known and the length of the cable(s) is (are) known. The assumption is considered valid for all expected operating conditions. Proof of the validity appears in the following section.

Four subclassifications of cable-angle measuring devices were considered: following linkages, plane piercing location, exit collar position, and force resolution.

Following Linkages

Three types of following linkages were considered:

1. Boeing linkage--This device was designed by Boeing-Vertol and is presently flying on the prototype HLH. It provides direct cable-angle readings although lateral angles require compensation as a function of longitudinal angles

2. Big arm gimbal--Analysis of the Boeing linkage revealed a possible source of uncompensable error should the load support cable become fouled or pick up debris. The big arm gimbal was conceived to overcome this problem. It provides the same load position information as the Boeing linkage, development requirements and risk are low, and cost is relatively low.

3. Separated linkages--This approach uses longitudinal motion of the cable cutter assembly to determine longitudinal cable angles and a pair of rollers (platens) for lateral angles. The approach appears to be simpler than either of the above linkages but may

be somewhat larger and heavier. Some development is required but the risk appears low. Costs should be relatively low.

Plane Piercing Location

The plane piercing location approaches are based on defining a plane which is parallel to the plane of the x and y axes of the helicopter and then determining the points at which the load supporting cables pass through this plane. Since the cable departure points at the winch are not fixed with respect to the helicopter x and y axes, these points must also be determined. The approaches consisted of cable contacting and noncontacting methods of locating the point at which the cables pierced the plane. The noncontacting approaches were emitter-detector arrays, point source-detector array, servoed shadow followers, proximity sensors, and emitter-detector beacons. Cable contacting methods included sensing rods pushed by the cable, which in turn actuate linear pickoff devices, and sensing lines which actuate pickoffs. Except for proximity sensing, all of the techniques were abandoned when it was determined that none of the approaches provided any significant advantages over cable follower techniques, while more development risk was involved. Also, the costs would have been greater. The proximity sensing approach promised considerable operational advantage because of apparent low development requirements, and so was investigated in more detail.

Force Resolution

The force resolution technique consists of mounting load cells and/or strain gages in the cable winch support assembly. The vertical and side forces are then resolved to determine the direction of the load as seen at the helicopter. This is tantamount to determining cable angle since a cable is capable of transmitting force in only one direction. The technique can be considered to have two approaches, load cells and strain gages; however, they are essentially the same, as both involve strain sensing and flexures.

The force resolution technique has many advantages. The hardware located in proximity to the cable winch can be very rugged with mechanical backup, the technique is insensitive to ambient conditions, crew intervention is not required, and helicopter/load/cable mishaps (such as a broken cable) will not affect the system.

LOAD TRACKING

The techniques which fall under this classification all utilize a tracking method to determine the angular location of the payload with respect to the helicopter frame. Thus, the payload position is known regardless of conditions of flight or wind. Distance may be measured by triangulation, if desired; however, using cable length as distance will result in minimal errors.

Five subclassifications of load position measurement were considered: radar, IR/visible light, nuclear, television, and sound/ultrasonics.

Radar

Three radar techniques were considered:

1. Pulse radar--This is the classical radar technique whereby pulse modulated RF energy is radiated toward a target and the echo detected. The transit time of the energy from the transmit point to the target and return is a precise measure of distance to the target. The accuracy of the measurement is dependent on the time discrimination of the equipment, 4×10^{-9} second error being equivalent to 1 foot error. Such time discrimination numbers are not common since pulse radar is not commonly used for highly accurate distance measurements.

2. RF interferometry--This technique consists of a small continuous wave RF source at the load. Energy from this source is received at three points on the helicopter. By phase comparison of the signal as it arrives at the three reception points, precise angle and distance measurements can be made.

3. FM altimetry--This approach uses continuous wave RF energy radiated toward and reflected from the load. The frequency of the radiated energy is continuously changed so that the returned echo signal will differ from the energy being radiated at that instant by an amount equal to the transit time multiplied by the rate of change of frequency.

This altimetry is the technique originally considered most likely, not only to be applicable to the load position sensing problem, but also to provide the circuits and hardware for early development programs. Altimeters for use with Category III Instrument Landing Systems use this technique for altitude measurements down to 10 feet.

High intensity passive reflectors, such as Luneberg lenses or corner reflectors, can be mounted on the load and at delivery points to implement precision tracking.

IR/Visible Light Tracking

Tracking point light sources mounted on the payload can provide very accurate angular information on the payload location. Light sources at delivery locations can also be used to provide precision delivery. The term light in this case can refer to visible light, either coherent, noncoherent, or infrared. Noncoherent visible light systems would be less expensive to develop and implement than IR and would provide more accuracy. Coherent light would be most costly while providing extreme accuracy--on the order of 10^{-3} inches.

Although visible light is preferred to IR from a development and implementation standpoint, environmental conditions may indicate the use of IR. IR energy will suffer less diffusion while passing through heavier concentrations of these air contaminants that can be tolerated for visible and IR systems.

Nuclear Techniques

Automatic tracking of a point radioactive source as a means of payload position sensing is attractive from two points of view. Very good accuracy can be achieved provided the source can be detected and the source requires no power. Unfortunately, radiation from AEC approved β sources will penetrate only a few feet of air and so would not be detectable over distances of interest. On the other hand, gamma rays from AEC-approved sources could prove to be a health hazard for ground crews and helicopter crews. As soon as these facts became apparent, nuclear techniques were abandoned and no further study was recommended.

Television Techniques

Two or more television cameras could be directed from the helicopter toward the payload, and by using automatic superposition of recognizable point features of the load or by man-in-the-loop tracking, the payload position could be determined quite accurately. The technique was not pursued because it provides no advantage over the less expensive point source tracking described above and suffers from the same limitations of fog, dust and other weather conditions.

Sonic/Ultrasonic

The use of sound waves in the measurement of payload position appears attractive in some areas but suffers from closer study. A limited investigation indicates that the development risk of any sonic/ultrasonic approach is very high. The technique was not recommended for further study.

INTEGRATED RATE APPROACHES

The use of elements normally found in inertial platforms such as rate gyros and accelerometers were considered since rate information alone may be sufficient for stability augmentation. They were not considered further since the primary objective of this effort is to study methods of load position sensing. Inertial platforms were rejected as a far too costly approach.

EVALUATION CRITERIA

The criteria to which the helicopter payload position sensor approaches were initially evaluated were suitability, applicability, requirements for development, development risk, and relative cost. A sixth criterion, flight or health hazard, was added when it was decided one possible approach constituted a health hazard.

Suitability refers to the lack of crew intervention required for the use of sensing equipment. Ideally, no intervention is required. Less desirable would be the situation wherein a crew member is required to place a device--energy source or reflector--at one or more locations on the load. Least desirable would be a system requiring a sensor operator, such as man-in-the-loop approaches. Suitability is rated as low, medium or high.

Applicability refers to the amount of information about the payload position which can be obtained by the sensor or technique. Cable-angle measuring systems permit computation of the load position with respect to the helicopter frame, assuming that cable length information is available. Rate signals may then be computed if required. Techniques such as radar, infrared and ultrasonics provide the capability of locating not only the payload but also surface features and by computation, determining payload position with respect to such surface features.

Requirements for development refer to the immediate availability of the technique to the payload position sensing problem. Technique development is required if previous applications of the technique were sufficiently different. Hardware development is required if the essential mechanism or device must be designed. Development requirements are rated as low, medium or high.

Development risk is a qualitative estimate of the probability of success of following the particular approach. Technique risk is a measure of the technique being successful; hardware risk is a measure of the probability of developing useful hardware provided the technique is viable. Usually the hardware risk is lower than the technique risk. However, in certain cases the reverse is true. For instance, the visible light techniques have high technique risk. Should further investigation prove these techniques applicable, the hardware development would be nearly risk-free because hardware has been previously developed for similar applications except for the dust and weather problems which are the source of the technique risk. Development risk is rated as low, medium or high.

Detailed estimates were not made of the costs of implementing the different approaches. Rather, estimates were made of the costs relative to each other. In general, the greater the capability of the approach, the greater the cost. Costs are rated as low, medium or high.

Table 1 summarizes in matrix form all of the sensor concepts, approaches and techniques discussed and shows the relative evaluation of each.

TABLE 1. SUMMARY OF POSITION SENSOR TECHNIQUES CONSIDERED

	Suitability	Applicability: Load Position With Respect to Helicopter	Applicability: Load Position With Respect to Helicopter and Ground	Development Requirement: Technique	Development Requirement: Hardware	Development Risk: Technique	Development Risk: Hardware	Cost: Development	Cost: Per Installation	Hazards
I CABLE-ANGLE DETERMINATION										
A Following linkages										
1 Boeing linkage	High	Direct reading. Requires computation	Not available	Low	Low	Low	Low	Low	Low	None
a Roller pickups										
b. Pivoted arms - drive transducers										
2 Big arm gimbal	High	Direct reading. Requires computation	Not available	Low	Low	Low	Low	Low	Low	None
3 Separated linkages	High	Available by computation	Not available	Low	Low	Low	Low	Low	Low	None
a Cable cutter movement - fore and aft										
b Arms and platens - lateral										
B Plane piercing location										
1 Emitter-detector arrays	High	By computation	Not available	Medium	Medium	Low	Low	Medium	Medium	None
2 Point source - detector array	High	By computation	Not available	Medium	Medium	Low	Medium	Medium	Medium	None
3 Servoed shadow follower	High	By computation	Not available	Medium	Medium	Low	Medium	Medium	Medium	None
4 Emitter-detector beacon	High	By computation	Not available	Medium	Medium	Low	Medium	Medium	Medium	None
5 X-Y axis sensing rods	High	By computation	Not available	Medium	Medium	Medium	Medium	Medium	Medium	None
6 Sensing lines	High	By computation	Not available	Medium	Medium	Medium	Medium	Medium	Medium	None
7 Proximity sensing	High	By computation	Not available	Medium	Low	High	Low	Medium	Low	None
a. Inductive										
b Capacitive										
C Force resolution	High	By computation	Not available	Medium	Low	Low	Low	Medium	Low	None
1 Strain gages										
2. Load cells										

TABLE 1 - Continued

	Suitability	Applicability: Load Position With Respect to Helicopter	Applicability: Load Position With Respect to Helicopter and Ground	Development Requirement: Technique	Development Requirement: Hardware	Development Risk: Technique	Development Risk: Hardware	Cost: Development	Cost: Per Installation	Hazards
II. LOAD TRACKING MEASUREMENTS										
A. Electromagnetic tracking										
1. Pulse radar	Medium	Direct reading	Direct reading	High	High	High	High	High	Medium	None
2. RF interferometry	Low	Direct reading	Direct reading	Medium	High	Medium	Medium	High	High	None
3. FM altimetry and FM radar	Medium	Direct reading	Direct reading	Low	Medium	Low	Low	High	Medium	None
B. IR/visible light tracking										
1. IR	Medium	Direct reading	Direct reading angles only	Medium	Medium	Low	Low	Medium	Medium	None
a. Source tracking										
b. Reflective tracking										
2. Visible light	Medium	Direct reading	Direct reading	Medium	Medium	High	Low	Medium	Medium	None
a. Source										
b. Reflective										
c. Pulsed										
3. Coherent light	Medium	Direct reading	Direct reading	High	High	High	Low	High	Medium	None
a. Laser sources										
C. Nuclear techniques										
1. Beta rays	Low	Direct reading	Not available	Low	Medium	High	High	Medium	Low	None
2. Gamma rays	Low	Direct reading	Not available	Low	Medium	Low	High	Medium	Low	Health
D. Television techniques										
1. Automatic tracking	High	By computation	By computation	High	High	High	Low	High	Medium	None
2. Man-in-the-loop	Low	By computation	By computation	Medium	Medium	High	Low	Medium	Medium	None
E. Sound/ultrasonics										
1. Generated sound	High	By computation	By computation	High	High	High	High	Medium	Low	None
a. Amplitude ratio										
b. Edge tracking										
2. Incidental sound	High	By computation	By computation	High	High	High	High	High	Medium	None
III. INTEGRATED RATE APPROACHES										
A. Position measurements	Low	By computation	By computation	High	High	High	High	High	High	None
1. Direct measurement										
2. Relative position										

PRELIMINARY STUDIES AND EVALUATION

As a result of the initial evaluation, eight approaches to the payload position sensor were selected for further investigation. These were

1. Boeing linkage
2. Big arm gimbal
3. Separated mechanical linkages
4. Force resolution
5. Proximity sensing
6. Sound/ultrasonic techniques
7. Electromagnetic tracking (radar)
8. Infrared/light tracking

Three of these approaches were rejected before the Phase I investigation began. The remaining approaches were evaluated further during Phase I.

The sensor techniques are described in detail in the following paragraphs along with the results of the preliminary evaluation.

BOEING SERIES LINK MECHANIZATION

Cable followers for cable-angle sensing are in current use. Figure 6 is a reproduction of a layout sketch provided by Boeing-Vertol for the HLH winch.

The function of measuring cable angles is divided between two links. The longitudinal cable angle is measured by the upper link, the lateral cable angle by the lower link.

The upper link is attached to, and pivots about, the cable cutter assembly. The cable cutter rotates freely in a support carriage which is free to travel longitudinally along rails which form a part of the lateral (side load) beam. As the cable takes a position from fore to aft, the cable departs tangentially from the drum and runs straight through the cutter assembly, which has aligned itself with the cable both longitudinally (fore and aft) and angularly. The upper link is held in alignment with the cable by the rollers at either end and the angular position is read out by a rotary position transducer. The shaft of the transducer is referenced to ground on the support carriage through a double link.

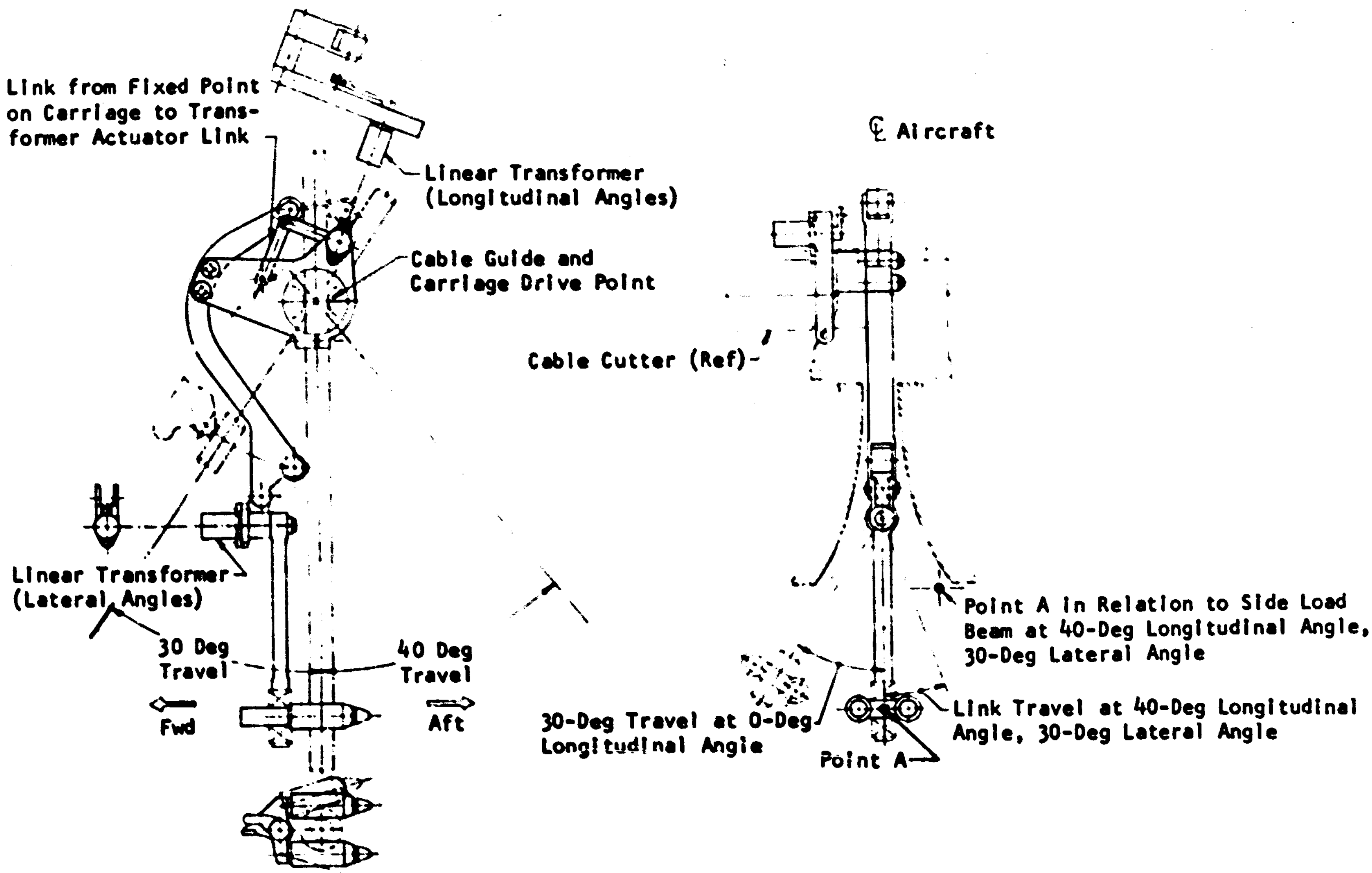


Figure 6. Sketch of Cable-Angle Sensing Mechanism Used by Boeing Vertol in the HLH Winch.

The lower end of the upper link carries the pivot shaft for the lower link which measures lateral angles. The lower link is driven laterally by a pair of spring-loaded rollers that capture the lower end of the cable between them. A transducer is located concentrically with the pivot shaft at the upper end, and measures the angle of the lower link relative to the upper arm.

Geometric Errors

The angle measured by the lateral (lower) link will differ from the true lateral angle because the pivot point is not coincident with the effective center of departure of the cable. In order to absorb lateral loads and limit the minimum radius of curvature of the cable, the vehicle is provided with side load beams. Thus, as the cable takes a position to the side of the zero (straight-down) position, the cable comes into progressively greater contact with the side load beam and the lateral angle error becomes progressively greater. Typical magnitude of this error, given Boeing geometry, is +4.0 deg at 30-deg actual lateral angle.

Another source of error, for the same reason as above, is the clearance between the side load beam and the cable. Due to this clearance, which may be 0.125 in. on either side of the cable, the lateral link will be deflected approximately ±1.2 deg without any significant cable angle actually having been achieved.

A further error in the measured lateral angle is due to the longitudinal position of the cable. This is due to the change in effective departure point of the cable from the load beam versus the lateral pivot center as the cable deviates from the zero (straight-down) position. At the extreme aft (+40-deg) position, this results in a measured angle 10.1 deg less than the actual 30-deg lateral angle.

All of the above errors are predictable and constant (except for wear effects) and could be compensated for, if necessary, in a computer operation.

Noncompensatory Errors

Due to clearance (typically 0.25 in.) in the cable guide at the cable cutter assembly, there will be an error in the longitudinal output angle unless special precautions are taken to preload in one direction. This error may vary from -5.1 to +2.5 deg depending upon which roller is in contact with the cable. Wear of similar magnitude will result in an equivalent error increase.

Roller and shaft wear of 0.50 in. will result in an error of about 0.5 deg. Zero-reference stop wear of 0.020 in. will result in an error of 0.7 deg.

This analysis of the Boeing mechanism was made to determine the sources and magnitudes of the various errors which might be present, with special attention given to random (noncompensatory) errors. When it was found that clearance errors could be as great as 5 deg, an alternate design was considered. The Big Arm Gimbal (BAG) represents a possible alternative.

BIG ARM GIMBAL

This approach, illustrated in Figure 7, embodies a gimbal-supported sleeve (tracking shoe) around the cable with linear transformers reading out the relative rotation about the two gimbal axes. The gimbal is supported by a two-link mechanism on the horizontal plane. The end of the first link is attached to the structure through a vertical axis. The two links are also jointed through a vertical axis. Thus the gimbal is free to track the cable movement, 6 in. below the side load beam, in the horizontal plane.

Due to the geometry of the links, the axes of the gimbal are skewed as the cable leaves the vertical (0 deg longitudinal and 0 deg lateral) position. This results in rotational errors in the sensed angles which are a function of the cable position. These errors are analytic and can be compensated with appropriate mathematics. These errors are of considerable magnitude; at a 40-deg longitudinal angle, the error in lateral angle is approximately 32 deg.

The major source of uncompensated error is probably the tracking sleeve clearance. This can be minimized by using maximum length. Some clearance is necessary even without wear, to allow for debris carried on the cable, unless spring-loaded elasticity is built in.

This approach is probably heavier than the Boeing roller link approach. Errors may be less, depending upon such factors as sleeve length and clearance. The use of the tracking shoe has several advantages over rollers. It is self-cleaning, insensitive to cable roughness, does not need additional lubrication within the wear limits, totally captures the cable and therefore will not suffer inadvertent disengagement, has a longer engagement length which may reduce errors due to clearance wear, and is easily accessible for inspection and replacement. Disadvantages include higher friction level, which results in higher cable wear, possible susceptibility to jamming by large pieces of debris, and the necessity of more frequent replacement.

A summary of the characteristics of the two mechanisms is presented in Table 2.

