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Some Aspects of Optimizing Kiebitz/ARGUS Flight Dynamics and Control System by Simulation and Flight Testing

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1. ABSTRACT

A brief system description of the tethered rotorplatform Kiebitz/ARGUS is given, which is designed to lift payloads of 150 kg to 450 m above 1000 m ground level for mission times of up to 24 hours.

After a short review of the main dynamic characteristics of an unmanned tethered rotorplatform in comparison to a normal helicopter, requirements for an operational control system are presented.

In the second part of the paper the methods used to optimize the control system are described using computer simulations to determine controller parameters and flight tests for verification.

2. THE KIEBITZ/ARGUS SYSTEM

Fig. 1 shows the Kiebitz unmanned rotorplatform which is connected to the ground station by a tether cable (fig. 2) that provides the data link and supplies fuel to the turbine. The continuous fuel supply practically enables unlimited mission time.

Fig. 3 shows the flight vehicle. The rotor is driven by ejection of compressed air at the blade tips. The compressed air is produced by a radial compressor powered by an Allison 250-C 20 B gas turbine. It is ducted through the rotor head and the rotor blades to the tip nozzles. The turbine exhaust gas is conducted to two yaw control nozzles. This system has a limited efficiency when compared to a gear drive system but eliminates the need of a tail rotor thus allowing a small symmetrical air frame with the advantage of reduced detectability and simplified ground support. Fig. 4 shows the flight envelope of the Kiebitz/ARGUS prototype.

3. DYNAMIC PROPERTIES

3.1 Vehicle dynamics

Translation and Rotation

Dynamical characteristics of a tethered rotorplatform are different from those of a conventional helicopter. In the Kiebitz configuration, the unstabilized rotorplatform shows monotonous instability in contrast to the oscillatory instability of a free-flying helicopter. Fig. 5 gives a pictorial representation. The short period frequency is well damped while the phygoide, which is oscillatory unstable in the case of the free-flying vehicle, is damped in the case of the tethered platform.

Attitude and translational dynamics are strongly coupled. This coupling, being a function of cable length, is one of the main design problems and was the subject of the optimization work discussed here.

Due to fuselage symmetry, platform longitudinal and lateral dynamics are identical for hover flight. Therefore only the longitudinal motion is discussed in the following.

Yaw dynamics

Yaw control is achieved by controllable exhaust nozzles. As the vehicle is tethered to the ground it is mainly operated under hover conditions. Therefore practically no coupling exists between the yaw axis and the roll and pitch axes. The yaw axis must be stabilized, because the vehicle shows a type 2 (double integrating) behaviour. The rotor torque exerted on the platform cell is low because of the pneumatic reaction drive. It is easily compensated by the two exhaust nozzles.

Vertical dynamics

While the conventional helicopter must hold altitude by collective rotor blade pitch and throttle position the tethered platform hovers in an altitude determined by cable length, wind conditions and rotor thrust. The platform is forced to move on a spherical surface with the radius being roughly determined by tether length and rotor thrust.

3.2 Control Modes

Fig. 6 shows the possible types of steady state control modes of tethered platforms.

1.) Attitude control, forcing the platform to assume a certain angular attitude in space.

2.) Position control, forcing the platform to assume a certain position with respect to the ground station.

3.) Combined attitude and position control

Control mode 1.) leads to large horizontal displacements under strong wind conditions. Control mode 2.) requires large steady state attitude angles and large rotor tilt angles relative to the wind vector. Therefore, in order to satisfy normal mission requirements which place restrictions on angular and positional freedom of motion it is necessary to use control modes of the type 3.) providing combined attitude and position control.

3.3 Cable Effects

Platform stability in general is rather insensitive to jerk-like tether force variations or to cable oscillations. The average tether force, however, is a dominant factor and has to be controlled at predetermined levels.

Fig. 7 shows the gust dynamics of the system for a rapidly increasing 8 m/sec gust. It shows strong attitude disturbances caused by the interaction of increasing thrust, increasing cable tension, increasing cable drag and changing of the cable angle relative to the vehicle.

Gust dynamics strongly depend on cable length, because the main roots of the system and cable drag depend on this parameter. Fig. 8 shows the characteristics (frequency and damping of cable force) of the system in the vertical axis. They are a function of cable and rotor characteristics and for low altitudes are also affected by ground station characteristics.

Fig. 9 presents the natural frequency in pitch and roll, slightly depending on thrust but not on cable length. The translatory natural frequency, also shown, strongly depends on cable length. It increases rapidly with short cable length.

Another problem is shown in fig. 10. The rotor is tilted by horizontal winds into the wind direction when the platform still sits on the landing pad prior to launch. As a result, after take off the vehicle will be horizontally accelerated into the wind direction by the horizontal thrust vector and held back by the cable. Depending on wind velocity this can lead to large disturbance torques affecting both vehicle attitude and position. The cable angle γ therefore is one of the most critical variables, since when it exeeds a certain value determined by the shape of the landing cone and the location of the cable mounting point, the cable will touch the side walls of the cone endangering the safety of the vehicle. In order to limit this motion during take-off, a position angle α is computed from the cable angle γ and the vehicle attitude angle Θ and fed back into the controller to reduce horizontal motion during take-off.