SEPARATED MECHANICAL FOLLOWERS

Figure 8 illustrates a simple approach, adapted to a specific suspension configuration where the longitudinal and lateral cable followers are separated. The top view shows the manner in which longitudinal cable angle is sensed. Since the cable cutter assembly follows the longitudinal motions of the cable, longitudinal angles may be easily sensed by installing a spring-loaded, wire-driven rotary position transducer so that it is driven by longitudinal motions of the cable cutter assembly. This arrangement would preload the cable cutter assembly against the cable so that hysteresis would tend to be minimized if friction were small between the cable cutter

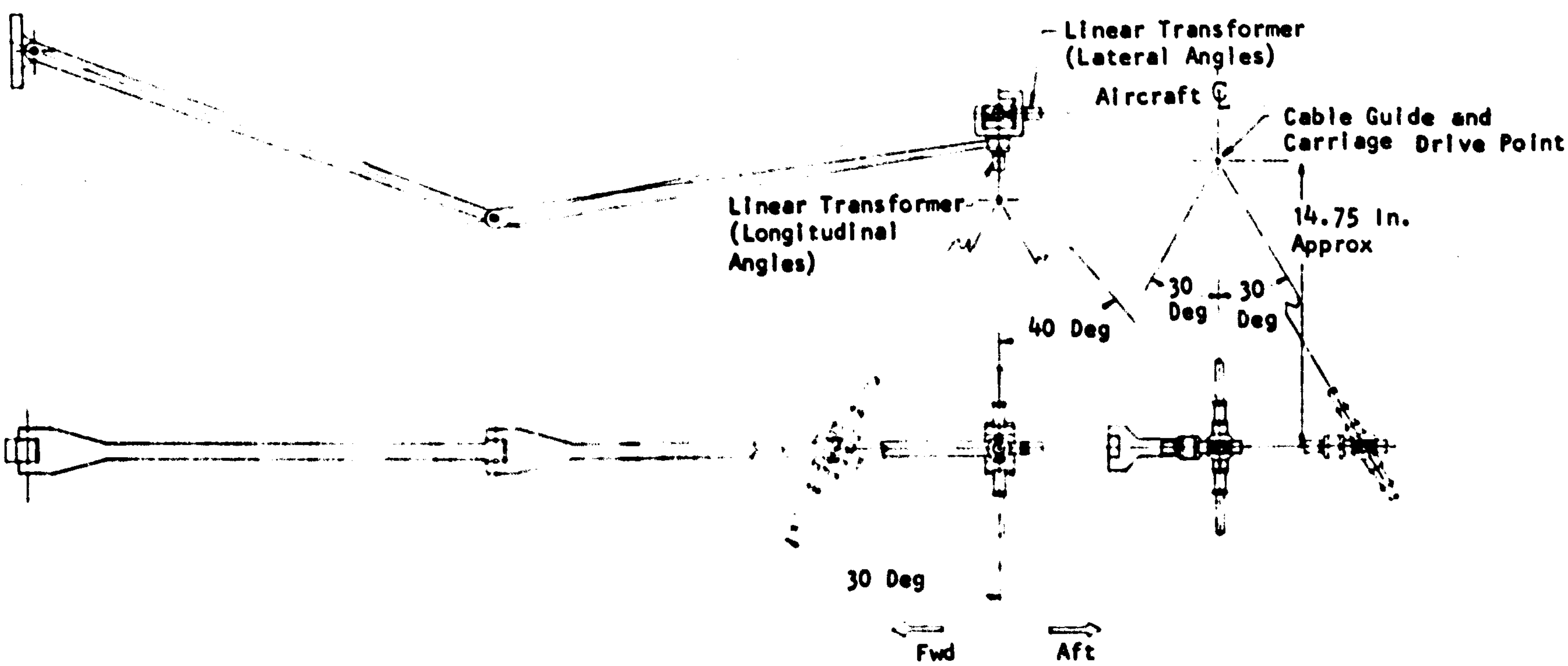


Figure 7. Big Arm Gimbal.

TABLE 2. COMPARISON OF THE TWO MECHANISMS

	Geometric Errors				Noncompensatory Errors					
	Longitudinal Angle, deg	Lateral Angle, deg	Longitudinal Error, deg	Lateral Error, deg	Type	Longitudinal Error, deg	Lateral Error, deg	Estimated Weight	Complexity	Cost
Boeing type CASM No. 1	0	0	0	0				5 to 10 lb	Moderate	$500
	0	30	0	+4						
	40	30	0	-10						
					0.25-in. clearance	-5.1 to +2.5	--			
					0.050-in. wear	-1.0 to 0.6	1.2			
Big Arm Gimbal CASM No. 2 (36-in. arms)	0	0	0	0				10 to 15 lb	Moderate	$500
	-30	-30	+18	-8						
	40	30	5.5	-32.2						
					0.050-in. clearance	±1.0	±1.0			
					0.050-in. wear	±1.0	±1.0			
					0.010-in. wear	-0.4				

Remarks

CASM No. 1 - Vibration prone, subject to cable roughness, requires frequent maintenance to clean rollers and lubricate.

CASM No. 2 - Vibration prone, requires occasional lubrication, periodic sleeve replacement, subject to large geometric errors due to axes skewing, requires large clear space for link articulation; however, provides positive cable capture.

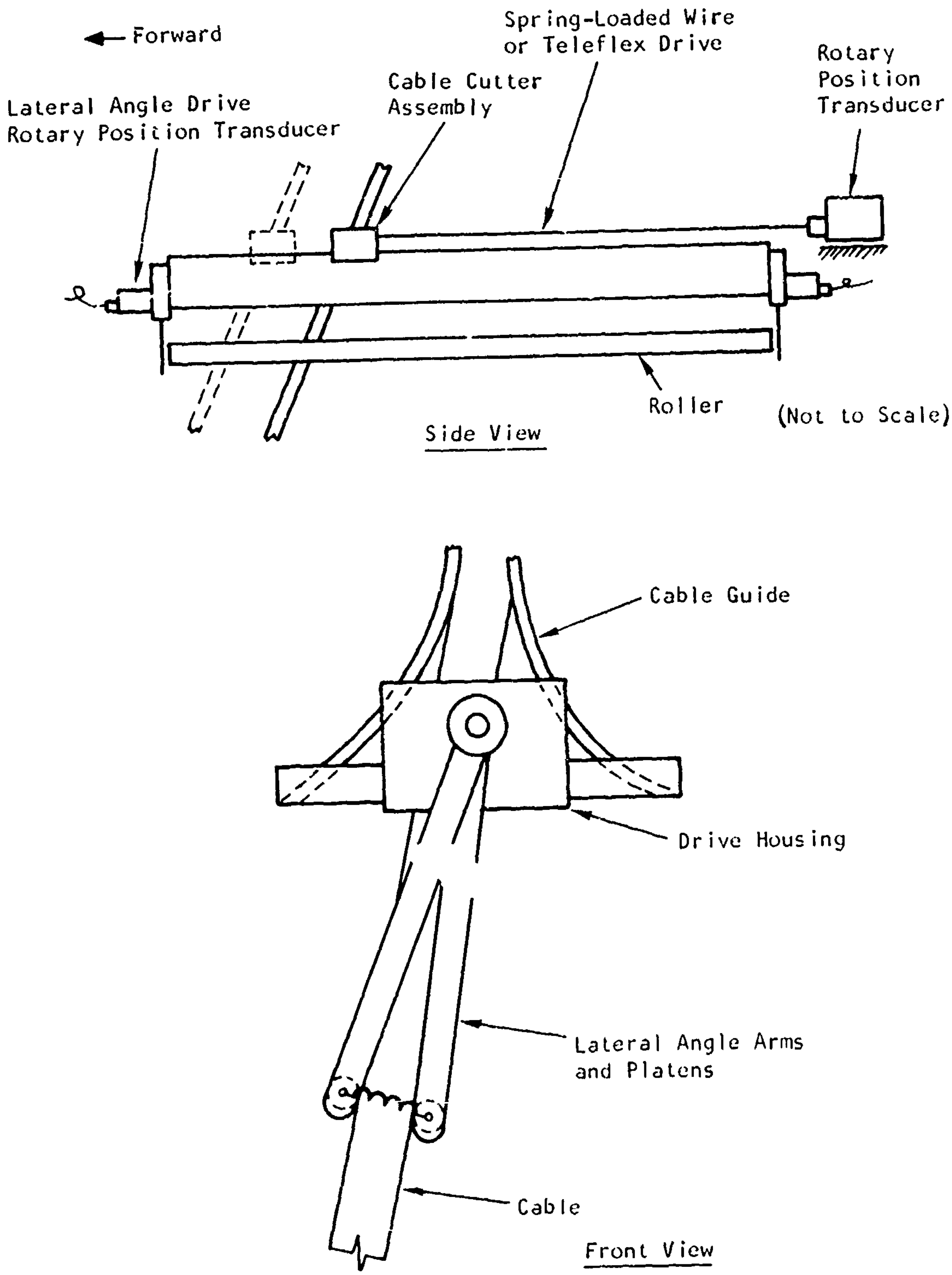


Figure 8. Approach Using Separated Mechanical Followers.

and the rails of the cable guide on which it rides. If the friction were such that wire tension were insufficient to drive the cable cutter assembly (with motion of the cable), then the cutter assembly would require redesign to minimize the hysteresis.

To sense lateral angles, a pair of rollers (platens) are suspended on arms that are pivoted at a point along the locus of the center of rotation of lateral cable motions. Rotary motions of the arms are sensed by rotary position sensors.

The advantages of this approach compared with the previous approaches are that it is simpler, lateral cable angles are not influenced by longitudinal angle, and disengagement of the lateral cable-following mechanism is not a problem.

The principal disadvantages are its somewhat greater weight and size, and roller wear. Roller wear due to longitudinal motions of the cable is the greatest problem, since it must be minimized without increasing wear of the cable. One final disadvantage is that the design is peculiar to a specific suspension-and-hoist configuration and would require redesign (if applicable) for each new configuration.

The minimization of roller wear involves optimizing materia selection and preloading of the rollers against the cable. It may also be possible to design the rollers so the roller and cable act as a gear pair and longitudinal motion of the cable drives the roller like a gear rather than sliding along it.

Pivot point selection for the lateral arms must also be optimized. The pivot points can be chosen to increase sensitivity near zero lateral angle at the expense of linearity, or linearity can be increased at the expense of sensitivity.

Provided the roller wear problem can be solved, this approach appears to have considerable merit. Errors in every category (as defined earlier) are smaller. Compensatory errors are smaller. Wear effects are smaller because the dual sensing mechanisms tend to cancel errors of this type (the wear surfaces occur in pairs and tend to be equal and opposite as sensed by the transducer mechanisms). Wear due to fit tolerances is less because of the arrangement of the followers and the preloading provided.

ANGLE TRANSDUCERS

All of the foregoing sensing approaches require rotary transducers. Three general types of rotary position sensors were considered: synchros, resolvers, and linear transformers. All operate on the principle of variable inductive coupling between one or more rotor windings and one or more stator windings. Hence, they are ac devices which produce signals whose magnitude and phase define the relative angle between the rotor and stator.

Synchros have a single-winding rotor. The stator consists of three windings spaced 120 deg apart and connected in a Y-configuration. Synchros are usually used in pairs to reserve an input angular position; however, synchro-to-dc converters are available which provide a dc signal proportional to the rotor-to-stator synchro angle. The accuracy of a synchro pair is about 15 min. A single synchro working into a synchro-to-dc converter is accurate to approximately 7 min; however, electronic conversion usually results in a total error of about 20 min.

Resolvers are primarily analog computing devices which were developed to solve coordinate transformation problems. They are built to extreme mechanical accuracy with respect to the placement of the windings, and many have temperature compensation to control the transformation ratios. They usually have two independent rotor windings spaced 90 deg from each other. They have two stator windings, sometimes with common center taps spaced 90 deg. The outputs from the stator windings are then proportional to the excitation voltage multiplied by the sine of the rotor angle for one output winding and the excitation voltage multiplied by the cosine of the rotor angle for the other winding. Since the accuracy of the resolver involves the transformation ratio as well as the rotor-to-stator angle, the total device accuracy is usually given in percentage of rated full scale. High accuracies are available, with 0.1 percent being common.

Of the several rotary position sensors, the linear transformer is the only one developed specifically to provide an output signal linearly proportional to the shaft mechanical angle. This result is obtained by restricting the operating range and by shaping the windings. For small angles the sine of the angular displacement is very nearly proportional to the angle. Up to 10 deg the error due to considering the sine linearly proportional to the angle is less than 0.25 percent. Thus, a simple angular position transducer that would be accurate to within ±0.25 percent up to ±10 deg of input angle could be constructed with a single rotor winding and a single stator winding. By winding the stator in two segments, with the axis of the segments displaced from each other, the range of the sensor can be extended. The use of multiple stator windings along several axes permits significant range and accuracy extensions. Linear transformers with linearity of ±0.25 percent over a range of ±50 deg are available, although 0.5-percent linearity over this range is more common.

All of the electromechanical angle sensors described operate on the principle of varying the transformation ratio between two windings. It should be noted that capacitive coupling also exists, causing a region of minimum coupling which will always be somewhat greater than zero. This will be especially true if the excitation voltage contains higher harmonics of the fundamental frequency. Thus, all of the sensor types will have an effective threshold below which angular motion cannot be sensed.

Table 3 summarizes typical operational characteristics of the sensor types.

TABLE 3. OPERATIONAL CHARACTERISTICS OF THE SENSOR TYPES

	Servo Pair	Resolver	Linear Transformer
Sensitivity, deg	0.393	0.454	0.2
Accuracy, deg (linearity or deviation)	±0.25	(±0.1 percent functional); ±0.028 deg at 28 v	±0.25
Operating range, deg	±180	±180	±50
Null voltage, v	0.030	0.026	0.015
Threshold, deg (null voltage divided by sensitivity)	0.076	0.062	0.075

Angular rate information may be derived from angular position measurement by either analog or digital computation. Each method has its advantages and limitations, but both are limited by the characteristics of input angle information. Analog computation of rate is characterized by rapid response and good accuracy, but requires dedicated hardware, i.e., the computation requires hardware that performs only the function intended. Digital computation can be more economical with the actual computation performed by general-purpose circuits, but has an information lag equal to the iteration time of the processor, and also characteristic noise of significant amplitude. Both methods require some means of phase-sensitive demodulation. Analog computation requires a dedicated phase demodulator, while digital techniques can utilize the analog-to-digital converter referenced to ac power for both position and rate signals. Figures 9 and 10 show the functions which must be performed for the two computational methods.

Regardless of the method of computation, high accuracy is obtainable in the computation of position. With the analog circuit the major problem affecting accuracy is determination of scale factor (v/rad/sec). Since the scale factor is a matter of definition, any errors are easily removed from the computation by calibration.

Digital computation will produce a time-dependent rate signal that averages to zero error over successive computations, but which is significant in absolute value. For instance, for an input angular range of ±50 deg (100 deg total), computer resolution of 12 bits (one part in 4096) and computer iteration time of 0.05 sec, a resolution/iteration of 0.488 deg will be seen, or the computed rate may be in error by ±0.488 deg per sec at any instant. Such errors will appear as noise on the rate signal with its

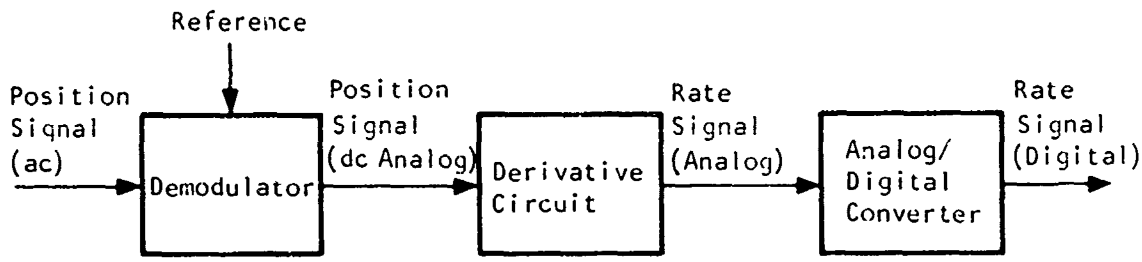


Figure 9. Analog Rate Signal Generator.

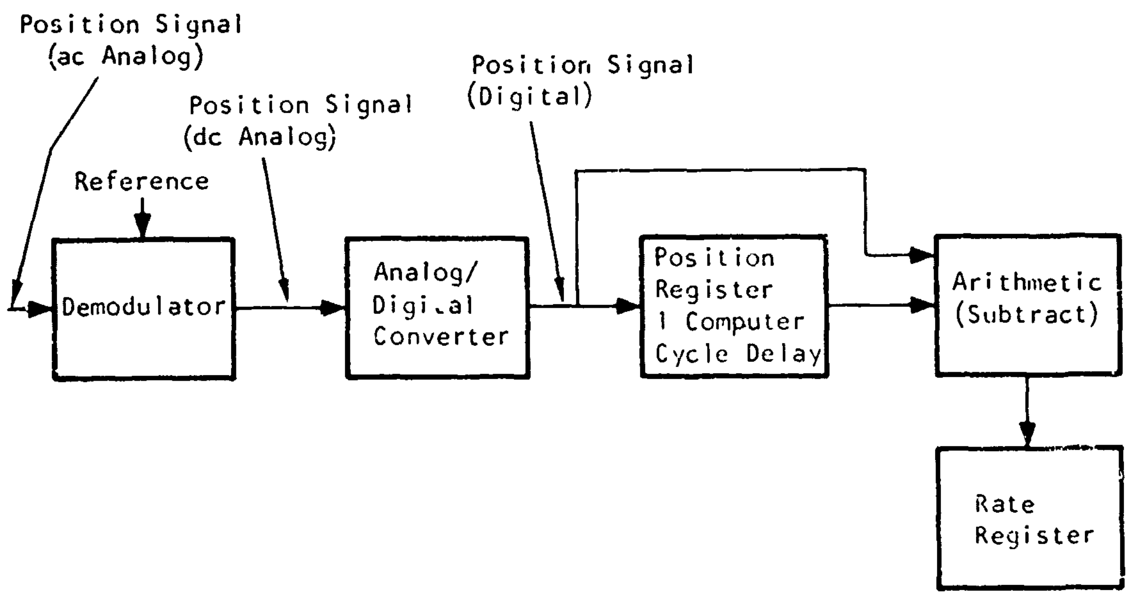


Figure 10. Digital Rate Signal Generator.

possible magnitude constant regardless of the actual rate. The fundamental frequency of the noise will be 20 Hz for the example given but will usually be approximately 5 to 10 Hz.

ANGULAR RATE TRANSDUCERS

Devices for direct measurement of rotation rate fall into two operational categories, which depend upon the reference coordinates. Angular rate transducers, such as rate gyros, measure angular rates with respect to inertial space. Tachometer generators provide signals proportional to the rate of rotation of a rotor relative to a stator element; therefore, they are referenced to the coordinates of the frame to which they are mounted.

The rate gyro is the most highly developed of the transducers which are inertially referenced. They are readily available, reliable, and may be obtained for a wide range of accuracies. Their output signals are usually in the form of synchro stator or linear transformer ac voltages.

Tachometer generators are also highly developed and readily available. The direct drive units are usually dc generators providing approximately 0.001 v/deg/sec for units of approximately 1.5 in. dia. Sensitivity increases at approximately π times the diameter increase ratio.

For a given input angular rate, techniques to increase the rate at which the transducer is driven include the use of step-up gear trains and resetting the input position with the position transducer geared down from the servo motor-tachometer. The step-up gear train is seldom used for ratios greater than about 5 to 1, due to the effects of reflected inertia. The servo technique is straightforward and provides an opportunity to modify the position signal as well as the rate signal.

Table 4 summarizes the important characteristics of the various methods of measuring angular rate.

TABLE 4. CHARACTERISTICS OF ANGULAR RATE MEASUREMENT METHODS

	Gyro	Direct-Driven Tach	Geared Tach	Servo Tach
Sensitivity, v/deg/sec	0.3	0.001	0.005	0.003
Max rate, deg/sec	80	46,000	9,000	390
Band pass, Hz	20	50	5	10
Threshold, deg/sec	0.1	1.0	0.5	0.1
Accuracy, deg/sec	0.08	1.0	0.2	0.4

FORCE RESOLUTION OF CABLE-ANGLE SENSING

Two force resolution techniques were considered: (1) the use of load cells with flexures, and (2) the use of strain gages on flexures. These approaches are essentially the same in that both use mechanical resolvers.

Although the arrangement of the flexures or load cells is strongly design-dependent, the principle can be discussed by considering a winch system which is fixed to the aircraft structure at four points. The first approach utilizes flexures at these points. The flexures support the vertical load, but allow small motions of the platform in the x-y plane. These motions are resisted by load cells which sense the forces in the x-y plane. In the strain gage approach, each flexure would support the vertical load and act as a mechanical resolver that reacts to forces in the x-y plane and would be strain gaged to measure the forces in the x-y plane.

Cable angle may be determined by resolving the cable tension into its components and measuring the components.

The components required are side forces in the horizontal plane and either cable tension or the vertical components of the cable tension. The outputs from these measurements can be used to compute the cable angle relative to the aircraft and to provide inputs to the aircraft control system or to an augmentation or damper system.

Vertical forces can be determined by measuring either the cable tension with an in-line load cell or by measuring the vertical loads applied to the aircraft structure by the hoisting assembly. The vertical loads applied by the hoist may be measured by mounting the hoist platform on f load cells or force links acting as support columns. The links must be capable of allowing translation in all directions in the horizontal plane, or they must react to the forces in such a fashion that the forces can be measured. The simplest design is a force link with a rod-end bearing at each end, which allows freedom of movement in the horizontal plane but reacts to vertical loads.

The average output of the four load cells would measure vertical force regardless of its points of application.

The measurement of the side forces applied to the aircraft requires either (1) a cable-guiding device attached to the aircraft through instrumented force links, or (2) measurement of the side force applied to the hoisting platform assuming that the cable guiding and hoisting operations are done by the same mechanism.

The side forces applied to the hoisting platform or cable guide could be measured using four force links in the horizontal plane to prevent both lateral translation and rotation. The signal resulting from the forces reacted to by each load cell would be summed to obtain the net side force in that direction while the difference in output of two force links on the same side would measure the torque applied to the platform. The links must not react to the vertical load and the vertical support must not react to the side loads. This could be done using rod-end bearings with the load cells.

If the cable tension approach is used, the system is simplified because the vertical load measurements between the aircraft and the hoisting platform are eliminated.

The outputs of these transducers would be fed into a computer, which would calculate the cable angle.

The currently available load cells that use foil type strain gages have outputs which range from 2 to 6 mv/v, with usual excitation being 10 v for good stability. Assuming that the minimum resolution of the instrumentation is 0.01 mv, the side forces could be determined to 0.02 percent of full-scale value. Semiconductor load cells such as those manufactured by Tyco have outputs that are approximately 30 mv/v, which, at 10 v excitation, results in an output signal of 300 mv. The advantage of the greater signal is that less amplification is required and the signal-to-noise ratio is improved, providing better accuracy. If the minimum resolution of the electronics is assumed to be 0.01 mv, the minimum force detected is 0.003 percent, which is better than the accuracy of the load cell. Conventional load cells have accuracies of 1 percent and special high-accuracy models have accuracies of 0.1 and 0.01 percent of full-scale values.

If cable angle is to be determined to within ±1 deg, the side forces must be measured to within 0.2 percent of cable tension for angles of 10 deg or less. This is well within the capability of the conventional load cell, as the accuracy required of the load cell is only 1 percent. The standard-accuracy load cell would handle this measurement without difficulty. If closer tolerances are required, a load cell of 0.1 percent accuracy could be used; this would permit measurements of sufficient accuracy to allow resolution of the angle to within ±0.1 deg.

An alternate system would be one where the sling load is not measured but is dialed in, using a thumbwheel switch. This information is combined with the measured side loads to determine the cable angle. For angles of less than 25 deg, an error of 1 percent in the estimated sling load would result in an error of less than 1 percent of sling load applied as a side load to the aircraft. If the action of the control or augmentation system is rapid, and if it prevents large angular excursions, then the effect of the error diminishes as the excursion is attenuated. Cable tension changes caused by vertical load oscillations would cause transient system errors.

The most attractive approach, considering system complexity and accuracy, would be the system using the side-load measurement with 0.1-percent-accuracy load cells and providing a sling load input, either from a load cell in the cable or from a cable tension-measuring device. This system would provide side force determination to within 0.01 percent of the sling load and an angle determination to within ±0.1 deg.

CABLE-ANGLE SENSING USING PROXIMITY PROBES

Three basic types of proximity probes are in common use: eddy current, capacitive, and permanent magnet. The last requires relative motion between the object and the sensor and is therefore eliminated from consideration. Of the eddy current and capacitive types, the former offers greater range capability but is less rugged.

Figure 11 is a plot of the range of a set of typical eddy current type probes versus the probe diameters. Range is defined as the distance over which the probe meets its accuracy specification, typically better than 0.5 percent of full scale for a flat aluminum plate target. It can be used for longer ranges at reduced accuracy; e.g., the 2.9-in. probe can measure distances up to nearly 4 in. with an error of about 1/8 in.

Consider the candidate proximity probe arrangement schematically depicted in Figure 12. This view represents the location of two probes used to sense lateral deflections of the cable, i.e., as viewed looking aft underneath the aircraft. For simplification, a fixed exit point is assumed. The probe locations in y and z are selected to allow ±30 deg lateral motion and to operate the probes within their range capability as given in Figure 11.

Note that the probe is sensitive to both the distance for determining the angle in the y-z plane and the angle of the target (cable) in the x-z plane. An angle of 30 deg in the x-z plane can easily contribute an output change of 10 percent or more, which would not be distinguishable from the desired distance measurement if a single probe were used in the y-z plane. To compensate for this error, four proximity probes should be used and connected in an amplifier configuration that would cancel the output signal due to the cable angle in the perpendicular plane. The output signals of each 180-deg pair could be fed into a differential amplifier. The signal due to the cable angle in the perpendicular plane (the x-z plane in Figure 12) would have the same effect on the two coils, and, since the amplifier must see a difference between its input terminals, no output would result due to the x-z cable angle. When the cable approaches one proximity probe in the y-z plane, however, the output of one proximity probe increases while the output of the other decreases. This differential is seen by the amplifier and an output signal is produced. To prevent possible interference between the two pairs of proximity probes, the second pair of opposing proximity probes could be above or below the first pair. Several other alternatives are available to prevent interference or beat frequency problems between opposite probes as well as the two pairs: (1) synchronizing the carriers so all proximity probes are at the same carrier frequency, (2) shielding the probes, and (3) operating the probes at different carrier frequencies.

Several other potential problem areas exist in this approach as seen in Figure 12. The restrained exit cannot completely restrain motion in the x-y plane at that point. Any motion at this point would result in a system error. Similarly, consider the bend radius shown for the cable. If the

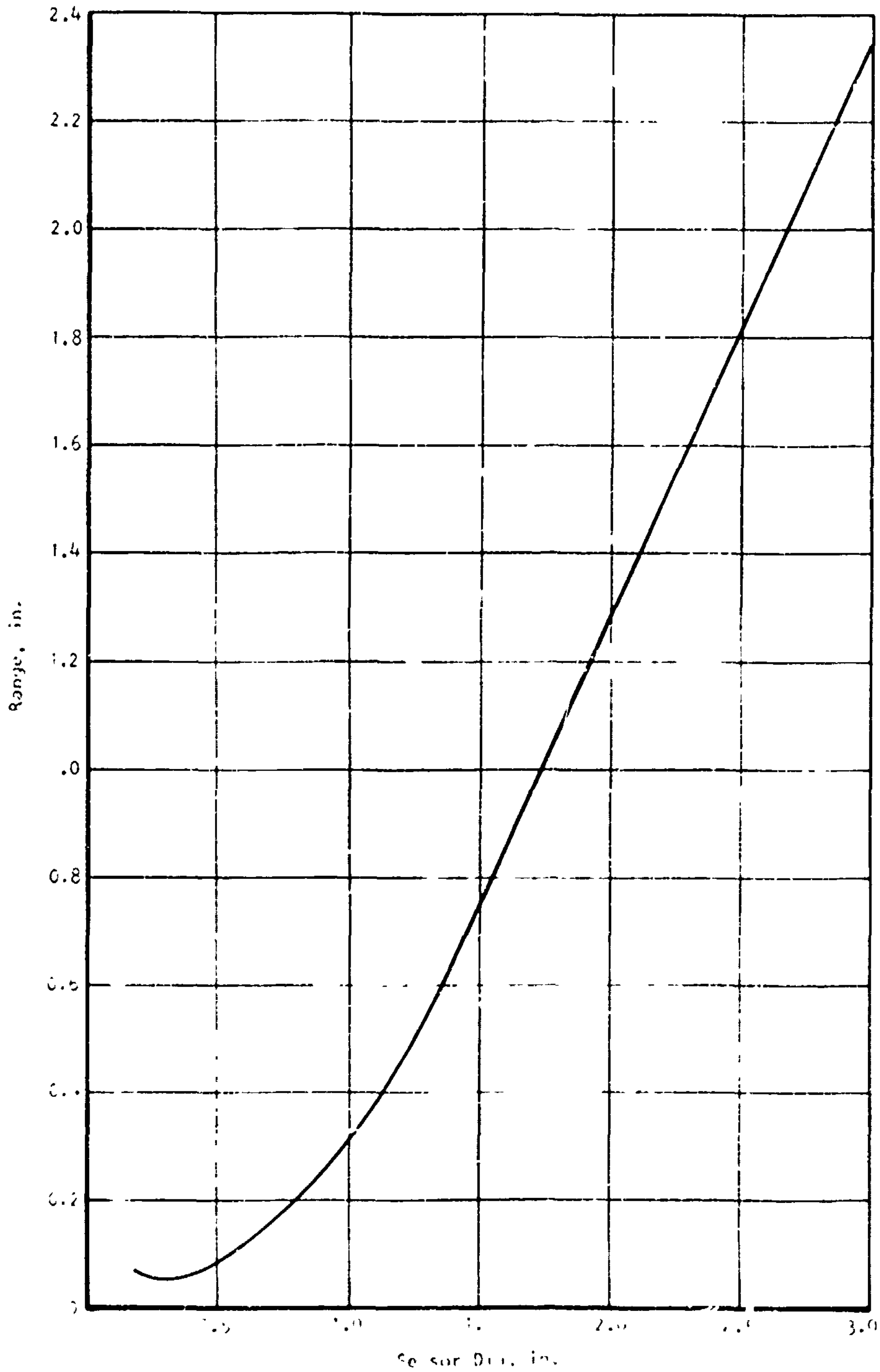
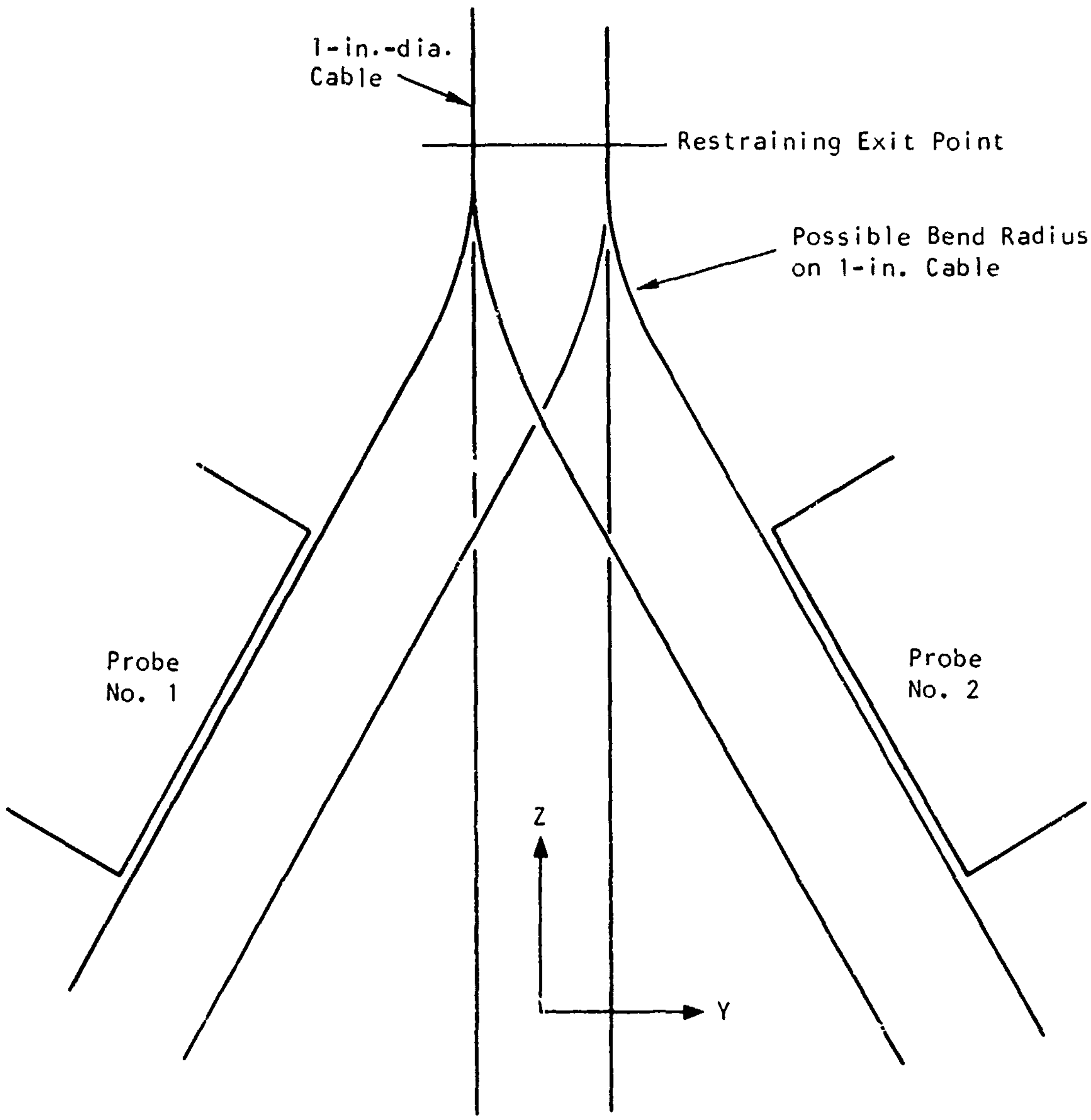


Figure 11. Relationship Between Diameter and Range of Eddy Current Type Probes.



Note: Total 4 probes required. Two probes 180° apart working in push-pull into an operational amplifier.

Figure 12. Candidate Proximity Probe Arrangement.

cable stiffness and the load weight are such that the cable is actually curved for the first few inches below the restraining point, the system would require compensation for this error. Note that the dimensions involved are necessarily small. Consequently, changes in cable tension due to load motion and even a small amount of linear motion of the cable (e.g., due to wind) could cause large angle-measurement errors. The probe indicated is the largest of those marked on Figure 11. The use of a smaller probe was considered. Both target size and target shape affect the sensor output. In the general application of proximity probes it is desirable to use a probe tip diameter that is smaller than the target area. The data in Figure 11, however, show that decreasing the probe diameter does not improve the geometrical situation. In fact, for some considerations, e.g., the lack of rigidity of the restraining point, the effect is detrimental; also as the diameter of the probe decreases, its sensitivity to surface irregularities in the cable increases. In terms of sensing cable angle, this is another possible source of error; however, this information could be used to measure periodic twisting of the cable and calculate yaw rate of the load for single cable suspension systems. In order to determine the accuracy of this approach, a cable would have to be selected and included in the analysis. The following paragraph discusses the use of a proximity probe for yaw rate detection.

For a typical steel cable, the large outer bundles could provide a signal usable for rate of yaw measurement. Again, assuming the cable leaves the aircraft through a hole where radial motion is restrained, a proximity probe near this point would sense the twisting of the outer cable bundle. A typical proximity probe for this would have a 1/4-in.-dia body and a 1/8-in sensing end.

The number of pulses generated per unit time would be determined by the number of cable bundles that passed per second. The signal appearance would be somewhat sinusoidal, due to the cable appearance to the probe and the probe diameter. For larger probe diameters the cable bumps would be less noticeable. In any event, the amplitude of the individual peaks would vary due to the asymmetry of the cable.

SONIC/ULTRASONIC DISTANCE MEASUREMENT TECHNIQUES

Background and Basic Principles of Operation

The basic technique employed in sonic/ultrasonic distance measuring devices is the pulse-echo technique. This technique is based on the principle that a reflecting wave is generated when an incident wave crosses a boundary of different acoustic properties. In practice, a sonic or ultrasonic pulse is sent out and the delay time between the transmitted pulse and the received pulse is used to calculate the distance between the transmitting point and the point where the echo is generated. Since the velocity of sound traveling in a medium is a known function of temperature, the distance traveled by the pulse can be obtained by simple multiplication of the velocity and the delay time if the temperature of the medium is known.

This means, for precise distance measurement, that a measurement of ambient temperature and a correction of sonic velocity for temperature is needed. The actual distance measured by a sonic/ultrasonic device is the straight-line distance between the transmission point and the reflection point.

Some of the more familiar applications of the pulse-echo technique are: (1) sonar, (2) Fathometers, (3) nondestructive testing, (4) tank or bin material level sensing, (5) tumor detection, (6) traffic signal control, and (7) thickness gaging. The frequencies range from about 16 kHz to 25 MHz. The choice of frequency depends on the requirements for the unit. In general, the higher the ultrasonic frequency, the smaller the target or fault which can be detected. As the frequency goes up, however, the range of the unit for a given power output decreases. Therefore, the lowest practical frequency for a given purpose is usually selected.

Type of Sensors and Electronics

The transmitter and receiver, separate or combined, are generally made up of solid-state ferroelectric crystal material such as barium titanate or natural or synthetic quartz. These types of transducers have operational temperature ranges from -65°F to +150°F and can withstand shocks and vibrations of several hundred g's. Electronics generally consist of an ultrasonic generator, transmitter, receiver, amplifiers, cathode ray oscilloscope, meters, and other time and amplitude measuring devices. Once the received signals have been properly conditioned they may be used for various recordings detection, and switching functions.

Application to Helicopter Load Position Measurement

Almost all previous applications of sonic/ultrasonic techniques in air have dealt with relatively short range (distance) measurement. In the measurement of helicopter load position, the need is to extend existing capabilities to distances of about 100 feet (see Table 5). One of the more recent and most promising applications of the ultrasonic technique in this range is an ultrasonic altitude-velocity sensor for airplanes in the vicinity of ground*. Another candidate system is a commercially available tank or bin material level sensing system with a maximum range of about 100 feet. Block diagrams of these two systems are shown in Figures 13 and 14.

There are two potential ways of using a sonic/ultrasonic system to measure payload position: (1) measurement of payload distance from the helicopter, based upon some initial reference condition, and (2) measurement of the load cable angle with respect to the helicopter. A short discussion of each method is given in the following paragraphs.

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* Maeda, H., and Ymeda, Y., AN ULTRASONIC ALTITUDE-VELOCITY SENSOR FOR AIRPLANES IN THE VICINITY OF THE GROUND, Journal of Aircraft, Vol. 9, No. 4, April 1972, pp. 294-297.

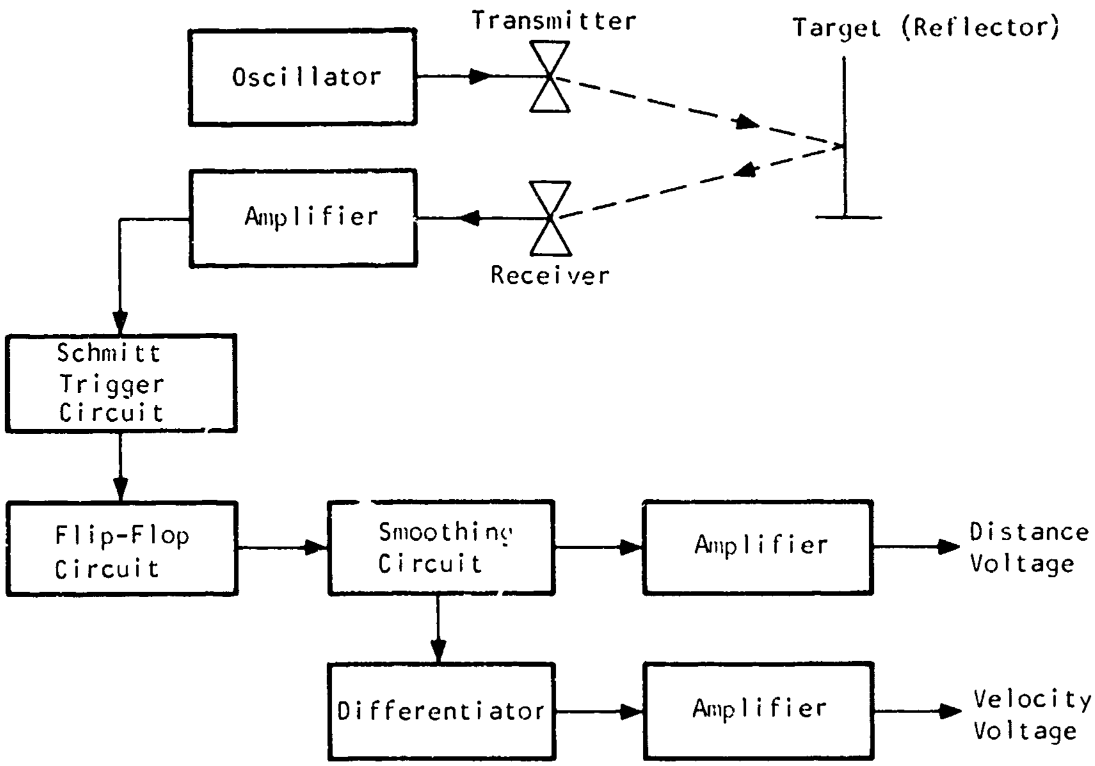

Figure 13. Block Diagram of a Distance-Sensing System.

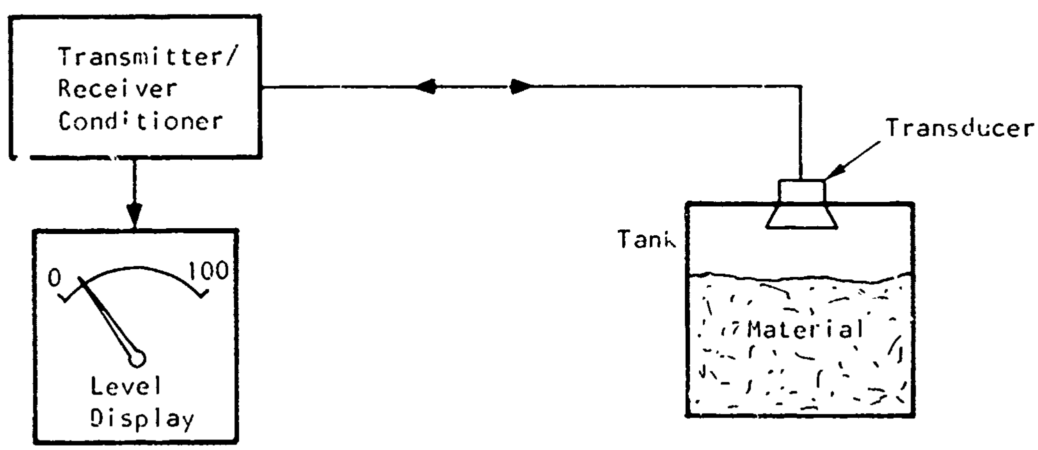

Figure 14. Block Diagram of a Tank or Bin Level-Sensing System.