4. STABILIZATION AND CONTROL REQUIREMENTS

Major operational requirements of the KIEBITZ/ARGUS system are:

- All weather operation	
- Low level operator qualification	
- Mission time	$\leq$ 24 hours
- Mission altitude	$\geq$ 450 meters
- Horizontal wind speed	$\leq$ 17 m/s
- Climb/descend rate	$\leq$ 3 m/s
- Attitude stabilization accuracy	$\leq$ 3°

These requirements in conjunction with the basic instability of a tethered rotor platform necessitate a stabilization system with the following characteristics:

- Stabilization of angular motion in pitch, roll and yaw
- Stabilization of horizontal translational motion
- Climb and descend rate control

Numerous flight tests performed with this system with the operator having manual control over pitch, roll and yaw angles, and climb and descend rates, showed that

- o The operator cannot stabilize the rotor platform
- o The operator cannot precisely carry out lateral translational flight manoeuvres
- o The operator tires during long mission periods increasing the likelihood of faulty control inputs.

This clearly indicated that an operational system required both optimization of the basic system stabilization functions and a higher degree of automization of the operator control functions than provided in the prototype system.

The highest demands are put on the automatic flight control system in the take-off and landing phases where lateral motion is highly restricted and the dynamic properties of the tethered platform change drastically as a function of cable length.

It was this flight range at low altitudes which was the subject of intense flight testing which produced a great deal of valuable test data concerning the level of system optimization and automatization required for the operational KIEBITZ/ARGUS system.

To illustrate the operator capabilities controlling the vehicle in a low hover altitude of 20 cm fig. 11 shows Pilot Induced Oscillations (PIOs) when the operator tries to stabilize vehicle motions by attitude commands. The PIOs are a result of visional disorientation because the operator cannot separate attitude and translational motions.

5. CONTROL SYSTEM CONFIGURATION

The basic configuration of the KIEBITZ/ARGUS control system is shown in fig. 12. It is divided into two sections:

- The on-board control system providing autonomous platform stabilization functions.
- The ground system providing system monitoring and operator control functions.

Both systems communicate via conductors embedded in the tether cable.

In the following the on-board control system will be considered in more detail as it was the subject of the optimization investigations.

The autonomous on-board control system components are shown in fig. 13.

The figure shows the three basic control loops:

1 Stabilization of attitude and horizontal translations

Combined control loops are used to provide attitude stabilization and positional control in the horizontal plane. For the latter both translational damping is provided using linear accelerometers and positional control using cable angle sensors.
As the KIEBITZ/ARGUS is symmetrical with respect to pitch and roll axes control loops in both axes are identical.
Flight states are measured using the following sensors:

2 rate gyros	measuring bodyfixed angular rates
2-axis platform	measuring attitude and linear acceleration
2 synchros	measuring the angles between cable and platform at the mounting joint.

2 Yaw stabilization

An azimuth control loop with an inner yaw rate control loop provides stabilization with respect to north. An additional radar scan compensation circuit reduces radar scan disturbances.
Flight states are measured using the following sensors:

1 rate gyro	measuring yaw rate
2-axis platform	measuring the north-referenced azimuth angle

3 Vertical stabilization

Rotor rpm is varied to maintain thrust and to limit cable forces.
Sensors employed are:

1 rotor-rpm sensor
1 cable tension sensor

Attitude and horizontal translational control loops are shown in fig. 14.
The inner loop of the multiple-control loop system provides rotational damping using pitch rate feedback. The second loop provides translational damping. For this purpose an integrator in the flight controller calculates horizontal vehicle speed from horizontal acceleration. The third loop provides pitch angle control. The pitch angle controller has proportional and integral characteristics to minimize control error.
The outer loop provides position control. For this purpose the position angle is derived from the measured pitch and cable angle.

Fig. 15 shows a detailed block diagram of the pitch axis flight controller as mechanized in the flight control electronics. This figure shows three blocks of the flight controller which were varied during the flight tests to achieve control system optimization. Switches were included to allow structural changes of the controller.

Block 1 : This block is the attitude controller with additional translational damping based on the minimal set of control laws. The parameters G_{IL} and G_B are made adaptive to account for variing rotor platform dynamics with cable length.

Block 2 : This block allows modification of translational damping by means of a first order low pass filter. The filter time constant is variable and related to the variable rotor platform dynamics. The advantage of this damping concept is the reduction of steady state attitude errors by decoupling the attitude control loop from the translational damping loop.

Block 3 : This block generates either a feed-forward signal to minimize longitudinal motions during take off or provides an attitude command signal to reduce steady state position errors in the horizontal plane.

6. SYSTEM OPTIMIZATION

6.1 Simulation Models

Fig. 16 shows the general approach taken to optimize Kiebitz/ARGUS dynamics. In addition to off-line calculations to determine specific values of significant system variables extensive use was made of computer system simulation using models of various complexity. Parameter optimization was accomplished employing optimization theoretical methods in the time domain.

Models included

- Linearized vehicle dynamics
- Non-linearized vehicle dynamics
- Rotor, cable, ground station dynamics
- Sensor, actuator, and flight controller characteristics
- Error models

The simulation models were permanently updated using the latest flight test results.

6.2 Optimization Steps

The optimization process was divided into several steps such that close correlation could be maintained between computer models and flight test results.

The cable angle γ was chosen as the main criterium for optimization because of its significance on system performance and safety of operation.

The following steps in optimizing the flight controller were performed:

STEP 1: Parametric optimization of the attitude controller (basic controller) (See fig. 15, block 1).