Measuring the payload distance from the helicopter imposes several severe requirements on the ultrasonic system. From Table 5 it can be seen that the sensor(s) must have a lateral range capability of ±30 deg (equivalent to ±25 ft for a 50-ft cable length) and a longitudinal range of +30 deg to -60 deg (equivalent to +25 ft to -43 ft for a 50-ft cable length). There are transducers available that have the angular range capability, but their distance range is only several feet. Another possible solution would be to use several narrow-angle, longer-range transducers mounted in a fan arrangement. This would make a more costly and complex system and also increase the total weight and power requirements, but would offer the advantage of a more thorough coverage of the area being viewed. Any system, using either single or multiple transducers, would require considerable design and development effort to determine overall performance and usability.

TABLE 5. PARAMETER RANGE REQUIREMENTS*

Lateral:	±30 deg
Longitudinal:	+30 deg, -60 deg (trail)
Yaw:	±20 deg
Lateral and longitudinal rates:	2 rad/sec
Yaw rate:	3 rad/sec (6 rad/sec extreme)
Pilot input:	30 deg/sec (roll)
Cable length:	20 to 50 ft (usual)
	75 to 200 ft (rare)
	Less than 100 to 25 ft (very rare)

*AiResearch Report 73-9333(2), July 5, 1973, page 8.

Load cable angular position sensing can be achieved by two different methods: (1) a system where tracking is used, and (2) a system where tracking is not used.

If one of the units is tracked, the angular position of each load cable can be determined with one transmitter/receiver and reflector. The position of the tracking system would be used to determine the cable position relative to the helicopter. The tracking system would have to have a very stable and high response control system. From a practical standpoint the tracking system would need to be mounted on the helicopter. If the reflector were mounted on the load cable hook it would always point toward the helicopter, assuming that the cable always remained taut. Figure 15 is a typical block diagram of this system.

The angular position of each load cable could also be determined without tracking. This would require a number of transmitters/receivers mounted on the helicopter and separated by known distances and a single reflector mounted on the load. The position of the cable, and thus of the load, would be determined by trigonometric equations based upon the known sensor locations and the received signal strengths. The time delay between transmitted and received pulses or pulse amplitudes could be used to determine load location. Figure 16 is a typical block diagram of this system.

Problem Areas

In either of the above approaches there are problem areas. There are serious problems due to signal attenuation, helicopter noise spectrum, helicopter speed, rotor slipstream, and the effects of altitude and ground conditions. Figure 17 shows the estimated attenuation characteristics of ultrasonic wave propagation in air. From this figure it is obvious that the lower the frequency, the greater the distance that can be measured. The noise spectrum of the helicopter, however, must be considered to be such that it seriously limits the use of any ultrasonic system. The effects of helicopter speed are shown in Figure 18. For speeds of less than 100 kmph, this factor could be ignored. Figures 19, 20, 21, 22 show the effects of the rotor slipstream. From these figures it can be concluded that the rotor slipstream induces errors in distance measurement and reduces the sensitivity of the receiver. Ground conditions (in this case, payload) will vary due to size, weight, physical shape, and material. To achieve maximum flexibility and usefulness of any system, the system should be essentially independent of the payload. One possible solution would be to mount the transmitter/receiver or the reflector on the load cable hook. This would make the system essentially independent of the payload.

Potential Accuracy and Resolution

A few simple calculations will show that there are serious limitations on the usefulness of sonic/ultrasonic systems. Utilizing equations available in the literature* and measurement ranges from Table 5, the following results are obtained:

Assume a frequency of 19 kHz. Therefore,

$$\lambda = \frac{c}{f} \cong \frac{1,127}{19,000} \simeq 0.059 \text{ ft } (\simeq 0.7 \text{ in.})$$

where λ = wavelength, ft
c = speed of light in air, ft/sec
f = frequency, Hz

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* Dean, D.S., TOWARDS AN AIR SONAR, Ultrasonics, January 1968

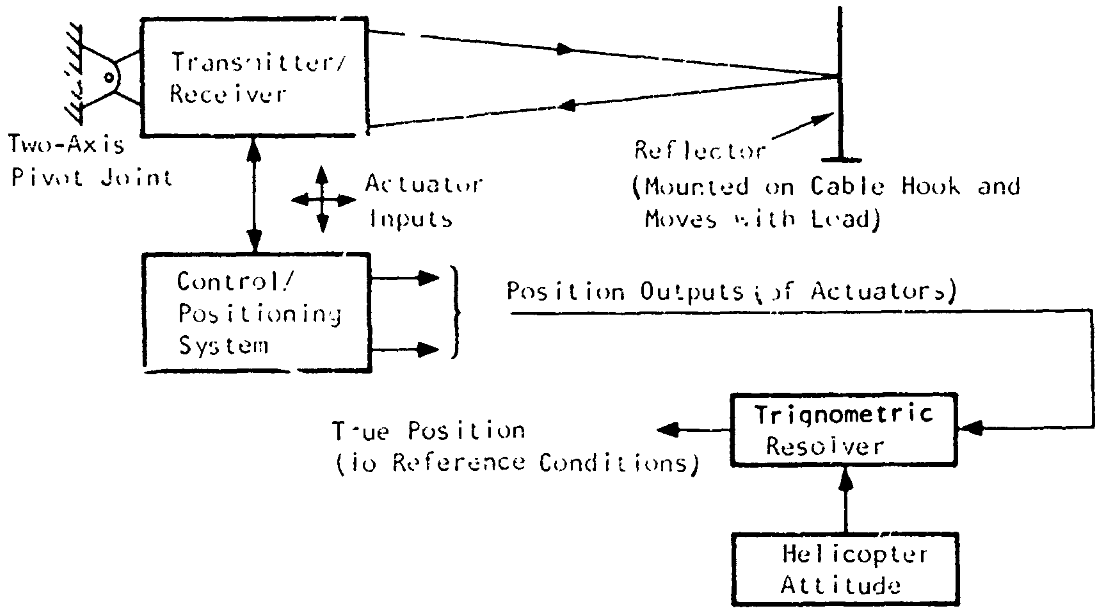


Figure 15 Block Diagram of an Angular Position-Sensing System--Tracking Type.

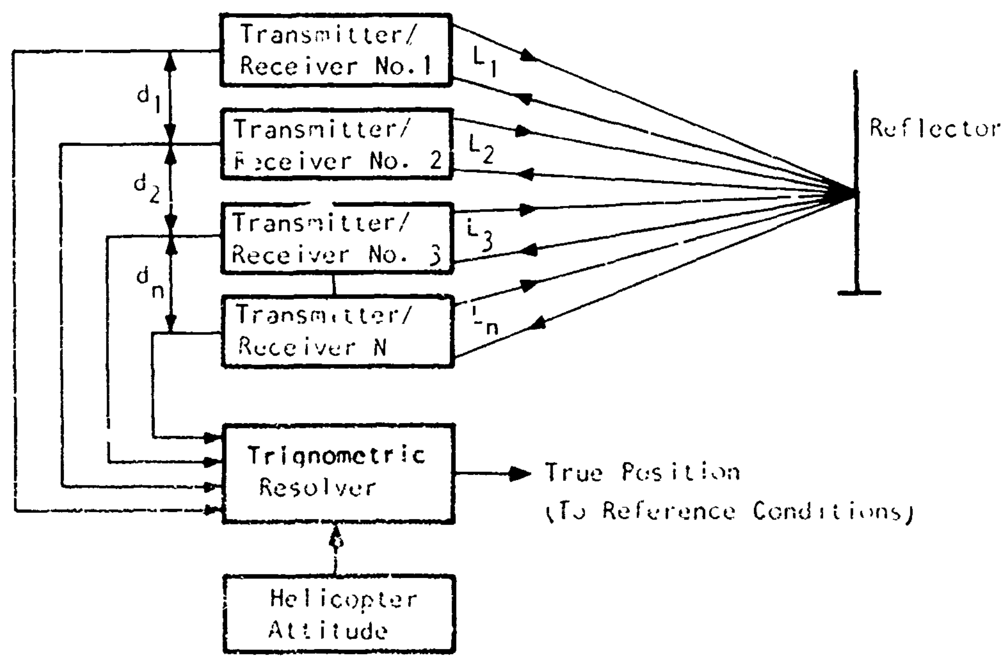


Figure 16. Block Diagram of an Angular Position-Sensing System--Nontracking Type.

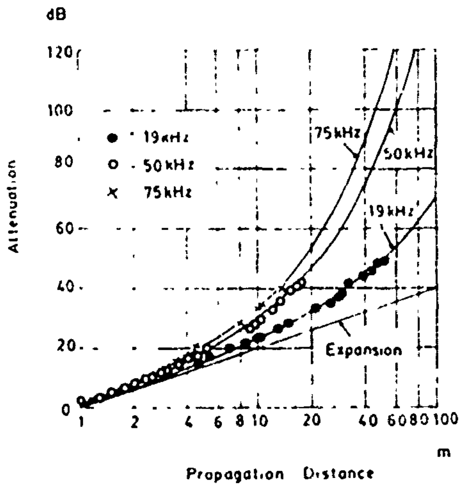


Figure 17. Attenuation Characteristics of Ultrasonics in Air.

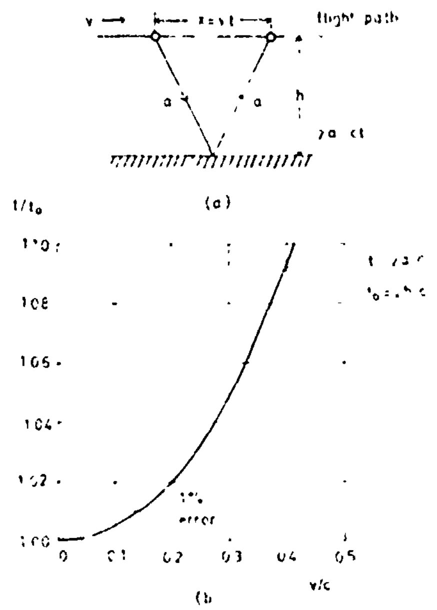


Figure 18. Effect of the Forward Velocity of an Airplane.

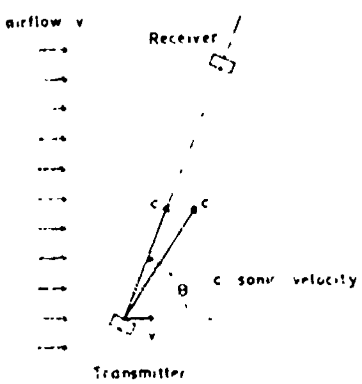


Figure 19. Effects of the Steady Wind.

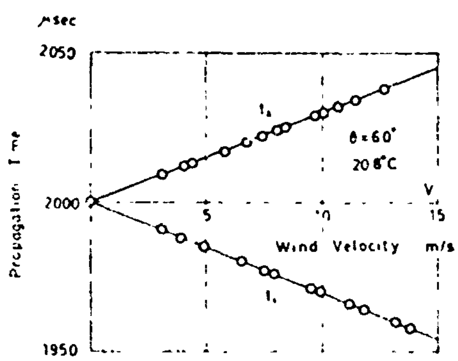


Figure 20. Variation of the Propagation Time due to the Steady Wind.

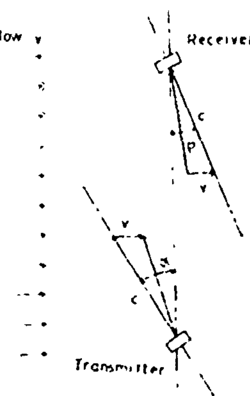


Figure 21. Effects of the Steady Wind.

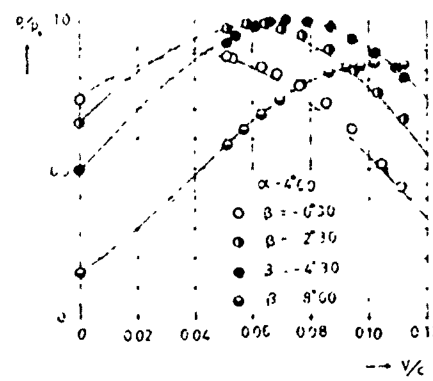


Figure 22. Variation of the Ultrasonic Pressure Ratio or the Sensitivity due to the Steady Wind.

For a 50-ft distance, the time for this pulse to travel the 50 ft and return is

$$t = \frac{(50 + 50)\ \text{ft}}{1{,}127\ \text{ft/sec}} \quad 0.088\ \text{sec}$$

For a worst-case condition of 2 rad/sec change in the lateral and longitudinal directions, a change of approximately 10 deg in load position occurs between the time at which the pulse is transmitted and received; this is not very good resolution. The next consideration is transducer size. If an angle of ±10 deg is to be covered,

$$a = \frac{0.61\lambda}{\sin\theta} \simeq 0.21\ \text{ft} \quad (\simeq 2.5\ \text{in.})$$

where a = radius of sensor, ft
θ = beam half-angle, deg

i.e., a 5-inch-diameter sensor would be required. Assuming 10 w/cm^2 of power from the sensor, 125 w of power would be required. If several sensors are required, our power requirements could become very large. From Figure 17, it can be seen that the received signal would be down by approximately 40 dB, i.e., the received signal would have a strength of approximately 1 watt. Obviously, the use of ultrasonic detection would require the solution of many problems.

Other Sonic/Ultrasonic Applications and Costs

The previously described techniques have been applied to the measurement of such things as flow, wind conditions, tank or bin material level sensing, etc. The costs of commercially available systems range from a few hundred dollars for the simplest level sensor to several thousand for the more complicated wind-condition measuring systems. In general, the cost would appear to be very high for the sophisticated systems required for the proposed payload application.

The use of sonic/ultrasonic techniques to determine helicopter payload position does appear to be feasible, but there is insufficient data and information at this time to make a final decision. Cost, size, weight, and complexity are unknowns at this time and can only be determined after significant research and development in design, fabrication, and testing of components and systems.

RADAR TECHNIQUES

One of the physical approaches considered by AiResearch as potentially applicable to load position sensing is radio frequency (RF) electromagnetic radiation. Initial evaluation of this is justified by several characteristics based on the ability of electromagnetic radiation in much of the RF spectrum to penetrate through air for distances great enough to be applicable to load sensing (e.g., 250 ft one way) without being significantly disturbed by the propagation path environment. For example, perturbations caused by high velocity air currents are essentially absent, in marked contrast to acoustic waves; attenuation and scattering from dust, fog, snow, and rain are substantially less than for the shorter wavelengths, such as infrared radiation. A disadvantage of the active RF approach is the possibility of enemy detection, although this becomes an element for tradeoff consideration after required system RF radiated power levels and patterns, and possibly less detectable modulation methods (e.g., noise), have been defined.

Potential RF techniques have been examined in accordance with the policy that any necessary technological building blocks must already be proven in the field of the art, and be readily adaptable for inclusion in this implementation.

Categories in RF technology that have been examined for pertinence to the position sensing application include (1) pulse modulation of RF carrier (pulse radar applications), (2) RF interferometry (used in surface-to-air missile terminal guidance, navigational position determination, and machine tooling precision position measurement), and (3) frequency modulation (FM) of the RF carrier (radio altimeters, spacecraft rendezvous and docking, FM radar applications, and collision warning devices).

Pulse Radar

Of the potential categories listed above, the pulse radar technique appears to provide the least-promising methodology for obtaining the spatial resolutions required. (An approximate 4-in. resolution is required at the 250-ft range.) Transit time resolution capabilities of a fraction of a nanosecond would be required.

RF Interferometry

The second category examined for applicability to load sensing is RF interferometry. The arrangement considered would be employed to provide distance measurement from one RF continuous wave (CW) radiating source located on the load to three or more receiving antenna locations on the aircraft. By comparing the electrical phase values of the RF signals as received at each station with an on-board generated reference RF signal, very accurate determinations could be made of displacement along the line of sight between the common single radiating (or passive reflecting) source and each individual receiving antenna location. As the reference signal and any one signal received from the load location pass through in- and out-of-phase relationships as distance changes, the senses of phase change and accumulated total phase shifts corresponding to increasing or decreasing distances can be accurately measured and stored. AiResearch studies have indicated, however, that the short wavelengths required to permit use of small antenna sizes and achievement of precise resolution require the resolution of phase comparison ambiguities. These ambiguities arise from the fact that the 250-ft maximum load distance is many wavelengths long, and therefore many identical phase shift cycles will be traversed as the load moves toward or away from the aircraft. Determination of the correct phase comparison cycle requires equipment complexity that makes the second category appear less promising than the third one.

FM Altimetry and FM Radar Applications

The most promising of the RF techniques considered for load position measurement is the technology of FM altimetry and FM radar applications. Schematically, a compact solid-state (e.g., Gunn diode) C- or X-band microwave CW oscillator would have its frequency changed linearly with time, following a repetitive triangular wave pattern. This RF carrier would be radiated toward the load through a small, directional, electromagnetic horn antenna mounted on the airframe lower side. At the load, a strong localized-source return signal could be obtained by use of a trihedral reflector (return path same as incident path, polarization insensitive) or possibly an active transponder (available in a package of approximately the dimensions of a king-size cigarette package). The return signal from the load location would be picked up by a horn adjacent to the transmitting horn.

During the round-trip time, t, required for the original RF signal to reach the target and return, the microwave oscillator frequency would shift so that the difference in frequency, f, between transmitting and returning signals would be equal to $t \times |df/dt|$, where df/dt is the linear frequency change rate. This difference frequency would be linearly related to the aircraft-to-load distance, and would be detected in a balanced mixer, further processed (e.g., to eliminate difference frequencies from more remote reflections, or to accommodate the difference frequency signal disruptions near the vertexes of the triangular function frequency sweeps), and finally digitized for onboard computation.

if distance-to-load measurements were made, as above, at two or more additional separated locations at the bottom of the aircraft, the load position relative to the aircraft could be continually tracked by computer triangulation. Expensive triplication of receiving equipment and undesirable weight and space features would be required to make these additional measurement locations available; however, it is hoped that only the compact dual (transmit/receive) horns are required at each station. Preliminary investigations indicate that this could be accomplished by utilizing high-speed, solid-state microwave switching devices to commutate a single receiver consecutively among the sets of antennas. The data rates available for distance determination from each station should be much greater than those required to track the load position variations.

Conclusions and Recommendations

AiResearch studies indicate that (FM) microwave radiation altimeter techniques are promising and worthy of more detailed investigation. There is good potential for developing an integrated computer-compatible system for load position determination that is basically an extension of existing short-range FM radio altimeters.

Areas meriting more detailed examination as a basis for final evaluation of this system in comparison with other systems are:

1. Radio altimeter performance characteristics applicable to load position sensing, including accuracy, sensitivity, and target selectivity.
2. Equipment cost, weight, and size trade-offs vs practical requirements for overall position sensing system.
3. Reflector types and transponders for compatibility with slung load handling, including determination of the ability of the load to act as the only reflecting surface.
4. Minimum radiated power requirements (to minimize possible enemy detection). This relates to the preceding item; e.g., a transponder could allow at least a 75-percent reduction in RF power from the aircraft.
5. Cable interaction with the measurement, and remedial steps if needed.
6. Antenna commutation interface requirements, e.g., AGC clamping during switching, to minimize acquisition transients and settling.

INFRARED AND VISIBLE LIGHT TECHNIQUES

Many features of infrared (IR) or visible light tracking appear highly attractive for application of this technique to helicopter load position sensing. Signal sources are inexpensive, reliable, and readily available. Reflection and absorption techniques are well developed, as is optical systems equipment for radiation between 0.1 and 100μ. Signal processing and tracking mechanisms are well developed and do not require special materials or components.

For load position sensing, IR could be generated aboard the helicopter and reflected from tracking points on the load, or it could be generated at two or more locations on the load. If generated aboard the helicopter, the energy could be radiated in pulses, the two-way transit time measured, and the distance to the load thus determined. Pulsing the energy, even if it is generated at the load, could also make it easier to isolate the energy from background radiation.

The areas of investigation required to determine the suitability of IR or visible light are (1) the transmittance of air under the worst conditions of fog, rain, snow, smoke, or dust; and (2) the availability of an appropriate detector.

The two areas are related. In general, a heavy concentration of particles suspended in air will cause diffusion of all light energy whose wavelength is not greater than the diameter of the particles. Diffusion of light through dense fog is typical of this phenomenon. IR will therefore penetrate heavier concentrations of large particles than will visible light. Also, long-wave IR (10μ and longer) will penetrate better than shorter-wave IR. Detectors which respond to 10μ and above, however, generally have lower sensitivity and slower response unless operated at cryogenic temperatures; detector cooling adds complexity and cost and should be avoided if possible.

The required investigation will consist of determining the lowest wavelength and energy intensity required to fulfill tracking requirements under the worst conditions of dust and weather. The appropriate detector for that wavelength or band will then be selected.

IN-DEPTH STUDIES

This section presents the analyses of the following five payload sensor approaches developed during the in-depth studies and evaluations:

1. Big arm gimbal
2. Separated mechanical linkages
3. Force resolution techniques
4. Radar interferometry
5. Infrared tracking

In addition, an analysis is included which shows actual load position compared to indicated load position based on supporting cable lengths and angles measured at the helicopter. Systematic corrections of indicated load position must be made for each position-sensing technique.

BIG ARM GIMBAL

Because of its link geometry, the big arm gimbal will experience a rotation of gimbal axes about the vertical axis of the aircraft as the links articulate to follow the cable. A correction for the resulting skew angle must be applied to properly relate gimbal angle information to the position of the load.