STEP 2: Optimization by modified translational damping including parametric optimization (See fig. 15, block 2).

STEP 3: Optimization of the combined attitude and position control loops, mainly optimizing position angle gain G_α (See fig. 15, block 3).

7. FLIGHT TEST RESULTS

The Kiebitz/ARGUS Optimization results for the take off and landing phase under wind conditions can be summarized as follows:

take-off wind-conditions

The maximum wind velocity under which take-off tests were performed was raised from 5 to 10 m/sec. An upper limit of 17 m/sec seems feasible without vehicle redesign.

take-off dynamics

The maximum cable angle γ was reduced from 12.5° to 5.5° for 5 m/sec wind.

Fig. 17 shows the flight test optimization results from more than 100 take-offs. In this diagram the maximum dynamic cable angle as the most critical system parameter is shown versus wind speed. Curve 0 shows the maxima of γ before optimization. The mechanical limit for the cable angle of 15° is reached at a windspeed of 5 m/sec.

Curve 1 shows the results obtained with the optimized basic controller of fig. 15, block 1 .

Curve 2 gives the optimization results with modified translational damping. Block 2 , fig. 15.

Curves 3a and 3b present the results of the combined attitude and position control alternatives (see fig. 15, block 3). Curve 3a shows the results using position angle feed forward, 3b using the position angle α as attitude command.

Curve 4 shows the simulation results of the optimized basic controller. Comparison of this curve with the flight test curve 1 shows a good agreement between simulation and flight test results.

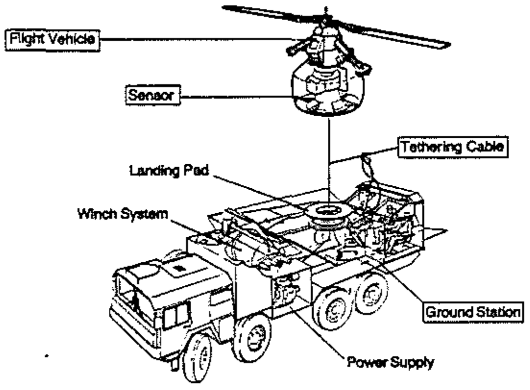

Fig 1 KIEBITZ

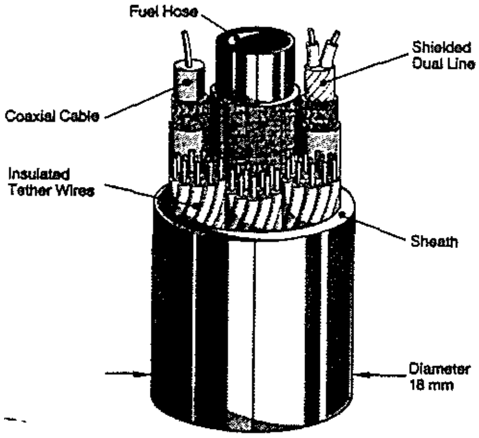

Fig. 2 TETHERING CABLE

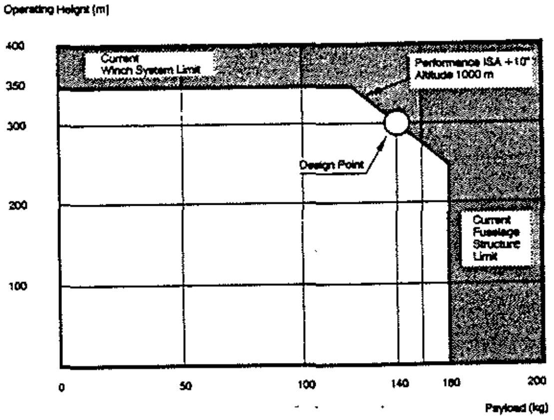

Fig. 4 PERFORMANCE LIMITS

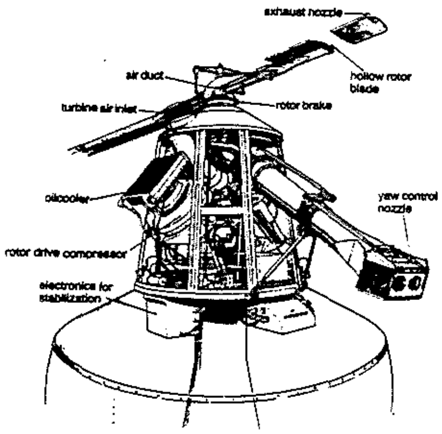

Fig. 3 FLIGHTVEHICLE

a) Translational Motions (unstabilized)

b) Attitude Motions (roll, pitch)