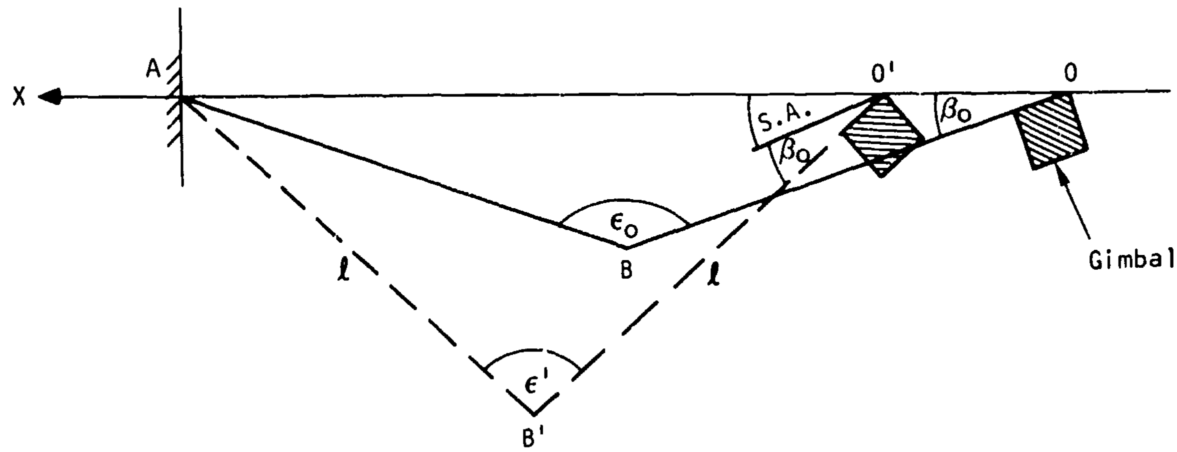
Figure 23(a) illustrates the way in which the gimbal coordinate axes are rotated during a simple motion of the gimbal along the longitudinal axis of the aircraft.

The general displacement of the gimbal to any location within its position envelope can be regarded as the sum of two independent component motions: a rotation about the axis of the grounded pivot (see Figure 23(b)) and a translation along the line, AO_1 in Figure 23(b), between the grounded pivot and the gimbal center.

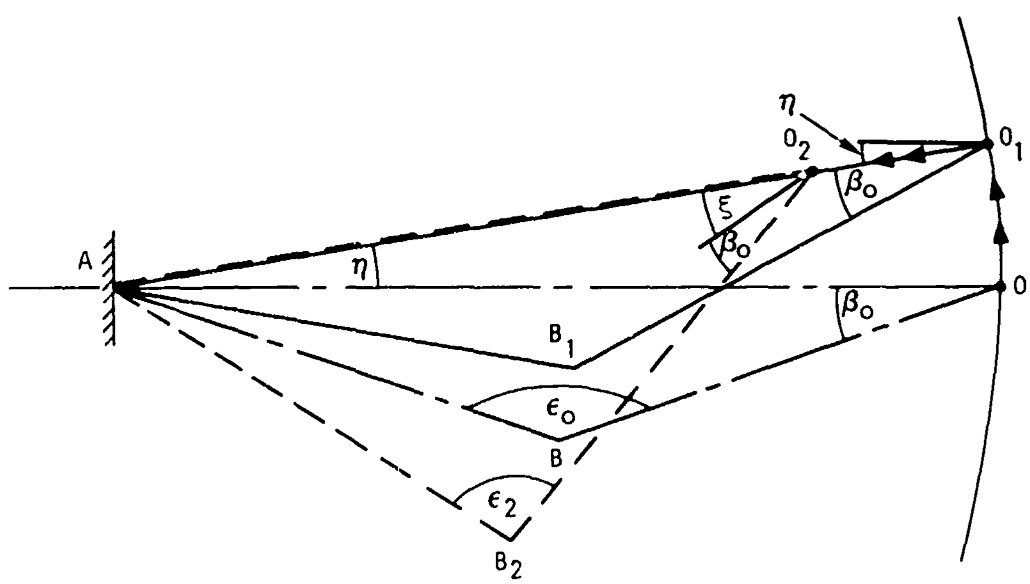
During the rotation of O to O_1, the isosceles triangle formed by the linkage assembly remains undistorted; the skew angle, η, which is thus introduced can be measured directly at the grounded pivot, A. Then, during translation of the gimbal along AO_1, η remains constant while an additional skew angle increment ξ, is created by the distortion of the linkage triangle.

The angles within the undistorted triangles ABO and AB_1O_1 are

$$\epsilon_0 + 2\beta_0 - 180^\circ$$



(a) Gimbal Motion Along X-Axis



(b) Rotation and Translation to 0_2

Figure 23. Gimbal Motion and Skew Angle.

After distortion to triangle AB_2O_2, the angles are

$$\epsilon_2 + 2\,(\beta_0 + \xi) = 180^\circ.$$

Hence

$$\epsilon_2 = 180^\circ - 2\beta_0 - 2\xi$$

$$= \epsilon_0 - 2\xi$$

$$\therefore \quad \xi = 1/2\,(\epsilon_2 - \epsilon_0).$$

That is,

$$\xi = 1/2\,(\Delta\epsilon),$$

where $(\Delta\epsilon)$ is the angular deflection sensed at pivot B.

Total skew angle (S.A.), then, is

$$S.A. = \eta + 1/2\,(\Delta\epsilon).$$

Therefore, it is concluded that angle transducers at A and B would be appropriate for the measurement of gimbal skew angle.

The initial proposal in this study was that cable angle and load position be derived from gimbal angles and their attendant skew angle corrections. Subsequently, it has been determined that a complete, more direct solution can be achieved in terms of the linkage angles ϵ and η, and the associated geometry shown in Figure 24. For this approach, angle transducers will be required at linkage pivots A and B only.

Table 6 lists design features of the big arm gimbal; Table 7 shows the cost analysis.

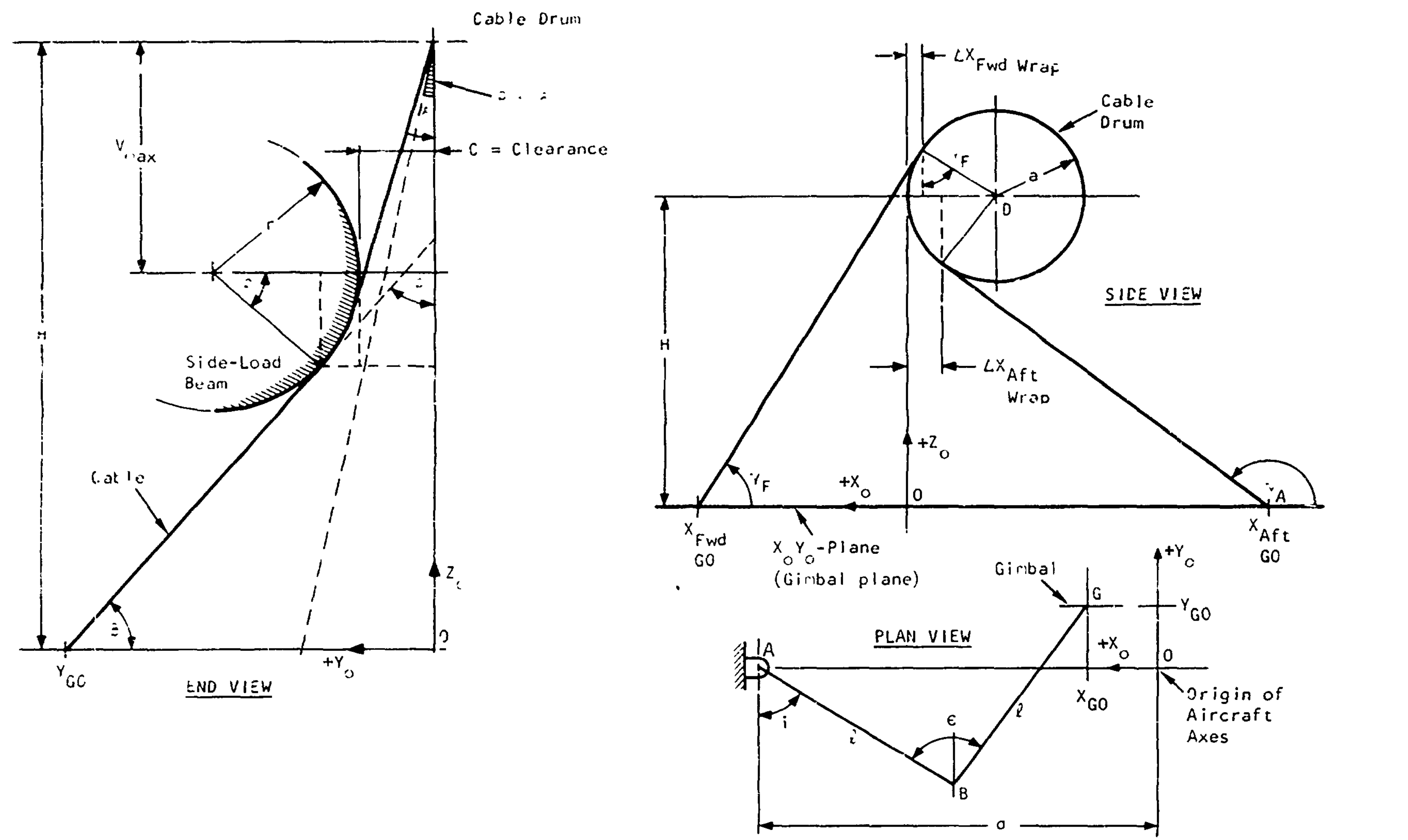


Figure 24. Big Arm Gimbal Geometry.

TABLE 6. EVALUATION SUMMARY - BIG ARM GIMBAL	
Sensors Required	Requires two angle transducers, one at grounded pivot, one at moving pivot; gimbal is not instrumented.
Structural Features	2 links, 36 in. long, with gimbal (2 axes) mounted at end of outer link. Tubular slipper pivoted in gimbal encloses cable - causes linkage to follow cable. Cable angles - longitudinal and lateral - are derived from link-angle sensors.
Performance Capability	Cable angles derived from link angles, higher susceptibility to transducer error, more compensation required to ensure accuracy.
Space Required	Slab of space, approximately 68 in. longitudinally, 24 in. laterally, 4 in. thick, vol = 3.8 ft^3.
Weight	Linkage and gimbal metal approximately equivalent to an aluminum bar 2-1/2 in. x 1 in. x 72 in. $\therefore W \simeq (180\ in.^3)(0.1 \frac{lb}{in.^3}) \simeq 18\ lb$ Two transducers at .08 lb each (negligible) $\therefore W_{TOT} \simeq 18\ lb$
Vibration Effects	Low frequency susceptibility (worst: vertical direction, but this is at right angles to transducer sensitivity). Gimbal will be held by cable, error confined to link flexure.
Dirt and Debris on Cable	Close fit of tracking sleeve will result in cleaning effect through wiping action on cable. Jamming due to large debris a rare possibility.
Wear	All cable follower wear is confined to single tracking sleeve. Wear rate will depend on clearance commensurate with tracking accuracy requirement. Rate could be high.

TABLE 6 - Continued	
Accessibility, Maintainability, and Ease of Repair	Readily accessible (arm-and-gimbal assembly and tracking sleeve). Entire unit may be removed as a single assembly.
Applicability of design to other aircraft	Readily adaptable to other aircraft without significant redesign.

TABLE 7. COST ANALYSIS - BIG ARM GIMBAL

Nonrecurring Design	$9,000
Development	$49,000
Fabrication (Mechanical Parts)	$4,650 each
Angle Transducers	$300
Total Angle Sensor	$4,950
Cost/Shipset (Assuming 300 Shipsets)	$5,140
Total Performance Evaluation Number: (Design/Function Score) + (Accuracy Score) x (Configuration Factor)	216 f
Development Risk Factor, f (only affects accuracy component of total performance number)	0.80

SEPARATED MECHANICAL FOLLOWERS

The helicopter payload position is determined by the separated mechanical followers measurements by solution of the equations in the following subsection. The geometry of the approach is shown in Figure 25. Table 8 lists the design features; Table 9 is the cost analysis.

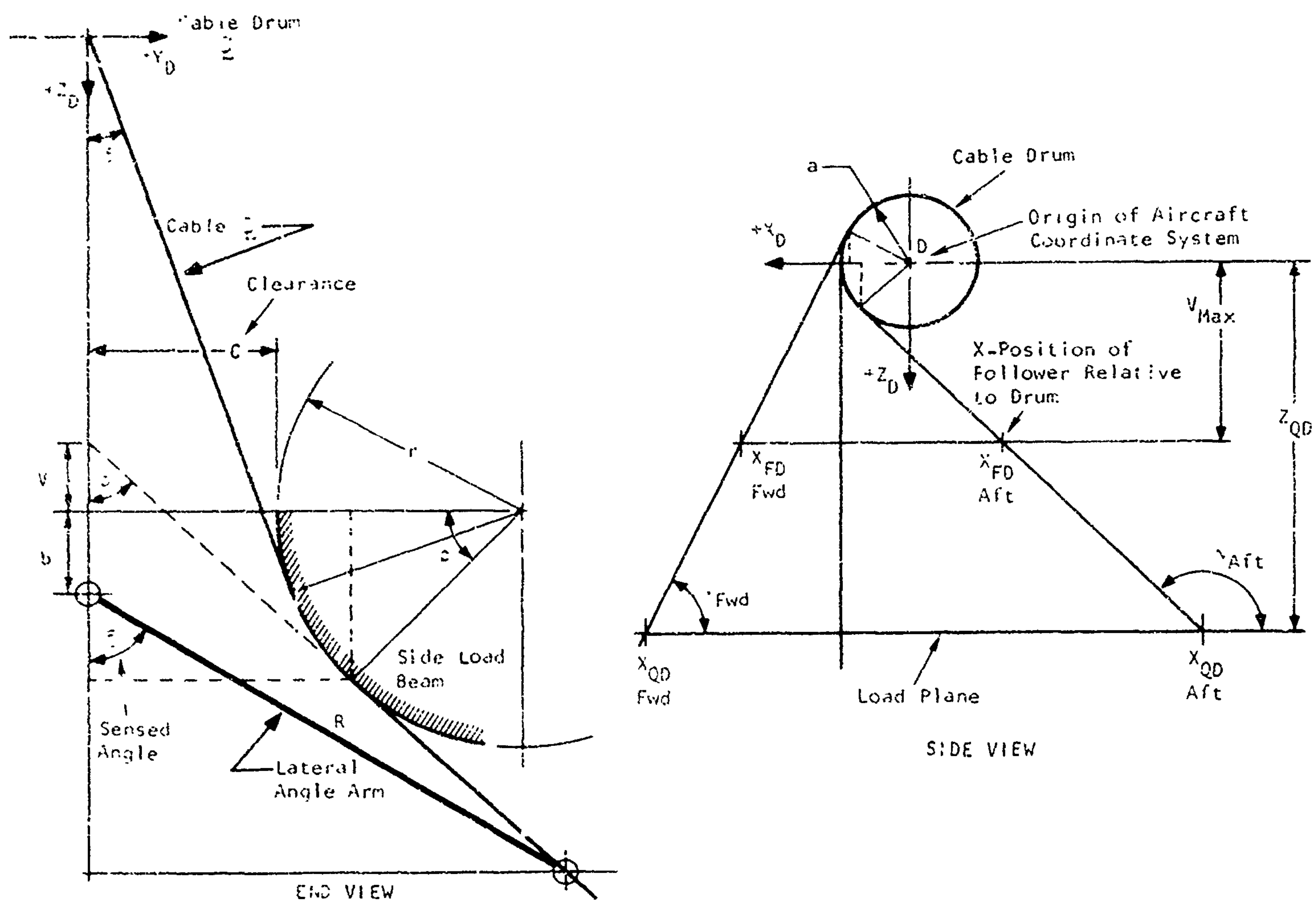


Figure 25. Separated Mechanical Followers Geometry

TABLE 8. EVALUATION SUMMARY - SEPARATED MECHANICAL FOLLOWERS	
Sensors Required	Requires one angle transducer coupled with separated mechanical followers, and one ten-turn potentiometer coupled with cable cutter assembly.
Structural Features	Cable cutter encloses cable above side-load beam and follows longitudinal motion of cable. Rollers, long enough (approximately 18 in.) to bear on cable at all longitudinal angles, are supported on arms which are pivoted to allow rollers to follow lateral cable motion. Longitudinal cable angle derived from fore and aft motion of cable cutter, lateral angles from angle sensor attached to roller support arms.
Performance Capability	Cable angles obtained more directly from transducer information; therefore less compensation required.
Space Required	Beneath side-load beam: roller space approximately 18 in. longitudinally, 15-1/2 in. laterally, and 1 in. vertically. Negligible space required for transducers, $\approx 0.2\ ft^3$
Weight	2 steel rollers: 1 in. diameter x 18 in. long $W \approx (29\ in.^3)(.29 \frac{lb}{in.^3}) \approx 8.5\ lb$ Miscellaneous support hardware: 2.5 lb; Total weight $\simeq$ 11 lb
Vibration Effects	Rollers may bounce against cable. Low frequency cable drive for longitudinal transducer may flap.
Dirt and Debris on Cable	Rollers will tend to ride on top of debris attached to cable. In very rare cases, could cause tracking error. Jamming unlikely. Cable follower built into cutter assembly can be designed similarly (i.e., with rollers). Less susceptible to debris, since this follower rides above slot through side-load beams.

TABLE 8. Continued	
Wear	Follower wear at cutter/follower assembly should be minor. Follower wear at lateral-angle rollers will be minimal if rollers are properly handled. Cable wear could be a factor.
Accessibility, Maintainability, and Ease of Repair	Cutter/follower assembly will be between cable drum and side-load beams. Lateral-angle rollers readily accessible. Total mechanism consists of three major subassemblies (cutter/follower, longitudinal sensor, lateral angle assembly).
Applicability of design to other aircraft	Redesign of parts will be required if this unit is to be applied to other hoist configurations.

TABLE 9. COST ANALYSIS - SEPARATED MECHANICAL FOLLOWERS

Nonrecurring Design	$8,400
Development	$49,000
Fabrication (Mechanical Parts)	$1,080 each
Angle Transducers	$60
Total Angle Sensor	$1,140
Cost/Shipset (Assuming 300 Shipsets)	$1,330
Total Performance Evaluation Number: (Design/Function Score) +[(Accuracy Score) x (Configuration Factor)]	216 f
Development Risk Factor, f (only affects accuracy component of total performance number)	0.90

SUMMARY OF EQUATIONS FOR LOAD POSITION AND CABLE ANGLE

Big Arm Gimbal

$$X_{QO} = \frac{Z_{QO} + Z_{OG}}{\tan\left\{\sin^{-1}\left[\dfrac{a(a + X_{GO}) \pm H\sqrt{H^2 + 2a\,X_{GO} + X_{GO}^{\;2}}}{H^2 + (a + X_{GO})^2}\right]\right\}} + X_{GO}$$

where $X_{GO} = d - l\,[\sin i + \sin(\epsilon - i)]$

$$Y_{QO}\Big|_{\rho<\delta} = Y_{GO}\left(\frac{Z_{QO} + Z_{OG}}{H} + 1\right)$$

Cable angle $\beta\Big|_{\rho<\delta} = \tan^{-1}\dfrac{H}{Y_{GO}}$

where $Y_{GO} + \ell\,[\cos(\epsilon - i) - \cos i]$

$$Y_{QO}\Big|_{\rho\geq\delta} = \frac{Z_{QO} + Z_{OG}}{\tan\left\{\sin^{-1}\left[\dfrac{-rE \pm F\sqrt{E^2 + F^2 - r^2}}{(E^2 + F^2)}\right]\right\}} + Y_{GO}$$

where $Y_{GO} = \ell\,[\cos(\epsilon - i) - \cos i]$

$$E = (Y_{GO} - r - c)$$

$$F = (H - V_{MAX})$$

Note that $\delta = \cos^{-1}\left\{\dfrac{rS \pm V_{MAX}\sqrt{V_{MAX}^2 + S^2 - r^2}}{(S^2 + V_{MAX}^2)}\right\}$

where $S = r + c$

Separated Mechanical Followers

$$X_{QD} = \frac{Z_{QD} + a \cos \gamma}{\tan \gamma} - a\,(1 - \sin \gamma)$$

where $$\gamma = \sin^{-1}\left[\frac{a(X_{FD} + a) \pm H\sqrt{H^2 + (X_{FD} + a)^2 - a^2}}{(X_{FD} + a)^2 + H^2}\right]$$

$$Y_{QD}\Big|_{\rho<\delta} = Z_{QD}\left[\frac{R \sin \xi}{V_{MAX} + b + R\cos \xi}\right]$$

Note: $\beta = 90^{\circ} - \rho$ with $\rho > o$ to one side of Z-Axis

$$Y_{QD}\Big|_{\rho\geq\delta} = c + r(1 - \cos \rho) + (Z_{QD} - V_{MAX} - r \sin \rho) \tan \rho$$

where $$\rho\Big|_{\delta} = \sin^{-1}\left[\frac{rB \pm A\sqrt{A^2 + B^2 - r^2}}{B^2 + A^2}\right]$$

and $$B = (b + R \cos \xi)$$

$$A = (R \sin \xi - c - r)$$

Note: $$\delta = \cos^{-1}\left[\frac{rS \pm V_{MAX}\sqrt{V_{MAX}^{2} + S^2 - r^2}}{(S^2 + V_{MAX}^{2})}\right]$$

where $S = r + c$

FORCE RESOLUTION APPROACHES

Three systems were investigated for the following criteria:

1. Lateral forces equal to 0.5 vertical force

2. Longitudinal forces equal to 0.866 vertical force

Various means of measuring the forces exerted on the aircraft structure were considered and evaluated.

Case 1

One such method is shown in Figure 26. A platform on which the hoisting mechanism is mounted is attached to the aircraft structure using eight load links. The devices are arranged in such a manner that four of them support the vertical weight of the hoist and sling load, two provide lateral restraint and two provide longitudinal restraint. In this system the outputs of the vertical force transducers are averaged so that they always indicate the correct load regardless of the point of load application in the horizontal plane.