Fig 5 STABILITY MODELS OF THE UNSTABILIZED KIEBITZ

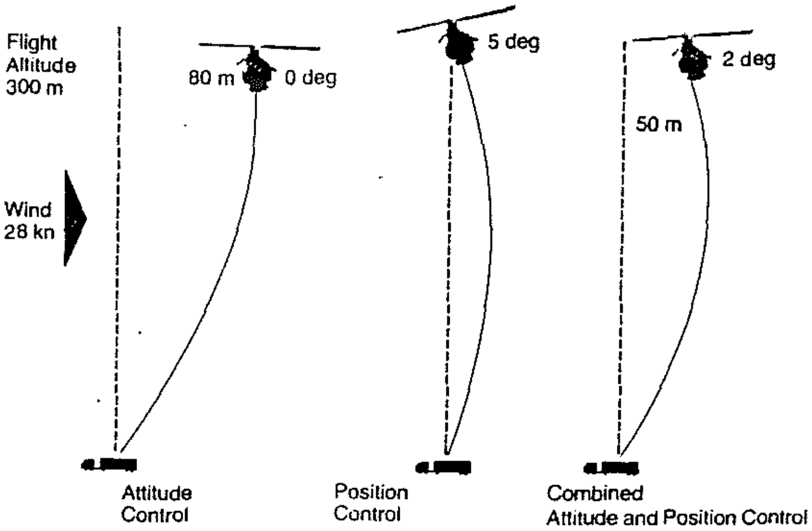

Fig. 6 CONTROL LAWS

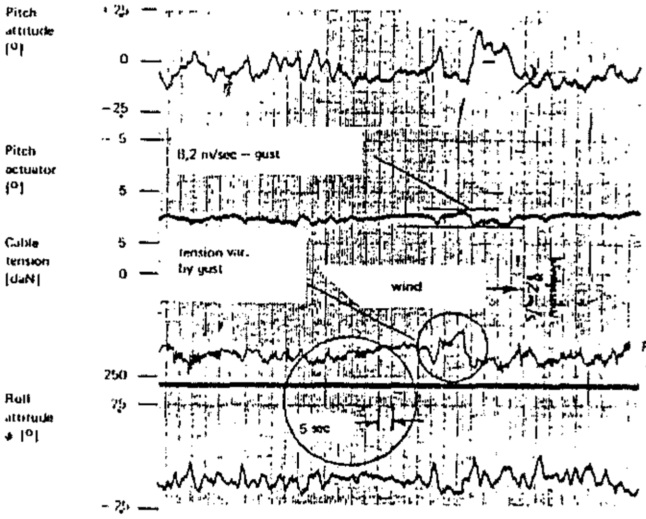

Fig. 7 GUST DYNAMICS

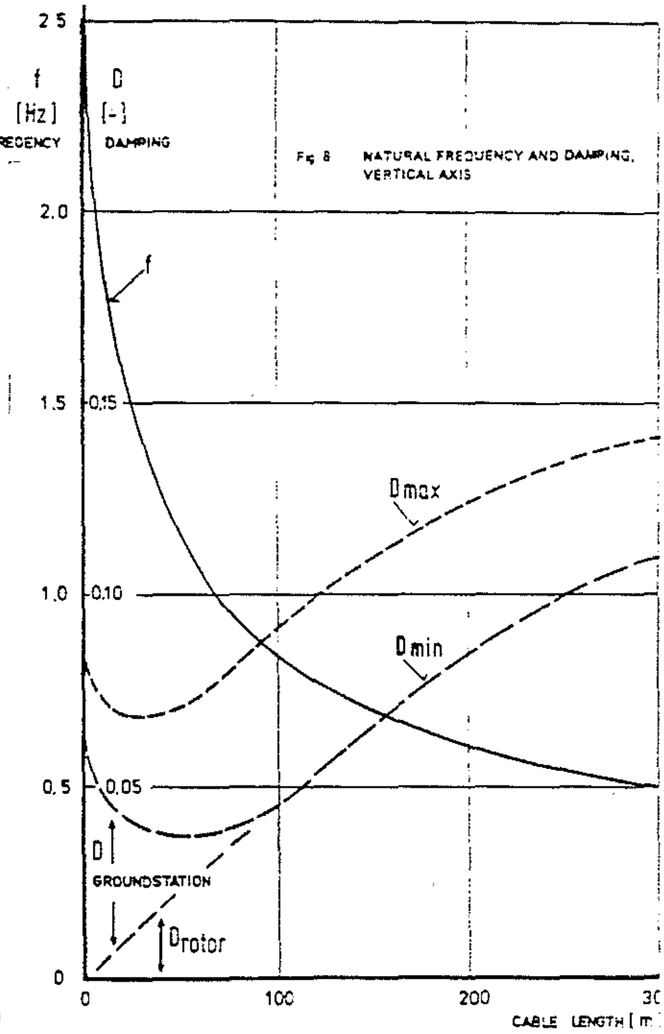

Fig 8 NATURAL FREQUENCY AND DAMPING, VERTICAL AXIS

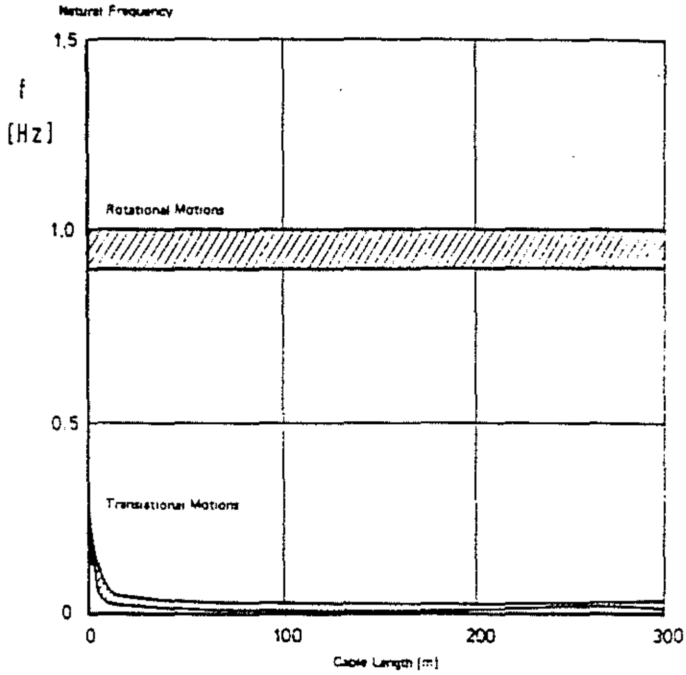

Fig. 9 KIEBITZ NATURAL FREQUENCIES

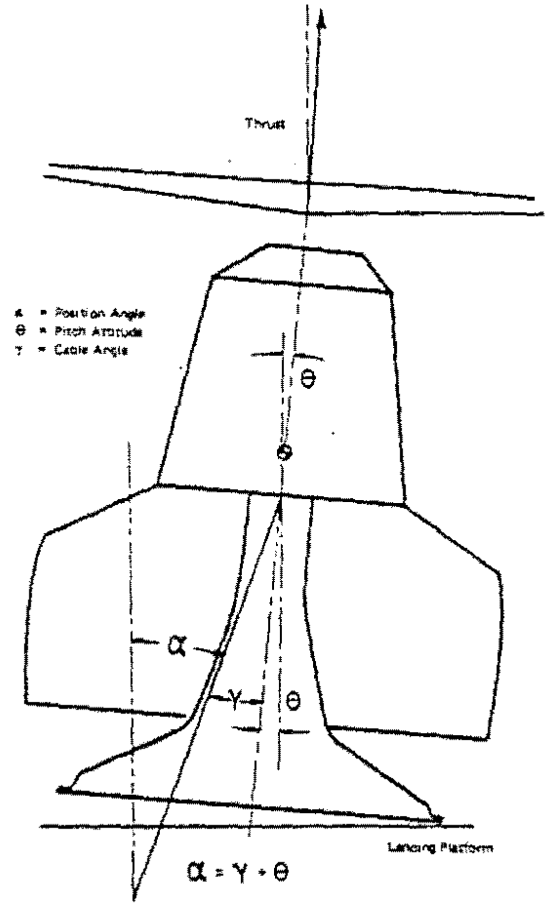