The lateral loads are reacted by force transducers which also react any moments introduced in the horizontal plane. The averaged output of these two devices provides a measurement of the lateral force with the effects of any moments in the horizontal plane being cancelled out.

The longitudinal forces are measured by a similar system with the averaged output being equal to the net longitudinal reaction of the hoist platform.

For a two-hoist system the vertical and longitudinal loads are averaged to provide a single output, or monitored individually and the lateral restraining forces measured separately to determine whether a yawing moment results from the sling load displacement.

Case 2

A similar system, in which the loads are reacted by a single transducer, was investigated. The problems associated with this approach are:

1. The lateral and longitudinal forces are measured as moments and the required resolution is difficult to obtain since the vertical load is also being transmitted through the device.

2. Assuming that no central cable guiding mechanism is employed to maintain a constant cable exit point from the aircraft, a problem arises from the cable paying off resulting in a change in the point of load application. This causes moments which interfere with the determination of the moments caused by sling load oscillation.

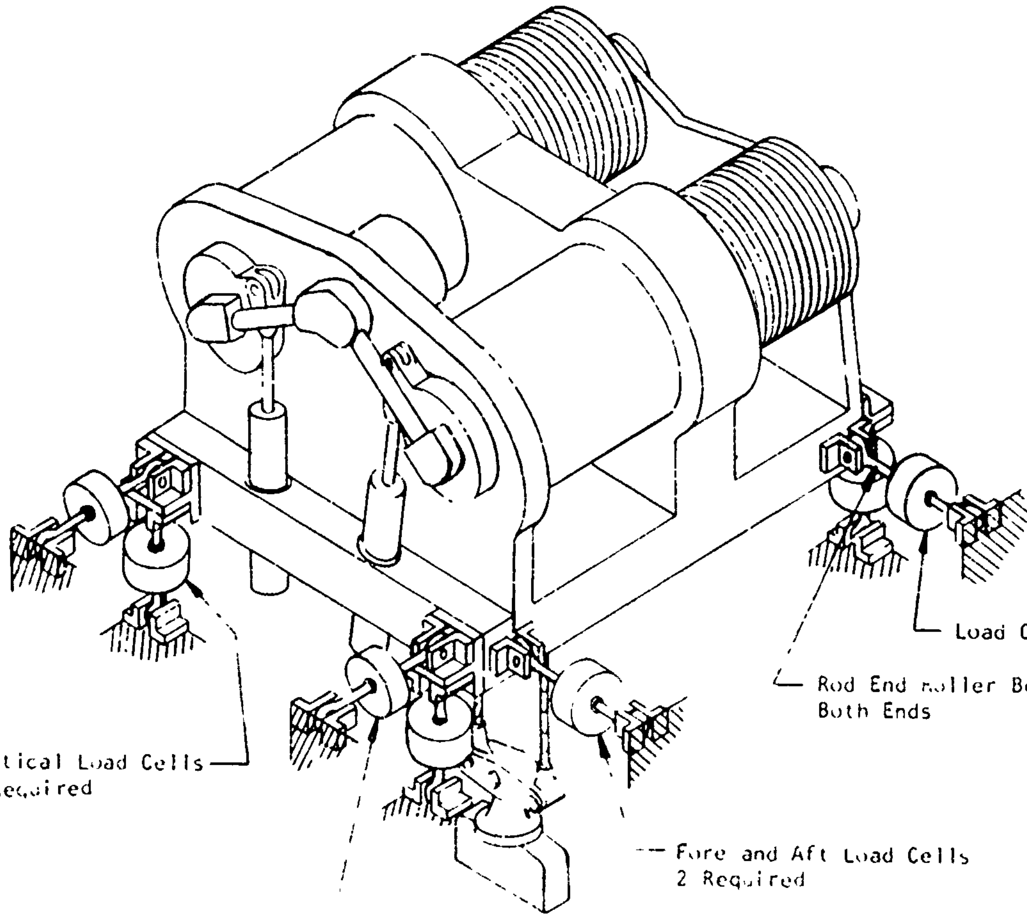


Figure 26. Details of the Force Resolution Approach

3. The attachment of such a device to the helicopter structure would require modification of the structure to carry the moments generated which would be on the order of several hundred thousand in.-lb. Assuming a cable spool length of 60 in. and two hoists, the moment due to cable payout would be at least 600,000 in.-lb.

4. Such a device would require an elaborate system of stops to restrain the system in the event of a failure of the load element.

Case 3

Another approach investigated uses a cable tensometer to measure cable tension at all times. This device rides on the cable but is anchored to the aircraft. The results of this measurement could be combined with either a mechanical device to measure the cable angle relative to the aircraft, or the horizontal forces could be measured as in Case 1. This system has the following disadvantages:

1. The device must ride the cable and is subject to fouling and bearing failures which could result in inaccurate measurements or no measurements.

2. Such a device must be handled and is therefore subject to damage from abuse or misuse.

3. This approach is also subject to error as the cable wears and would have to be calibrated at specific intervals of use with a given cable to ensure accurate results. It would also be restricted to use with a specific cable diameter.

System Evaluation

Of the various methods of force resolution, the arrangement using eight force transducers has several advantages over the other cases:

1. It distributes the load over the airframe at several points, making it possible to reduce the local modification of the structure required, whereas single attachment methods would introduce large local bending moments which could require extensive modification to the aircraft structure.

2. Only the desired force is transmitted through the element and the stiffness of the various elements is high enough to limit the deflection to very small displacements. This prevents all except very minor interactions (much less than one percent) while the single element type unit can have much larger interactions (several percent).

3. It is much safer than the single element; any one of the transducers could fail and the load would still be carried.

4. The multiple transducer approach uses uniaxial elements which are simple to calibrate and can even be deadweight calibrated in the field.

5. The eight elements of the one system could be interchangeable, requiring only a few low-cost spares to be kept on hand, and could be replaced quickly. It is possible to use the same size units in systems of various capacities, which would further reduce the spares problem.

The eight-point restraining system has the following advantages:

1. The failure of any one link will not cause damage to the aircraft.

2. The individual elements are available from commercial suppliers and thus would not require extensive design and fabrication time.

3. The arrangement of two transducers in the fore and aft direction and two in the lateral irection makes it possible to measure the forces acting in those directions by averaging the load cell outputs, which cancels the effects of moments in the horizontal plane. Thus, if one link were to fail, the platform would still be restrained from movement and only the measurement in one direction would be affected. If three transducers were used to react the forces in the horizontal plane, the outputs would have to be combined such that the failure of a link in one direction would affect the measurement in the other horizontal direction, resulting in a measurement error in two parameters.

System Characteristics

The system characteristics are based on the assumption that eight load transducers will be utilized. There are several parameters which can be improved, but for the present only those characteristics of off-the-shelf hardware are given. The characteristics of two competitive manufacturers, Transducers, Inc. and Interface, are compared. The data given is based on system output only.

Resolution

The resolution of the strain gage type load cell is infinite and is limited only by the readout device.

System Deflection

The deflection of the transducer is less than 0.010 in. at full load, not including the attachment fittings.

Environment

The transducers are sealed so that the only point of entry is the cable entry, and this area is potted with a compound to prevent damage on exposure to moisture. Such units have survived many years in an environment where they were washed daily with a brine solution.

Output

	Transducers, Inc. Series ML	Interface
Range	10,000 lb	10,000 lb
Output (max)	3 mv/v, 15v max = 45 mv	4 mv/v at 2v = 8 mv
Accuracy (total combined error)	±0.08 percent	±0.09 percent
Temperature range	-65° to +250°F	-65° to + 200°F
Temperature effect at full load	0.07 percent full scale/100°F	0.08 percent full scale/100°F
Safe overload	150 percent	150 percent
Overall length of transducer	5.94 in.	3.12 in.
Diameter of transducer	2.40 in.	4.12 in.
Cost	$595 (system $5160)	$490 (system $4320)
System weight	40 lb	50 lb

The method of attachment would be spherical roller bearing such as Rex DM-8-10A series, which would weigh 5 lb each. Fatigue life of the load cell should exceed 10^6 cycles.

RADAR TECHNIQUES

General

The early investigation of radar for application to the helicopter payload position sensing problem indicated that FM altimetry techniques provided the greatest promise of a payload position sensor at reasonable cost. However, the subsequent detailed study revealed two significant facts which indicate otherwise.

First, several reports revealed that the theoretical accuracy of FM altimetry is seldom achieved despite manufacturer's claims and published specifications. A typical final report is Flight Evaluation AN/APN191, Radar Altimeter prepared by the Army Aviation Systems Test Activity at Edwards Air Force Base, California. The AN/APN191 radar altimeter has a specified accuracy of ±1 foot plus 1 percent of absolute height but often showed much greater errors. In addition, the errors were random (not repeatable); therefore they could not be calibrated out. In view of such negative reports, FM altimetry could not be recommended as a means of finding payload position.

Earlier investigations indicated the RF interferometry was not appropriate for payload position sensing because the use of existing hardware would lead to ambiguity problems while development of new hardware would be too costly.

The second significant development of the subsequent investigation was the discovery that application costs of all radar techniques are being reduced dramatically. The development of integrated circuits for processing microwave frequencies has made such cost reductions possible. In view of these developments, it is now feasible to consider the application of RF interferometry with hardware designed to avoid the ambiguity problem.

<u>Theory of Operation</u>

RF interferometry, or high resolution angle measurement, is a radar technique for accurate angle measurements. The technique is based on the principles of the speed of propagation being constant (2.998×10^{10} cm/sec) and that the signal will induce an ac voltage into a receiving dipole whose electrical phase angle, as compared to the transmitting antenna, is one revolution for each complete wavelength traveled plus a fraction of a revolution for any additional fractional wavelength traveled. When two receiving antennas are used and electrical phase angles of the signal induced in each are compared, their relative distances from the signal source are found by comparing the relative phase angle of the two signals. Each degree of phase shift is equal to 1/360 times the signal wavelength.

As can be seen, when the distance from transmitter to receiver is many wavelengths, the technique is not suitable for distance measurement, only for angular measurement. Ambiguity problems can arise, even for angular measurements, when the signal wavelength is very short or the distance between the receiving antennas is relatively large. Thus, system parameters such as signal wavelength and receiving antenna relative location must be selected carefully for each application.

For the helicopter payload position sensor application, the optimum frequency is approximately 300 MHz (λ [illegible] 1m) with receiving dipole antenna spacing of 1.155 meters. These parameters provide 360 degrees of phase difference at the two receiving antennas for the full range of payload motion. Thus, the maximum signal phase shift is provided per unit payload motion while avoiding ambiguity.

<u>System Description</u>

The RF interferometry payload position sensor system consists of two RF signal sources which are mounted at known positions on the load, an antenna system consisting of four fixed dipoles mounted to the helicopter and an RF receiving system with phase discrimination capability. The three components are integrated into an angle measuring system which determines payload swing (fore and aft), sway (side to side) and yaw (differential sway) angles. These angles are determined by measurement of the electrical phase angle of the RF signal from one source as the energy arrives at two separated dipoles. The geometric relationships for these computations are shown in the next subsection.

The signal sources are battery powered Gunn diode oscillators radiating approximately 0.05 watt of energy at a frequency of about 0.1 GHz. The frequency difference between the two oscillators is sufficient to allow discrimination by use of simple tuned circuits. The complete signal source, including batteries for 3 to 5 hours of operation, could be mounted in a package approximately 1 in. by 2 in. by 3 in. with an external dipole radiator approximately 12 in. long.

The optimal mounting orientation has not been determined; however, at zero load angle, the signal source dipoles should be parallel to the receiving dipoles at the helicopter.

The antenna system mounted to the helicopter consists of four dipoles. These should be arranged such that the distances between fore to aft and side to side pairs are approximately 40 in. Also, both load signal sources should be visible from all of the antennas for every possible load and helicopter relative position.

The receiving system is fabricated from microwave integrated circuits of a type very recently announced. The availability of microwave integrated circuits is the major breakthrough which makes the radar approach to helicopter payload position sensing economically feasible. There are five RF front end tuners, three of which are tuned to accept the frequency of the payload forward signal; the remaining two are tuned to accept the frequency of the payload aft signal. Two of the first three RF tuners are driven by the forward antenna dipole pair; the third is driven by an aft dipole. The last two RF tuners are driven by the aft dipoles. Thus, one of the aft mounted antenna system dipoles drives two RF tuners, one for each frequency.

The RF signals are processed and the phase relationships of such signals are compared as follows:

1. The phase of the signal originating at the load forward source and arriving at the right forward dipole is compared to the phase of the signal from the same source and arriving at the right rear dipole. The phase angle between these two signals is an accurate function of the load swing (fore and aft) angle.

2. The phase of the signal originating at the load forward source and arriving at the right forward dipole is compared to the phase of the signal from the same source and arriving at the

left forward dipole. The phase angle between these signals is an accurate measurement of the sway (side to side) angle of the forward end of the payload.

3. The aft sway angle of the payload is measured using the signal from the load aft signal generator as it arrived at the right and left aft dipoles.

4. The payload yaw angle is computed from the difference between the fore and aft sway angles and the cable length.

Geometry of Payload Position Measurement by RF Interferometry

The RF interferometry system determines the payload position by the solution of geometric equations as illustrated in Figure 27. The point X_A, Y_A defines the location of one fixed receiving dipole on the helicopter while X_F, Y_F defines the position of another. The point X_G, Y_G is the location of a signal source mounted on the load with the load suspended on a cable of length C and with no relative movement of the load with respect to the helicopter. With the load so suspended, the RF signals travel paths D_1 and D_2 to arrive at the receiving dipoles. The electrical phase angle between the signals as they arrive is proportional to the difference between the two distances. When the load moves such that the coordinates of the signal generator change to X_G', Y_G', (the cable rotates through angle θ), the distances change to D_1' and D_2', respectively. The relative distances are related to θ as follows:

$$D_1^2 = (X_F - X_G)^2 + (Y_F - Y_G)^2 \tag{1}$$

and

$$D_2^2 = (X_G - X_A)^2 + (Y_A - Y_G)^2 \tag{2}$$

where

$$X_F > X_G > X_A$$
$$Y_F > Y_G$$

and

$$Y_A > Y_G$$

To simplify the illustration, it is assumed that

$$Y_A = Y_0 = Y_F$$

Now $$C = Y_0 - Y_G$$

or $$Y_G = Y_0 - C$$

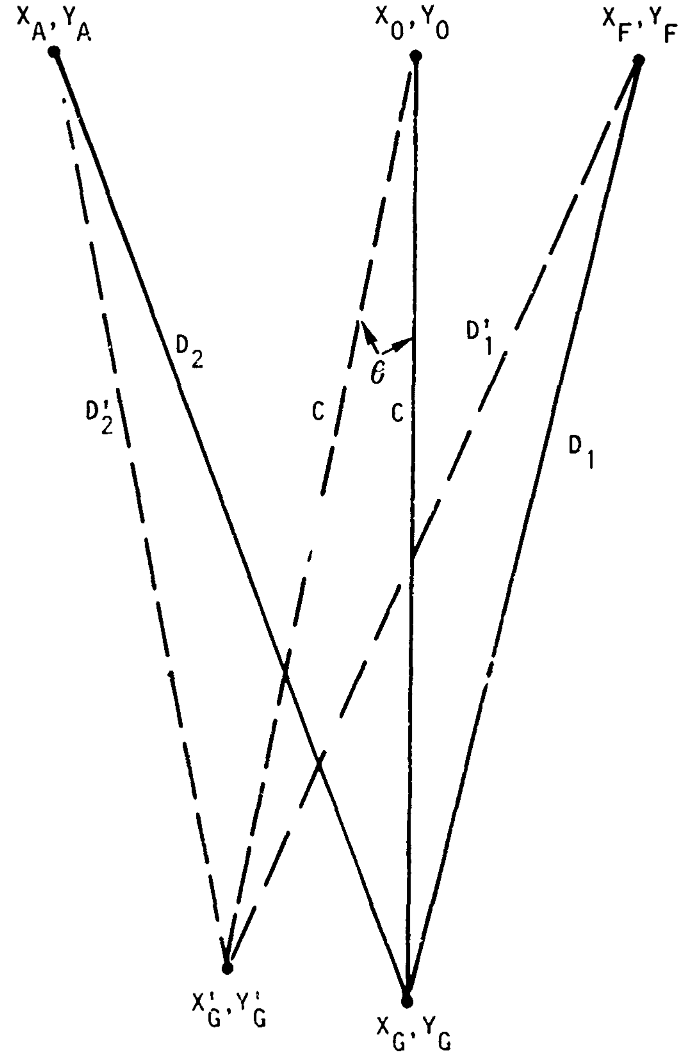


Figure 27. Geometry of Angle Measurement

When the load and generator swing through angle θ

$$X_G - X_G' = C \sin \theta \quad (3)$$

and

$$Y_G' = C - C \cos \theta + Y_G \quad (4)$$

or

$$(D_1)^2 = [X_F - X_G + C \sin \theta]^2 + [Y_F - C (1 - \cos \theta) = Y_G]^2 \quad (5)$$

$$(D_2)^2 = [X_G - X_A - C \sin \theta]^2 + [Y_F - C (1 - \cos \theta) - Y_G]^2 \quad (6)$$

As can be seen by comparing equations (1) and (5), when the load moves through the ang'- θ, the X component of the distance D_1 increases by an amount dependent on C and proportional to sin θ, while the X component of D_2 decreases by a similar amount. These distance changes are unique functions of the load angle θ and produce the signal phase angle which is then a unique measure of the load angle dependent only on the cable angle C.

Radar Evaluation

Environmental

It was assumed that environmental conditions would not degrade the performance sufficiently to change performance factor rank values.

Physical

Electronics, approximately 50 in.^{3}, 5 lb; waveguide, 1 in. x 1/4 in. x 40 ft, 10 lb; reflectors (4), approximately 1 ft^3, 1 lb.

Reliability/Maintainability

It is assumed that a 1000-hr MTBF can be achieved, that a 10-min MTTR can be achieved and that these are satisfactory goals. These assumptions are based on achieving similar figures with equipment of comparable complexity.

Development Risk

Development risk is considered relatively low in view of the similarity of the application to previously reported uses. A development probability of 0.85 has been assigned as a positive results multiplier.

Costs

The investigation failed to reveal actual equipment which could be installed and used for development; therefore, a design and development program would be required involving hardware design and fabrication followed by an operational test program. It is estimated that a 1-yr development program at a cost of $250,000 would be required. It is assumed that the subsequent flight test would be performed using GFE aircraft and supported by an average of one man. The cost of such a program has not been estimated. The cost of operational payload sensor systems is estimated at approximately $5000 per shipset.

Intangible Factors

Positive intangible factors of the radar approach to payload position sensing include growth potential, operational safety and extended accuracy.

Negative factors include the requirement that two signal generators must be mounted at precise locations on the load.

Intangible factors were not considered during evaluation.

INFRARED INVESTIGATION

General

It was determined early in the investigation of the applicability of IR/visible light to the payload position sensor problem that a major area to be considered is that of transmissiblity of signals under severe conditions of fog, smoke or dust. Much empirical data exists showing atmospheric transmission versus wavelength at various temperatures and with varying humidity. Data also exists which relates energy attenuation to fog density. Transmission through smoke and dust, however, must be determined by analytical means since transmissibility is related to particle size as a function of energy wavelength.

Atmospheric Absorption Bands

Figure 28 shows the atmospheric absorption bands due to carbon dioxide (CO_2) and water vapor (H_2O). These bands represent the total absorption at the indicated wavelength including scattering and diffusion as well as heating of the absorbing material. The significance of this fact is that by selection of a given wavelength, the scattering due to particles with radii of approximately one wavelength has been accounted for.

Transmissibility Through Clouds

Clouds become increasingly transparent to infrared radiation as wavelength is increased. The optical density of thickness of a cloud is approximately inversely proportional to its visibility.

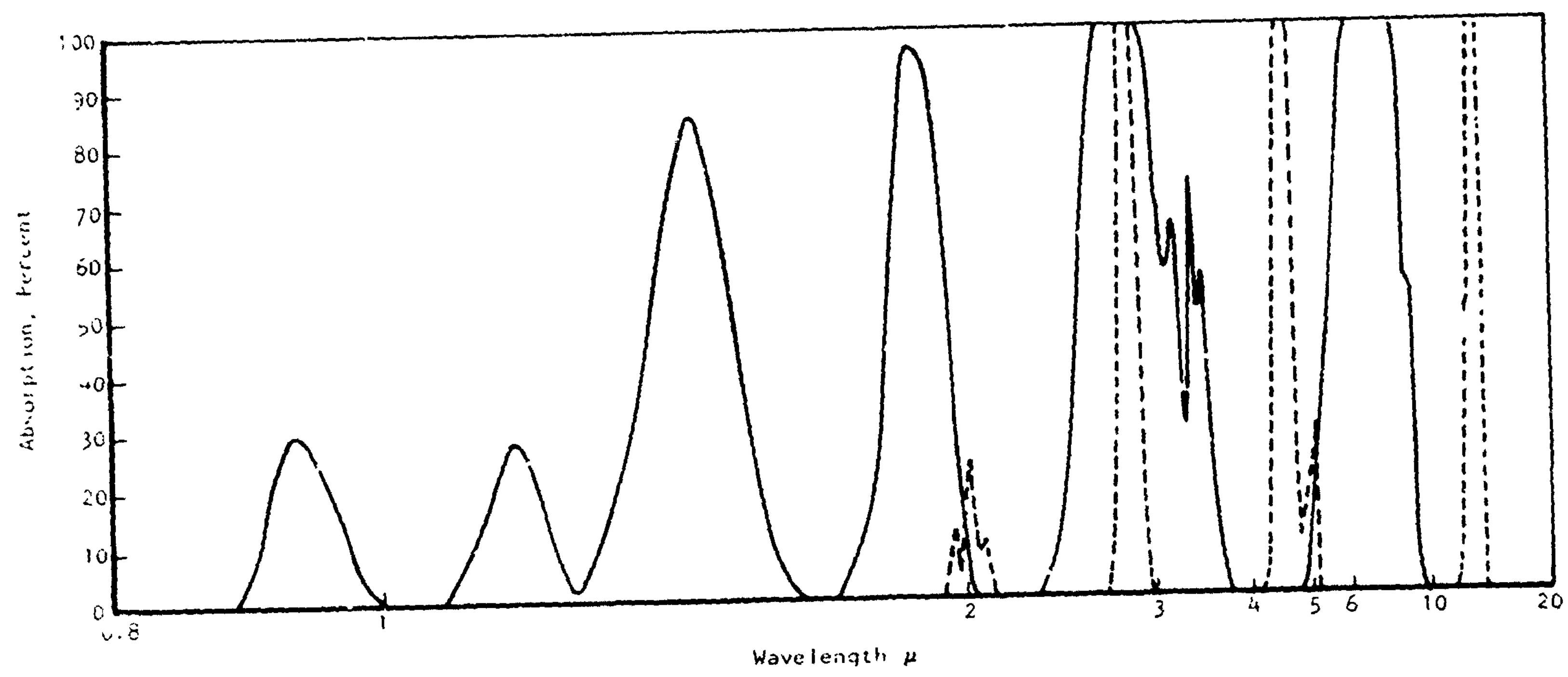


Figure 28. Atmospheric Absorption Bands due to CO_2 and H_2O.