Fig. 10 KIEBITZ, DEFINITION OF ANGLES

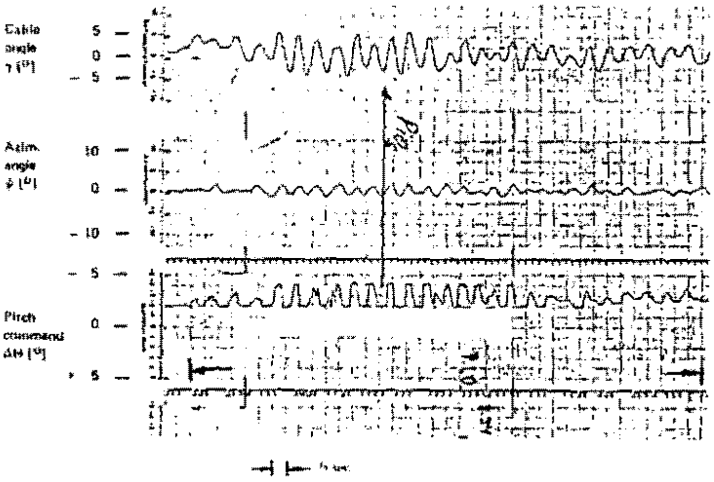

Fig. 11 PILOT INDUCED OSZILLATIONS

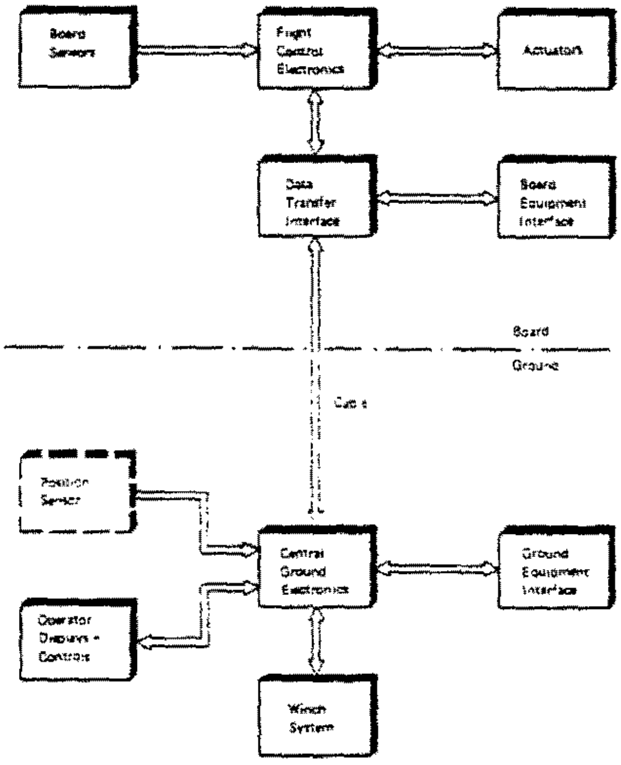

Fig. 12 KIEBITZ, CONTROL SYSTEM CONFIGURATION