Figure 29 shows cloud attenuation of infrared radiation as a function of visibility. These data were obtained by viewing an infrared source with a detector at various ranges and measuring the change in energy viewed by the detector when the measuring path was obscured by clouds of various measured densities. The optical density of a cloud was measured by determining the maximum range at which a maximum contrast object could be discerned in a given cloud. The figures relate attenuation to thickness of cloud, and the results do not necessarily apply to the various types of clouds.

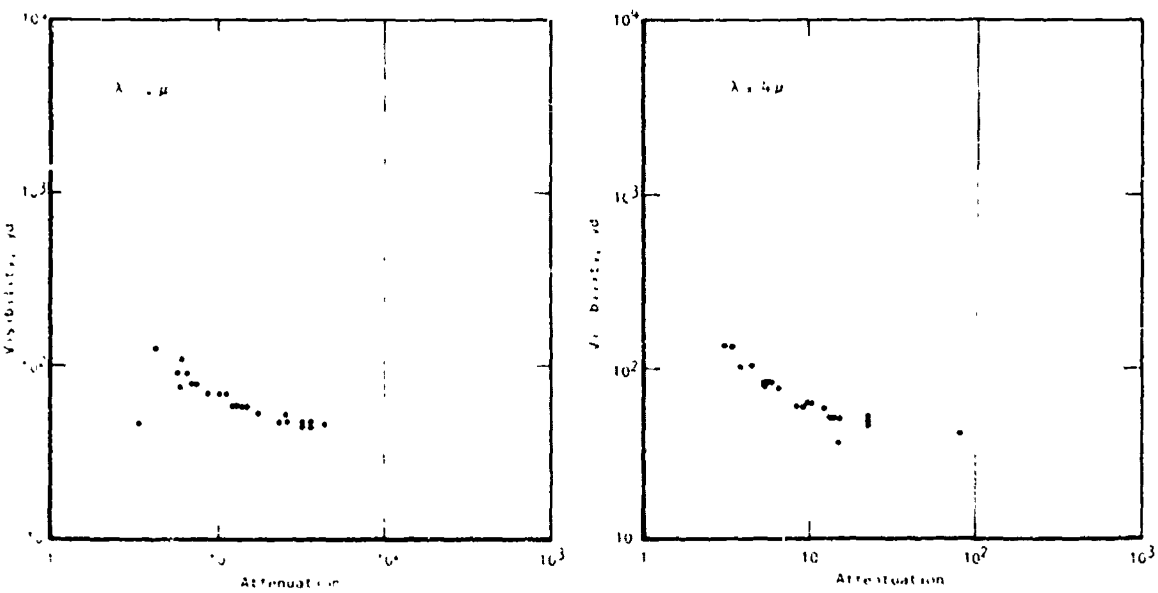


Figure 29. IR Attenuation by Clouds.

Transmissibility and Scattering Analysis

Scattering occurs if there is no absorption of the radiation, hence no loss of energy, but only a redistribution of it. This phenomenon can be observed when viewing a point light source through fog. As the density of the fog increases, more and more light appears to originate from a halo around the light source. At some fog density, the source can no longer be discerned although much of the light is still visible, appearing to emanate from a diffused source.

The attenuation of a collimated beam due to scattering depends upon the field of view of the receiving instrument. If the field of view is very large, some light scattered at small forward angles will still be accepted and recorded; if the field of view is very small, virtually all scattered radiation can be rejected and only transmitted radiation registered.

The ratio of the amount of radiation registered through the small field of view to the total energy radiated is the transmissivity. The scattering coefficient is related to the transmission (or transmissivity) of a given path by the relationship

$$T = e^{-\sigma x} \tag{7}$$

where T = transmission of optical path of length x (dimensionless)
x = optical path length
σ = scattering coefficient

Scattering can be treated theoretically in three separate approaches according to the relationship between the wavelength of the radiation being scattered and the size of the particles causing the scatter. These approaches are 1) Rayleigh scattering 2) Mie scattering and 3) non-selective scattering.

Rayleigh scattering applies when the radiation wavelength is much larger than the particle size. The volume scattering coefficient for Rayleigh scattering can be expressed as

$$\sigma = (4\pi^2 NV^2/\lambda^4)(n^2 - n_o{}^2)^2/(n^2 + 2n_o{}^2)^2 \tag{8}$$

where N = number of particles per unit volume
V = volume of scattering particle
λ = wavelength of radiation
n_o = refractive index of medium in which particles are suspended
n = refractive index of scattering particles

For spherical water droplets in air ($n_o \cong 1$; $n \cong 1.33$ for the visible and near infrared, except in the vicinity of absorption bands where anomalous dispersion is encountered), Equation (8) becomes

$$\sigma = 0.827NA^3/\lambda^4 \tag{9}$$

where A = the cross-sectional area of the scattering particle. This expression must be integrated over the range of λ and A encountered in any given circumstance. As long as the original requirement is met for all λ and A; i.e., the particle diameter $(2\ A/\pi)$ is very small compared to λ, the equation applies for most spherical particles such as smoke and gasses found in the atmosphere.

Mie scattering is applicable where the particle size is comparable to the radiation wavelength. The Mie scattering area coefficient is defined as the ratio of the area of the incident wave front that is affected by the particle to the cross-sectional area of the particle itself. The form of relationship between scattering-area coefficient and particle-size parameter is shown in Figure 30. The value of K rises from 0 to nearly 4 and asymptotically approaches 2 for large droplets. The scattering coefficient, σ, is related to K by

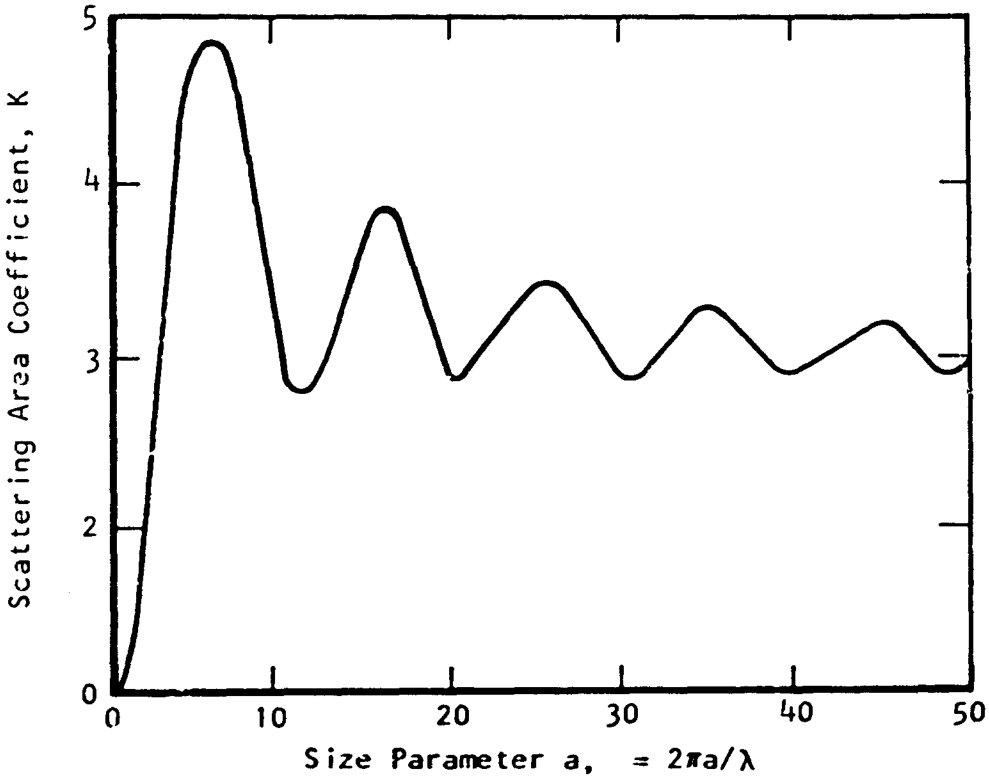


Figure 30. Form of the Relationship Between Scattering-Area Coefficient and Particle Size Parameter.

$$\sigma = NK\pi a^2 \tag{10}$$

or, for the almost universal condition in which there is a continuous size distribution in the particles, by

$$\sigma\lambda = \pi\int_{a_1}^{a_2} N(a)K(a,n)a^2 da \tag{11}$$

where $\sigma\lambda$ = scattering coefficient for wavelength
$N(a)$ = number of particles per cubic centimeter in the interval da
$K(a,n)$ = scattering area coefficient
a = radius of spherical particle
n = index of refraction of particle

With a and N expressed in cm and cm^{-3}, respectively, σ is expressed in cm^{-1}.

Nonselective scattering occurs when the particle size is very much larger than the radiation wavelength.

Large-particle scattering is composed of contributions from three processes involved in the interaction of the electromagnetic radiation with the scattering particle: (1) reflection from the surface of the particle with no penetration; (2) passage through the particle with and without internal reflections; and (3) diffraction at the edge of the particle. It has been shown that for particles larger than about 2 times the wavelength of the radiation ($\alpha > 20$), the Mie theory is valid, and for $\alpha > 20$ the two predictions converge on 2.

Since the empirical data, presented earlier, shows transmissivity (1 - absorption) as related to wavelength, it follows that selection of an operating wavelength removes the necessity of determining the Mie scattering by calculation since wavelength determines the scattering coefficient. It remains to determine the effects of particles much smaller than one wavelength and of particles larger than one wavelength; in particular, smoke, whose particles are a few tenths of a micron in diameter, and dust, whose smallest particles are many tens of microns.

Assuming a transmissivity of 0.25 (25 percent of the energy from the source will reach the detector without diffusion), a value for the scattering coefficient can be found by solving equation (7) for all values of x. Figure 31 shows the relationship between x and σ. If x is 50 meters (164 ft), σ is 28.

If we assume a smoke particle is 0.5×10^{-9} m in diameter and the energy wavelength is 4000×10^{-9}M (4 y), then Equation (9) yields

$$\sigma = 2.44 \times 10^{-17} N \text{ per meter}$$

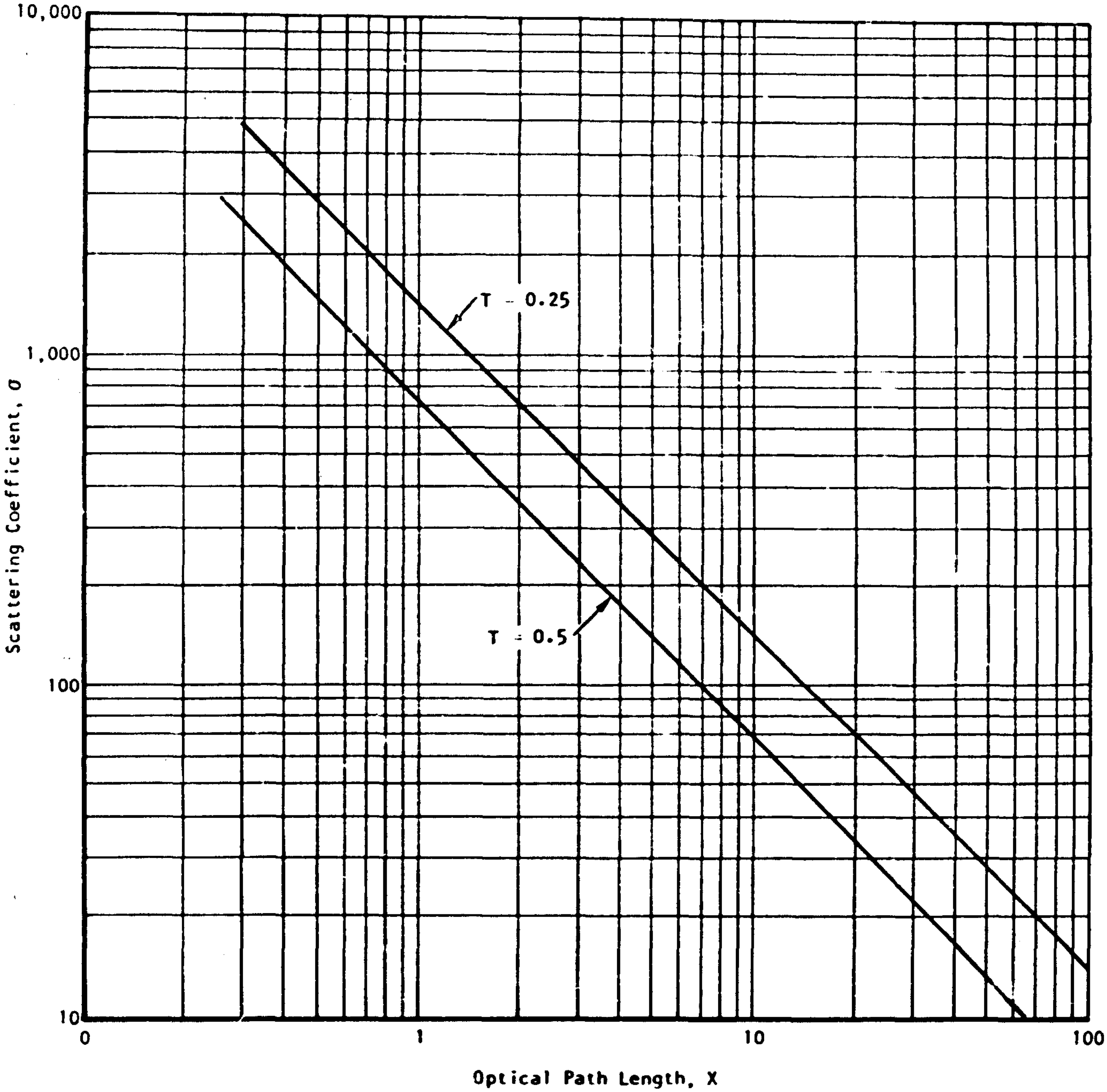


Figure 31. Relationship of Optical Path Length and Scattering Coefficient.

where N is the number of smoke particles per cubic meter. For $\sigma = 28$,

$$N = 1.14 \times 10^{18} \text{ particles per } m^3.$$

The volume of a smoke particle is

$$V_{ps} = 4/3\pi\, \sigma^3$$

$$V_{ps} = 6.54 \times 10^{-20} m^3$$

Each cubic meter of air can contain 0.075 cubic meters of smoke, or 75,000 parts per million of smoke will produce IR transmissivity of 0.25 over a distance of 50 meters.

For dust, we will assume that the particle diameter is 40 microns or greater. Equation (9) then applies with K = 2.

$$\sigma = 2N\pi a^2$$

$$\sigma = 251 \times 10^{-9} N \ (M^{-1})$$

and $$N = 1.11 \times 10^{1C} \text{ particles}/m^3$$

for $$\sigma = 28$$

The average volume of a dust particle

$$V_{pd} = 2.68 \times 10^{-13} m^3$$

and the total volume of dust per cubic meter of air is

$$V_D = 2.68 \times 10^{-13} \times 1.11 \times 10^{10}$$

$$V_D = 2.98 \times 10^{-3} m^3$$

This is equivalent of 3000 parts per million of dust to reduce IR transmissivity to 0.25 through a distance of 50 meters.

The 75,000 ppm of smoke and 3,000 ppm of dust which can be tolerated are extremely high concentrations of these contaminants. Smoke concentration of 75,000 ppm approximates a rating of three on the Bureau of Mines Ringleman scale. Three is the highest Ringleman rating (densest smoke) and is defined as "that which cannot be seen through to a depth of one foot at the source". The possibility of such concentration of smoke existing in the downwash of the helicopter rotor is very remote.

The possibility of dust concentration of 3000 ppm appears nearly as remote. World Health Organization data indicate that 250 ppm dust concentration has been observed in certain desert areas with winds of 100 km/hr (50 ppm of dust is considered toxic).

The helicopter rotor downwash can be expected to raise dust from dry ground to well above toxic levels (thus requiring protective devices for anyone required to work in the downwash). However, it would appear that a concentration of 3000 ppm is very remote.

It appears, therefore, that IR tracking techniques can be designed to operate satisfactorily under any expected ambient conditions for helicopter payload position determination.

CABLE-ANGLE ERROR ANALYSIS

The errors in indicated payload position due to the assumption that the position is defined by cable angles measured at the helicopter and the length of cable paid out fall into two types. The first error is the lateral error caused by the cable bowing in the wind; the helicopter will be downwind of the position indicated by the line-of-sight angle of the load. The second error occurs because the chord of the arc described by the cable is shorter than the arc, and therefore the actual distance is less than the cable length. The second error is not significant; only the first is analyzed here.

Wind force F_L on the load is

$$F_L = C_{DL} A_L \frac{\rho}{2} V^2, \text{ lb} \tag{12}$$

where C_{DL} = aerodynamic drag coefficient of MILVAN, assumed to be 1.44

A_L = cross-sectional area MILVAN presents to the wind; 64 ft^2 head-on, 160 ft^2 for sidewind

ρ = air density = 0.002378 lb-sec^2/ft^4 at sea level

V = velocity of wind, ft/sec

Angle of departure of cable from the load (from the vertical) is

$$\theta_L = \tan^{-1} \frac{F_L}{W_L} \tag{13}$$

where W_L = weight of MILVAN, gross lb

Wind force F_C on the cable perpendicular to the cable and tending to bow it is

$$F_C = C_{DC} A_C \frac{\rho}{2} V^2 \tag{14}$$

where C_{DC} = aerodynamic drag coefficient of cable, assumed to be 1.2

A_C = cross-sectional area cable presents to the wind in sq ft (cable diameter in ft times length of cable paid out)

The angle of departure of the cable from its suspension point on the helicopter is determined by the total weight supported at that point (the portion of the MILVAN weight supported by that cable plus the cable weight) and the horizontal wind force (that part of the wind force on the MILVAN restrained by that cable plus the wind force on that cable). This angle, with respect to the vertical, will be

$$\theta_C = \tan^{-1} \frac{F_L/N + F_C}{W_L/N + W_C} \tag{15}$$

where N = number of cables supporting the load

and W_C = total weight of that part of each cable which is paid out.

As the parameters associated with the cable, F_C and W_C, become small compared to the load parameters, F_L and W_L, the value of θ_C approaches θ_L. At the limit (an imaginary cable with zero weight and zero wind drag) the two angles are equal and the load position is defined exactly by cable length and θ_C. The practical case of $\theta_C = \theta_L$ is when there is no relative air movement, hence $F_L = F_C = 0$ and both angles are zero.

For all other cases, hovering with wind, or during flight, F_C and F_L will not be zero and θ_C will differ from θ_L. This difference is the error in the angle to the load as measured at the helicopter. The load position offset error is

$$E = L \sin (\theta_C - \theta_L) \tag{16}$$

where L = the length of cable paid out.

Figure 32 shows the error in load position information versus wind velocity for three load configurations. In all three cases the load is an 8- x 8- x 20-ft, 5000-lb MILVAN supported by two 100-ft cables, one cable at either end. The cables are assumed to be 1-in. in diameter and weigh 1.55 lb/ft.

The top curve is for an empty MILVAN oriented so that its 8- x 8-ft surface is directly toward the wind. The middle curve is for the same MILVAN oriented so that its 8- x 20-ft side is toward the wind. The lower curve is for the MILVAN with its 8- x 8-ft surface directly toward the wind but loaded to a gross weight of 20,000 lb.

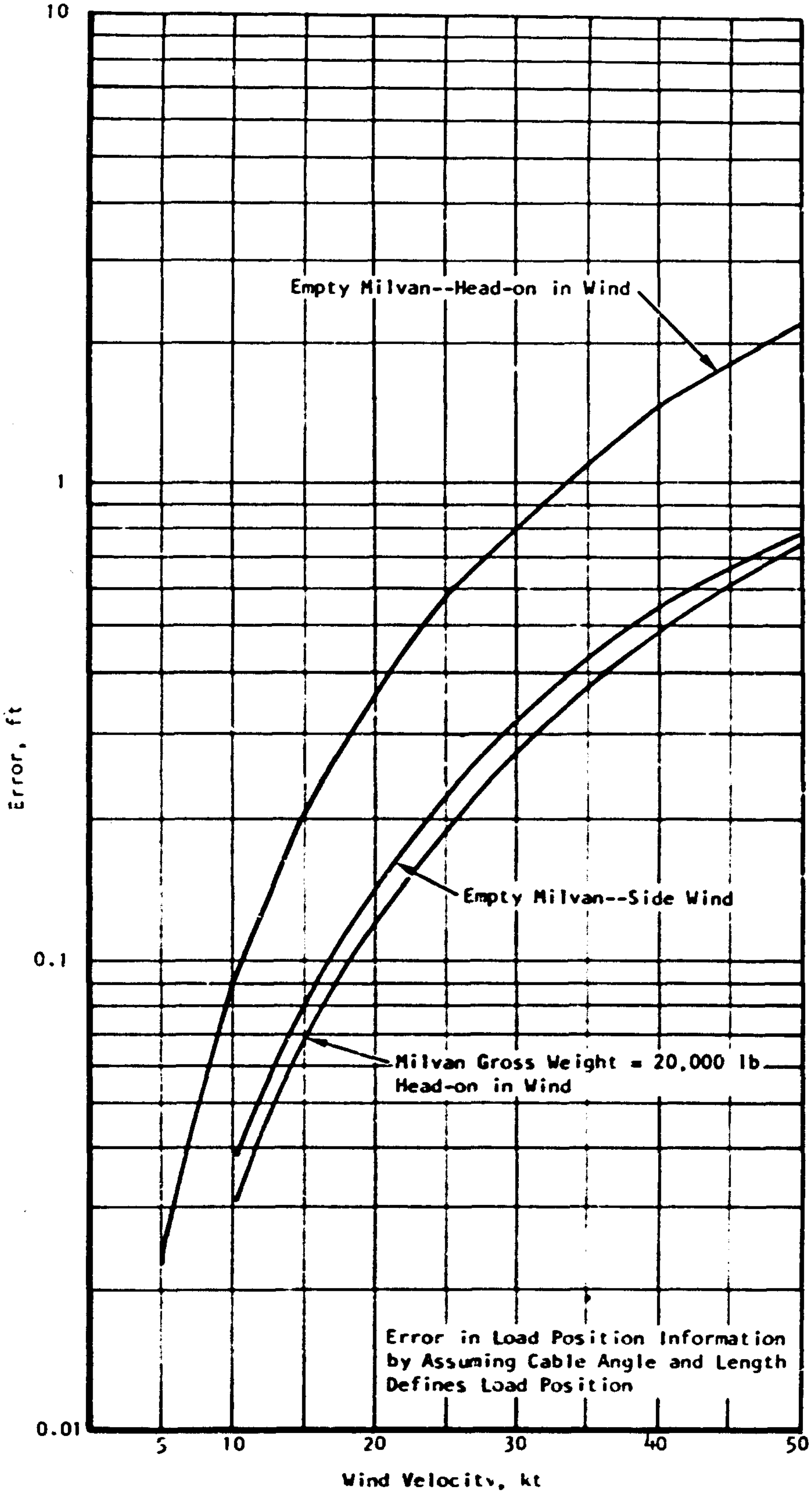


Figure 32. Error in Load Position Indication due to Assuming Cable Angle and Length Defines Load Position

EVALUATION OF APPROACHES

SUMMARY

The five payload position sensor concepts were subjected to a comparative evaluation of performance capabilities, development risk, development costs, unit production costs, physical characteristics, and intangible factors. The results of the evaluations show:

1. All of the approaches exhibit high performance capabilities.

2. Development risk is low in all cases.

3. While development costs vary widely, the influence of this factor is low when amortized over many (e.g., 300) units.

4. Unit production costs are the greatest influence factor.

5. Physical characteristics vary, but all of the approaches are acceptable.

6. There are wide variations in intangible factors; this leads to the recommendation that two of the sensor approaches be developed for operational comparison.

PERFORMANCE CAPABILITIES

Performance parameters and requirements were identified and discussed earlier in this report. Figure 33 illustrates the mechanics involved in calculating the performance index and the adjusted performance index for the approaches. The tabulation also shows weighting factors for the various performance factors. A value is estimated for each performance factor. The rank value is then assigned as follows:

If the Requirement Range is:	And the Estimated Value is:	The Rank is:
0.1 to 1.0	1.25 to 0.85	1
	0.85 to 0.65	2
	0.65 to 0.45	3
	0.45 to 0.25	4
	0.25 to 0.0	5
0.5 to 1.0	0.4 to 0.6	1
	0.6 to 0.9	3
	0.9 to 1.1	5
1.0 to 2.0	0 to 1.0	5
	1.0 to 1.5	3
	1.5 to 2.0	1

Sensing Technique: ______________

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal: 0.2 to 5 deg Lateral: 0.2 to 3 deg Yaw: (See instructions)			4 4		
Sensitivity/resolution	0.1 to 1.0 deg			9		
Hysteresis	0.1 to 1.0 deg			9		
Frequency response (3-dB point)	0.5 to 1.0 Hz			9		
Rate threshold	±1 to ±2 deg/sec			6		
Rate accuracy	±1 to ±3 dB			3		

Figure 33. Performance Evaluation Worksheet.

If the Requirement Range is:	And the Estimated Value is:	The Rank is:
0.2 to 5.0	4.4 to 5.6	1
	3.4 to 4 4	2
	2.0 to 3.4	3
	0.8 to 2.0	4
	0 to 0.8	5
0.2 to 3.0	3.35 to 2.65	1
	2.65 to 1.95	2
	1.95 to 1.25	3
	1.25 to 0.55	4
	0.55 to 0.0	5
1.0 to 3.0	2.0 to 3.0	1
	1.0 to 2.0	3
	0 to 1.0	5

The rank value is then multiplied by the weighting factor to obtain the performance factor result. The total performance score is the sum of the results.

DEVELOPMENT RISK

The risk factor is estimated based on the investigation and assigned a value between 1.0 and 10, with 1.0 representing least risk and 10 representing greatest risk. The risk factor is the reciprocal of risk value and will then fall between 0.1 (low probability of success) and 1.0 (high probability of success).

COSTS

Development cost estimates of the cable-angle measuring devices--big arm gimbal, separated mechanical linkage, force resolution--are based on estimates of design drawings, fabrication of two units, and low-quantity prices of purchased parts. These estimates are believed to be reasonably accurate. Development cost estimates for the radar and infrared approaches are more nebulous in that laboratory development is involved; however, the 50-percent confidence factor applies.

Unit production costs are based on unit costs of other equipment of similar complexity.

PHYSICAL CHARACTERISTICS

Size, weight, and power requirements are always important factors in aircraft applications, and so their characteristics were estimated for each sensing approach. These factors had a negligible influence on the evaluation of the comparative merits of the approaches.

INTANGIBLE FACTORS

The following factors cannot be quantified, but are nevertheless of interest in a detailed evaluation. These factors were developed in the evaluation and are offered as supplementary, qualitative information.

Flexibility of Application

The capability to apply a sensing concept to a variety of suspension configurations would be advantageous and was therefore considered.

Growth Potential

A system that is capable of expanding to include expanded design limits is more valuable than one that lacks growth potential and must be completely redesigned.

System Safety

Items that may be injurious or hazardous to either crew or aircraft were evaluated. Ground crew operations in the vicinity of the aircraft were also considered.

Training

Traditionally, the burden for poor or inappropriate design is shifted to the training area, requiring unusual skills or inordinately long training cycles. Sensor systems were rated according to the type and amount of special training required to both maintain and operate the system.

Logistics Support

Considerations in this area were (1) complexity, indicating a requirement to handle a larger number of parts; (2) unique storage requirements; (3) fragility, indicating designs that are sensitive to rough handling; and (4) spares requirements.

Producibility

Unique materials or fabrication processes associated with the production of a particular design were identified.

OTHER CONSIDERATIONS

Other factors considered were reliability, maintainability, and environmental capability. All of the sensor approaches considered for the final evaluation were acceptable in each of these areas. Other sensing approaches were eliminated during earlier preliminary evaluations for these and other reasons.

Performance Evaluations

The performance evaluation worksheets for the final evaluations are shown in Figures 34 through 38.

Numerical Evaluation

The helicopter payload position sensor evaluation, based on factors reducible to numerical values, is shown in Table 10.

Sensing Technique: Big Arm Gimbal

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal (γ): 0.2 to 5 deg	0.2 deg	5	4	20	Two angle transducers required with total accuracies of ±0.4 and ±0.25 percent.
	Lateral (β): 0.2 to 3 deg Yaw: (See instructions)	1.0 deg	4	4	16	
Sensitivity/resolution	0.1 to 1.0 deg	0.1 deg	5	9	45	
Hysteresis	0.1 to 1.0 deg	0.1 deg	5	9	45	
Frequency response (3-dB point)	0.5 to 1.0 Hz	1.0 Hz	5	9	45	
Rate threshold	±1 to ±2 deg/sec	1.0	5	6	30	
Rate accuracy	±1 to ±3 dB	1.0	5	3	15	
Total					216	

Figure 34. Performance Evaluation Worksheet, Big Arm Gimbal

Sensing Technique: Separated Mechanical Followers

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal (γ): 0.2 to 5 deg	0.4 deg	5	4	20	±1 percent total accuracy required
	Lateral (ρ): 0.2 to 3 deg	0.9 deg	4	4	16	
	Yaw: (See instructions)					
Sensitivity/resolution	0.1 to 1.0 deg	0.1 deg	5	9	45	
Hysteresis	0.1 to 1.0 deg	0.1 deg	5	9	45	
Frequency response (3-dB point)	0.5 to 1.0 Hz	1.0	5	9	45	
Rate threshold	±1 to ±2 deg/sec	1.0	5	6	30	
Rate accuracy	±1 to ±3 dB	1.0	5	3	15	
Total					216	

Figure 35. Performance Evaluation Worksheet, Separated Mechanical Followers.

Sensing Technique: Force Resolution

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal: 0.2 to 5 deg	0.4 deg	5	4	20	
	Lateral: 0.2 to 3 deg	0.4 deg	5	4	20	
	Yaw: (See instructions)					
Sensitivity/resolution	0.1 to 1.0 deg	0.15 deg	5	9	45	
Hysteresis	0.1 to 1.0 deg	0.15 deg	5	9	45	
Frequency response (3-dB point)	0.5 to 1.0 Hz	1.0 Hz	5	9	45	
Rate threshold	±1 to ±2 deg/sec	1 deg/sec	5	[illegible]	30	
Rate accuracy	±1 to ±3 dB	1 dB	5	3	15	
Total					220	

Figure 36. Performance Evaluation Worksheet, Force Resolution.

Sensing Technique: Radar

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal: 0.2 to 5 deg Lateral: 0.2 to 3 deg Yaw: (See instructions)	0.2 0.2	5 5	4 4	20 20	
Sensitivity/resolution	0.1 to 1.0 deg	0.1	5	9	45	
Hysteresis	0.1 to 1.0 deg	0.1	5	9	45	
Frequency response (3 dB point)	0.5 to 1.0 Hz	1.0	5	9	45	
Rate threshold	±1 to ±2 deg/sec	1.0	5	6	30	
Rate accuracy	±1 to ±3 dB	1.0	5	3	15	
Total					220	

Figure 37. Performance Evaluation Worksheet, Radar.

Sensing Technique: Infrared

1	2	3	4	5		
Performance Factor	Requirement Range	Estimated Value	Rank Value	Weighting Factor	Result	Comments
Accuracy	Longitudinal: 0.2 to 5 deg Lateral: 0.2 to 3 deg Yaw: (See instructions)	0.25 deg 0.25 deg	5 5	4 4	20 20	
Sensitivity/resolution	0.1 to 1.0 deg	0.125	5	9	45	
Hysteresis	0.1 to 1.0 deg	0.125	5	9	45	
Frequency response (3-dB point)	0.5 to 1.0 Hz	5 Hz	5	9	45	
Rate threshold	±1 to ±2 deg/sec	1 deg/sec	5	6	30	
Rate accuracy	±1 to ±3 dB	1 dB	5	3	15	
Total					220	

Figure 38. Performance Evaluation Worksheet, Infrared.

TABLE 10. HELICOPTER PAYLOAD POSITION SENSOR EVALUATION SUMMARY

Sensor Approach	1 Confidence Factor	2 Performance Number	3 Development Cost, Dollars	4 Unit Cost per Shipset, Dollars	5 Value
Big arm gimbal	0.80	216	49,000	4,950	33.80
Separated mechanical linkages	0.90	216	49,000	3,240	57.1
Force resolution	0.80	220	27,000	4,320	39.9
Radar	0.85	220	250,000	5,000	32.0
Infrared light	0.80	220	300,000	4,500	32.0

1. Confidence Factor: Estimated probability of the success of a development program to produce a viable, manufacturable sensor.
2. Performance Number: See Performance Evaluation Worksheets.
3. Development Cost: Estimated cost to design, fabricate and test one prototype sensor system. Confidence level, ±50 percent.
4. Per-Unit Cost: Estimated cost per shipset. Confidence level, ±25 percent.
5. Value: Performance per unit cost (including amortized development cost) multiplied by the confidence factor.

CONCLUSIONS

The conclusions of the in-depth investigation of the five payload position sensor approaches are summarized in Table 10, it can be seen that

1. The confidence factor is high in all cases.

2. The performance number is high in all cases.

3. The development cost, when amortized over 300 production units, has only a minor influence on the value figure.

As a result, the relative value score for the five payload sensors is primarily determined by the unit cost. Based on an estimated shipset cost of $3240, the separated mechanical linkage provides the best payload position sensor approach.

The separated mechanical linkage cable-angle sensor is shown mounted to a typical cable winch assembly in Figure 39.

The unit cost estimate is considered to have an accuracy of ±25 percent. Therefore, it is quite possible that one of the other approaches could have a higher value should its cost be lower than estimated or the separated linkages cost be higher than estimated. Particularly, the force resolution approach could be nearly equal in value under such circumstances. A review of intangible features listed with the approach descriptions indicated that the force resolution method is also a desirable approach.

The conclusions of the investigative program are:

1. The separated mechanical linkage approach provides high performance at lowest cost.

2. The force resolution approach also provides high performance at competitive cost.

3. The big arm gimbal, radar and infrared approaches all provide high performance, but their cost is less competitive.

RECOMMENDATIONS

It is recommended that a development and test program be initiated to develop, fabricate, and test the separated mechanical linkages load position sensor.

It is also recommended that consideration be given to a program to develop, fabricate, and test the force resolution method of load position determination. Details of the force resolution approach are shown in Figure 26.

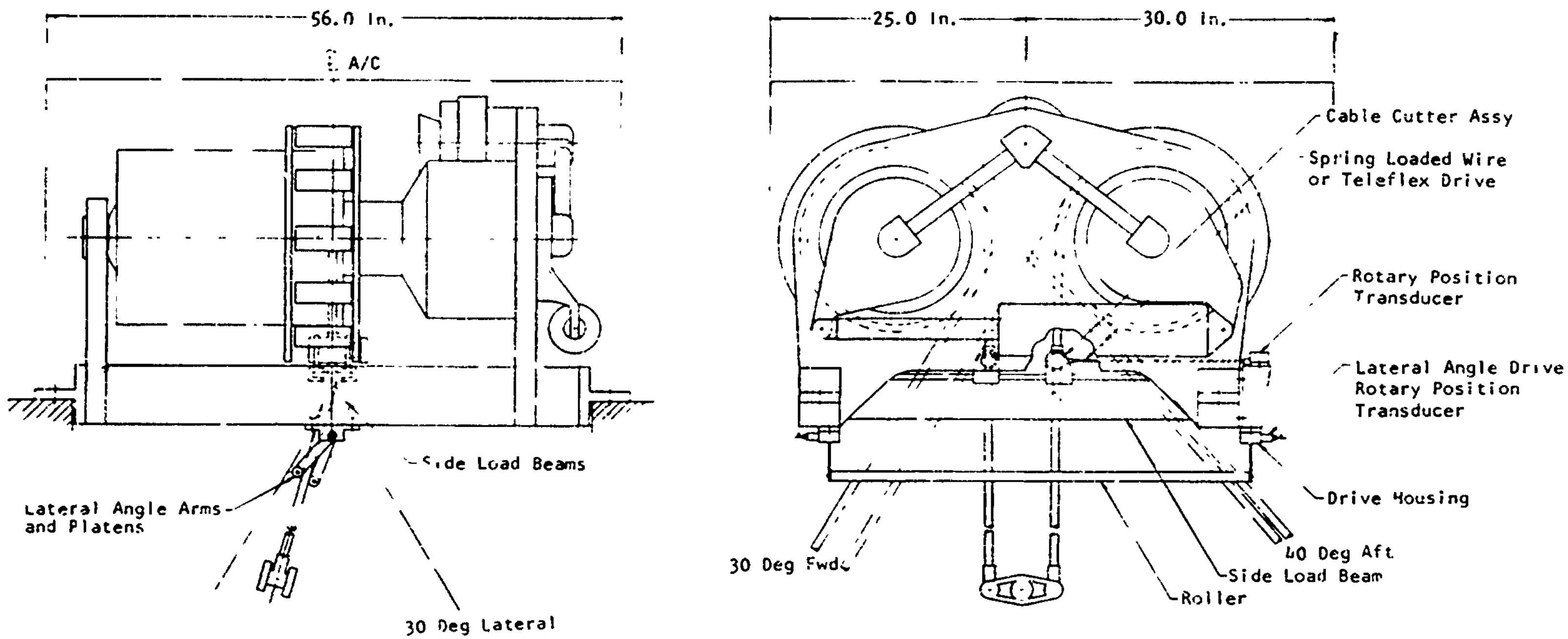


Figure 39. Separated Mechanical Followers -- Typical Installation.

DESIGN REQUIREMENTS

This section establishes the design and test requirements for the selected helicopter payload position sensor, i.e., the separated mechanical linkages. The alternate selection, force resolution methods, is also discussed.

SEPARATED MECHANICAL LINKAGES--DESIGN

Design of the separated mechanical linkage approach is illustrated in Figure 39 The top view shows the manner in which longitudinal cable angle is sensed. Since the cable cutter assembly follows the longitudinal motions of the cable, longitudinal angles may be easily sensed by installing a spring-loaded, wire-driven rotary position transducer so that it is driven by longitudinal motions of the cable cutter assembly. This arrangement would preload the cable cutter assembly against the cable so that hysteresis would tend to be minimized if friction were small between the cable cutter and the rails of the cable guide on which it rides. If the friction were great enough that wire tension were insufficient to drive the cable cutter assembly (with motion of the cable), then the cutter assembly would require redesign to minimize the hysteresis.

To sense lateral angles, a pair of rollers (platens) are suspended on arms that are pivoted at a point along the locus of the center of rotation of lateral cable motions. Rotary motions of the arms are sensed by rotary position sensors.

The advantages of this approach compared with other approaches are that it is simpler, lateral cable angles are not influenced by longitudinal angle, and disengagement of the lateral cable-following mechanism is not a problem.

Roller wear due to longitudinal motions of the cable is the greatest problem, since it must be minimized without increasing wear of the cable. Another disadvantage is that the design is peculiar to a specific suspension-and-hoist configuration and would require redesign (if applicable) for each new configuration. Figure 8 shows the design in a typical installation.

The minimization of roller wear involves optimizing material selection and preloading of the rollers against the cable. It may also be possible to design the rollers so the roller and cable act as a gear pair and longitudinal motion of the cable drives the roller like a gear instead of the roller sliding on the cable.

Pivot point selection for the lateral arms must also be optimized. The pivot points can be chosen to increase sensitivity near zero lateral angle at the expense of linearity, or linearity can be increased at the expense of sensitivity.

The geometry of the separated followers is shown in Figure 25. The equations of the geometry are given on page 69.

Table 8 summarizes the design and performance characteristics of the system.

SEPARATED MECHANICAL LINKAGES--DEVELOPMENT TEST PROGRAM

The design of the separated mechanical linkages payload position sensor is sufficiently straightforward that functional development is not required. Instead, design effort and development testing should be directed toward possible wear problems due to cable-roller contact.

Environmental qualification testing should be in accordance with MIL-STD-810B as follows:

Test	Method	Procedure	Limit
500	Altitude	II	30,000 ft
501	High Temperature	II	154°F
502	Low Temperature	I	-55°F
507	Humidity	V	5 cycles
514	Vibration	I	Category C, Curve B of Figure 514.1-3, of page 514.1-19

It is also recommended that an operational flight test program be undertaken to verify the utility of the design. Such flight testing could be accomplished in conjunction with prototyping and flight test of HLH systems or components.

ALTERNATE DESIGN--FORCE RESOLUTION

The principle of the force resolution design is shown in Figure 26. The hoisting mechanism is attached to the aircraft structure using eight load links. The devices are arranged so that four of them support the vertical weight of the hoist and sling load, two provide lateral restraint and two provide longitudinal restraint. In this system, the outputs of the vertical force transducers are averaged so that they always indicate the correct load regardless of the point of load application in the horizontal plane.

The lateral loads are reacted by force transducers which also react any moments introduced in the horizontal plane. The averaged output of these two devices provide a measurement of the lateral force with the effects of any moments in the horizontal plane being cancelled out.

The longitudianal forces are measured by a similar system with the averaged output being equal to the net longitudinal reaction of the hoist platform.

For a two-hoist system the vertical and longitudinal loads are averaged to provide a single output or they are monitored individually and the lateral restraining forces measured separately to determine whether a yawing moment or a rolling moment results from the sling load displacement.

Justification for presenting the force resolution approach as a possible alternate payload position sensor is based on the following:

1. Since the load cells are integral with the hoist mechanism mounting, they are not subject to damage from external sources such as broken cables.

2. With multiple load cells for each axis the system is operable even with a failed cell.

3. The influence of movable suspension points--such as from active arm stabilizers--on cable angles does not influence force vector determination; i.e., load stabilization methods do not influence load position sensing.

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