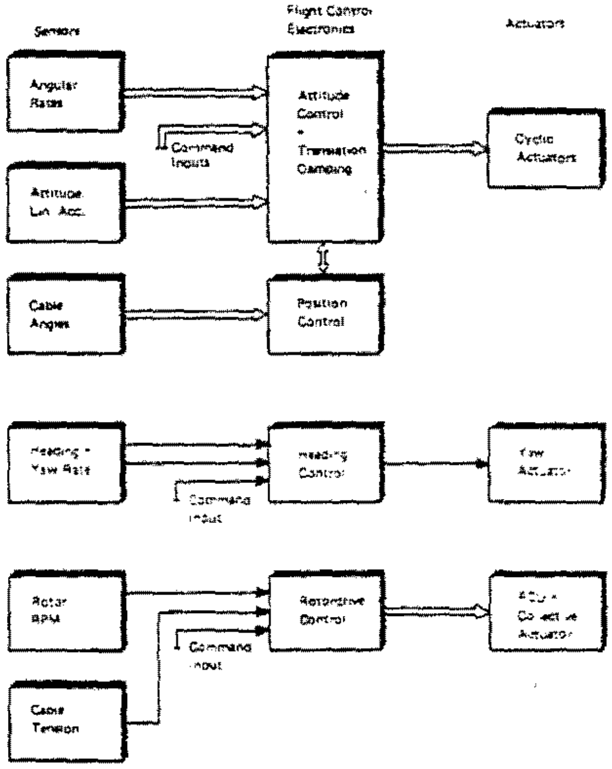

Fig. 13 KIEBITZ, ON BOARD CONTROL SYSTEM COMPONENTS

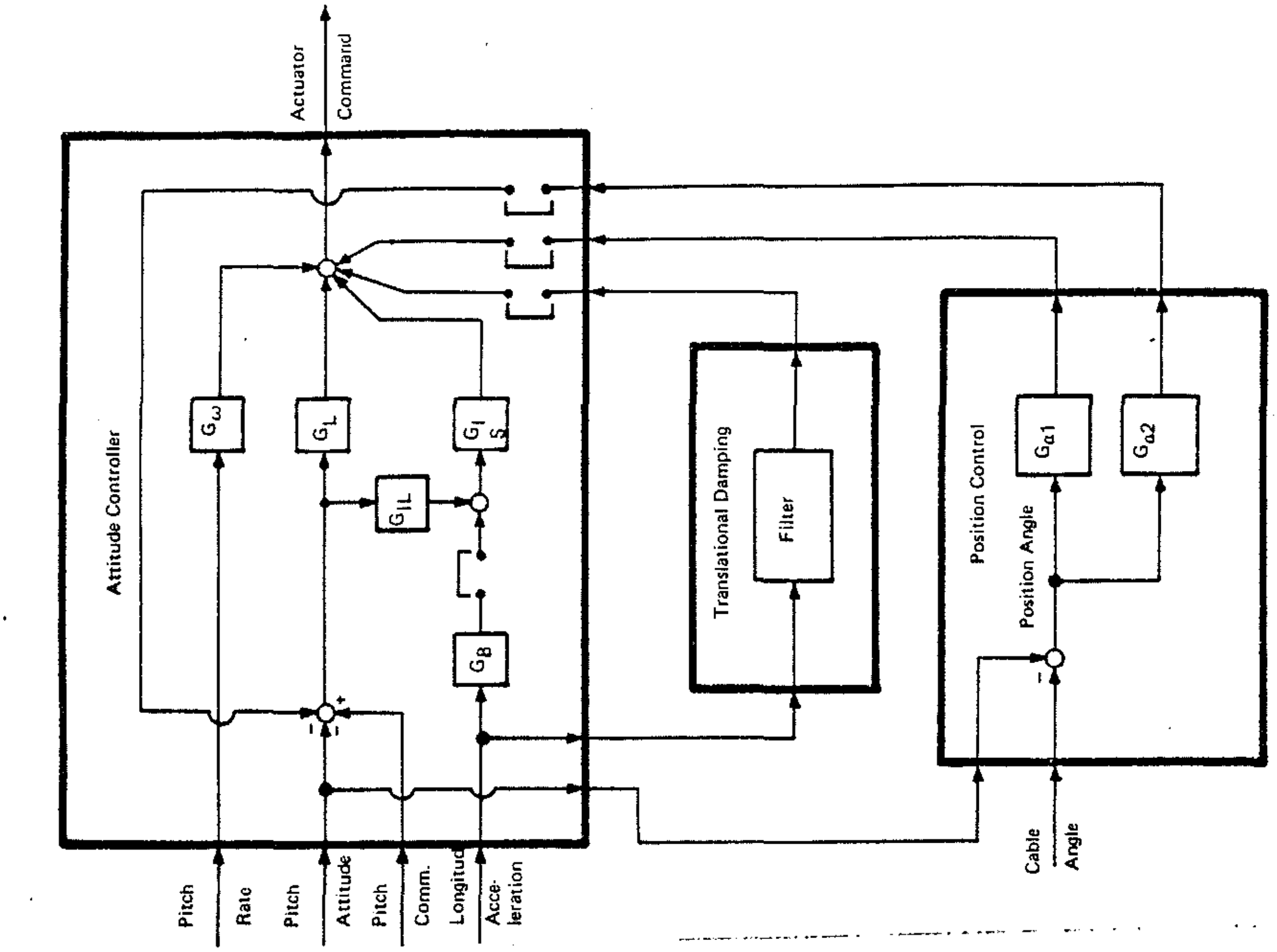

Fig. 15 KIEBITZ, FLIGHT CONTROLLER PITCH AXIS

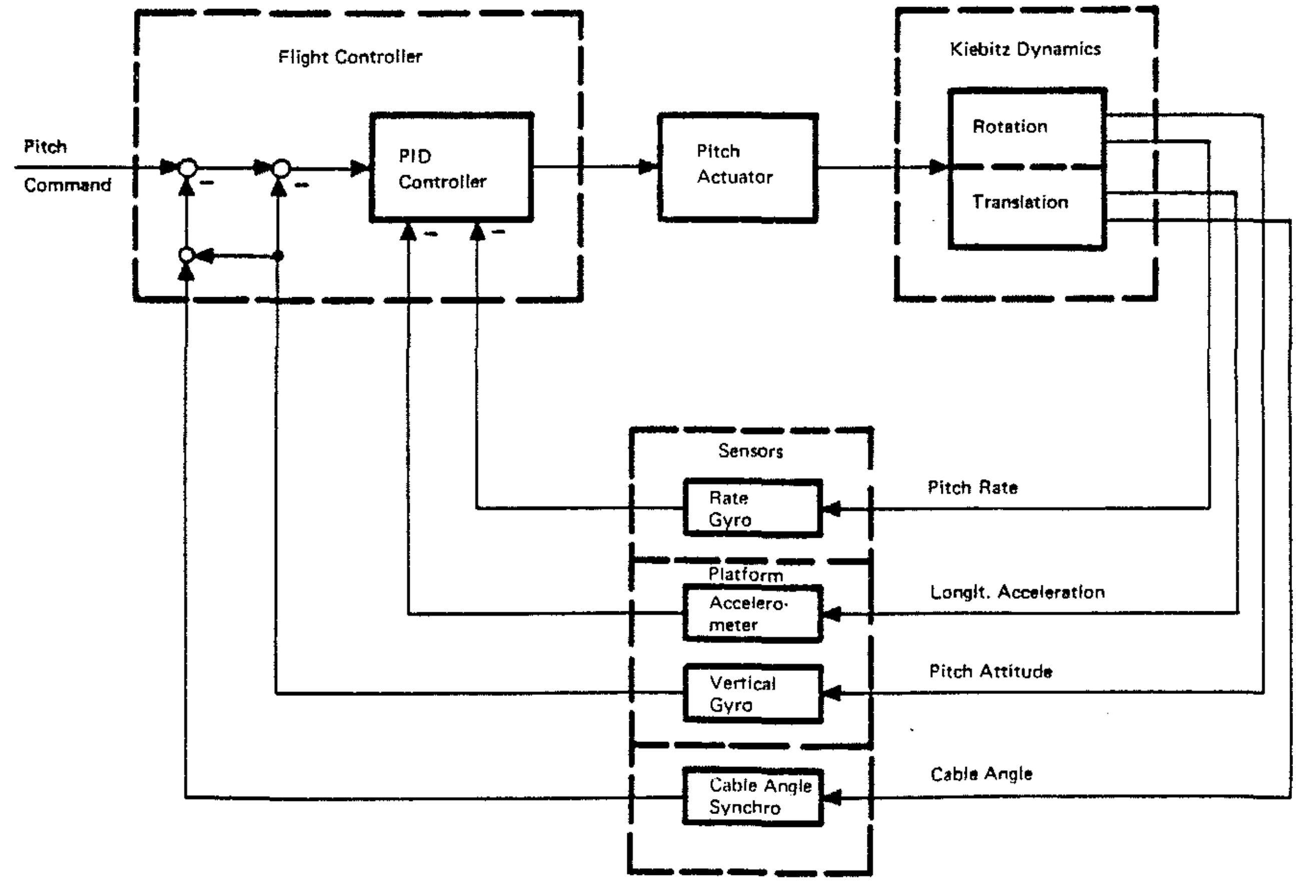

Fig. 14 KIEBITZ, CONTROL LOOPS PITCH AXIS

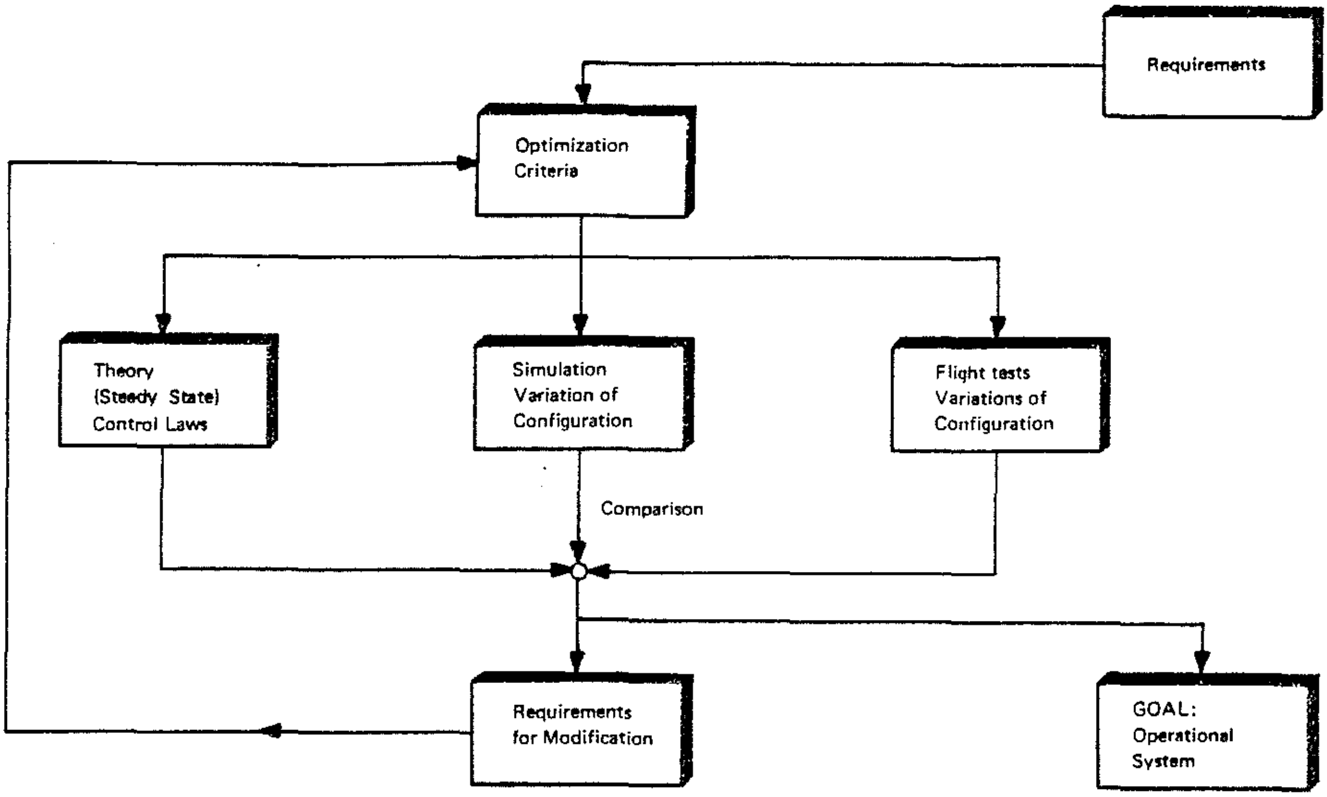

Fig. 16 OPTIMIZATION PROCEDURES

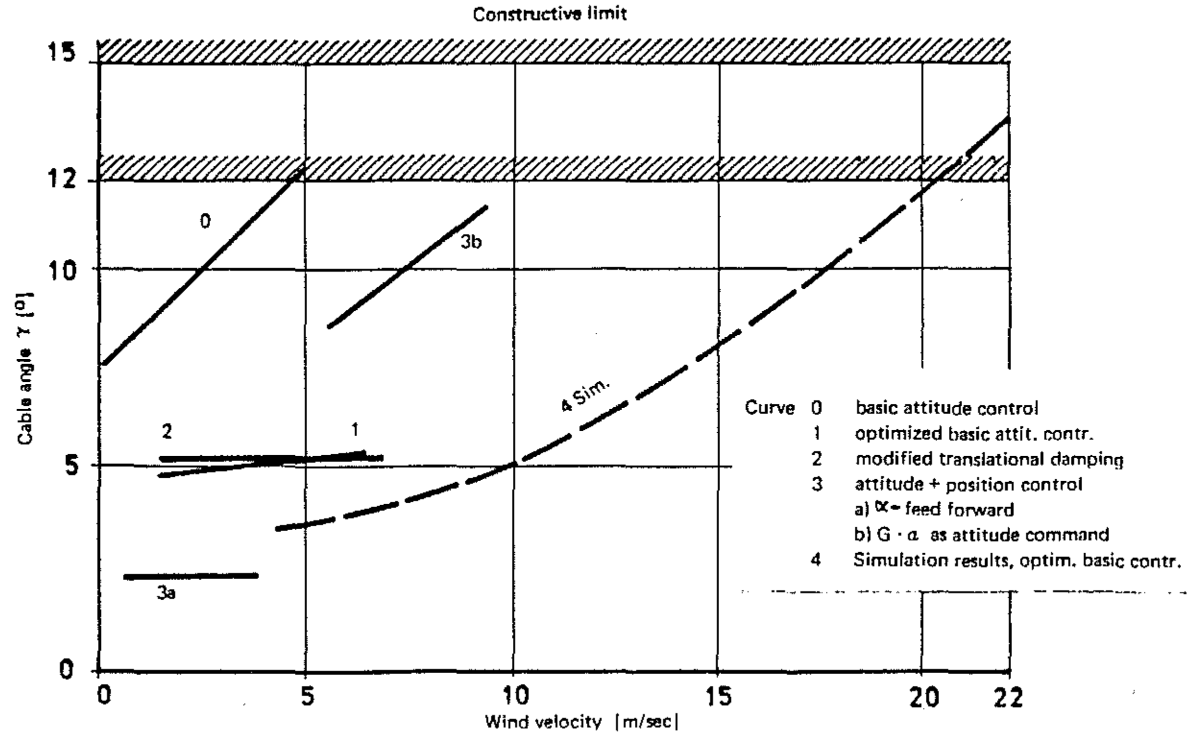

Fig. 17 FLIGHT TEST RESULTS