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A DIGITAL SYSTEM FOR HIGHER HARMONIC CONTROL OF A MODEL ROTOR

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ABSTRACT

For the four-bladed hingeless model rotor used at the DFVLR a computer based higher harmonic control (HHC) system was developed.

The description of the complete system is divided into three topics:

- the electrohydraulic servo actuator system
- the static and dynamic balance system
- the digital quick-look and control system

The electrohydraulic assembly consists of three closed loop positioning systems working independently. Electrical inputs produce proportional piston strokes and feedback circuits perform a constant transfer function in the frequency range of interest.

A six component balance system is integrated directly beneath the rotor hub sensing the static and dynamic rotor forces. The static force measuring is performed by load cells with strain gauges while the dynamic forces are measured by piezoelectric load cells.

The digital quick-look and control system performs three tasks. These are the computing and generating of the higher harmonic control inputs, the monitoring and displaying of the most important sensor signals in the frequency domain and finally the recording of all sensor signals for off-line data reduction.

For these three subsystems the important design criteria are evaluated and the hardware and software realizations are described.

1. INTRODUCTION

In normal flight conditions, but especially near the boundary of the flight envelope, the helicopter rotor must operate in a severe aerodynamic/dynamic environment. This includes

- stalled and reversed flow on the retreating blade
- transient Mach number effects on the advancing blade
- atmospheric turbulence
- impulsive flow due to blade-vortex interaction
- blade-fuselage interference flow
- rotor instabilities
- blade aerodynamic/dynamic mismatch

The conventional monocyclic blade control is unable to avoid these effects or to reduce the consequences. One major advance in rotorcraft design to aleviate these disadvantegeous effects will be the introduction of higher harmonic control. In recent years theoretical work in this domain has been intensified. But to obtain improvements for the design of such new helicopter systems it is necessary to verify theoretical results with corresponding test data.

In the DFVLR Institute for Flight Mechanics a rotor test stand for testing in large wind tunnels has been developed in a joint program with the German industries under contract by the German Ministry of Defence. Since the start of operations in 1976 several test programs have been carried out and the test techniques have been improved continually /1/. In 1979/80 the possibility for high-frequency dynamic control of the rotor was provided by extensive hardware modifications. With this, an essential prerequisite was fullfilled for the experimental application of higher harmonic control.

At present two Mach scaled model rotors are available:

- a hingeless four blade shaft driven rotor, and
- a two-bladed teetering rotor which can be either shaft or reaction driven.

For the application of HHC the hingeless rotor model, shown in Figures 1 and 2, is the prime candidate. This rotor has soft flapwise and soft inplane blades.In the design of the scaled rotor care was taken to model the stiffness and mass distribution of the MBB BO 105 main rotor accurately.The following table gives some important characteristics of the rotor.

diameter	$2*R = 4m$
number of blades	$n = 4$
solidity	$\sigma_{0.7} = 7.73$ %
blade planform	rectangular
blade profile	NACA 23012
tip speed	$U = 220$ m/s
flapping frequency ratio	$\omega_\beta/\Omega = 1.12$
lagging frequency ratio	$\omega_\zeta/\Omega = 0.71$
design thrust	$T = 3630$ N
maximum thrust in hover	$T_{max} = 4400$ N

For rotor control a swashplate system is used. The non-rotating part of the swashplate is moved by three electrohydraulic actuators, adjusting both colective and cyclic blade pitch angles and in addition moving the swashplate dynamically.

In order to measure the forces and moments at the rotor hub a six-component balance has been installed. This balance measures the steady-state loads with good accuracy (error <1% of maximum load); it also provides dynamic load data up to 8 per revolution.

Generally it is necessary to obtain data from the rotor concerning blade motion, blade loads and other variables. Data from the rotor are transmitted to the stationary test stand by a PCM-system which is equiped with thirty-two channels. Each channel has a sample-rate of 750 Hz.

The dynamic data system is fitted with digital and analog computers to perform various tasks:

- acquisitioning and storing all the data measured in the non-rotating as well in the rotating parts of the test stand
- providing quick-look data, which makes it possible to control the model manually
- computing and generating control inputs for the higher harmonic control of the rotor

This measuring and data processing equipment is very complex in hardware and software. Therefore the major parts will be described in greater detail in the following chapters.

2. DESIGN CRITERIA, /2/

The first effect to be achieved by the application of HHC is the reduction of the oscillating hub forces and moments. Therefore the 3-rd, 4-th and 5-th harmonic are generated and superpositioned /3/. The phase lag and amplitude of every harmonic is variable. The values of these parameters are computed by an optimization algorithm implemented in the supervisor and control processor.

To generate the 3-rd, 4-th and 5-th harmonic in the rotating system only the 4/rev in the stationary system is necessary. Figure 3 shows the interpendence of the three harmonics. In this example a 3/rev blade pitch angle is performed by oscillating the three actuators with 4/rev and same amplitude. The key point of this effect is the phase lag of 120 degrees between the three signals. One could imagine that a 4/rev wave rides on the swashplate in the same direction as the pitch link. In this case the effective frequency of the pitching is the 3-rd harmonic. The contrary effect can be achieved by a positiv phase shift. The result is a 5/rev blade pitch oscillation. Consequently no phase shift produces a 4-th harmonic blade pitching. A superposition of these three signals also produces a 4/rev signal for each hydraulic actuator but with different amplitudes and phase shifts.

In normal test conditions the rotational speed of the rotor is 1050 rev/min. That is a rotational frequency of 17.5 Hz and a corresponding blade passing frequency of 70.0 Hz. Therefore the hydraulic actuators have to move the swash plate with harmonic oscillations of 70.0 Hz. Theoretical investigations have shown that the maximal amplitude of HHC inputs is nearly one degree, but in the practical application the amplitude can be greater /4/.

These two parameters, frequency and amplitude, must be achieved by the hydraulic servo system. Further important parameters are the accuracy of the amplitude and phase shift. An illustration of the sensitivity of the vibration reduction caused by varying these parameters is given in Figure 4. It is clear that the exactness must be nearly 5% of full scale range or in absolute values: precision of amplitude <= 0.05 deg, precision of phase shift <= 9.0 deg.

3. THE SIX COMPONENT BALANCE

One of the sensing parts of the rotor test stand is the dedicated six component balance. Figure 5 shows constructional details. The construction consist of two steel plates, one lower plate and an upper plate attached to the rotor shaft bearing box and the three hydraulic actuators. The lower plate and the upper plate are connected via the force transducer systems. Four sensor equipments operate in z-direction, two in y-direction and one in x-direction. Additional a torque indicator is installed in the rotor shaft below the upper plate.

Each force transducer assembly is fitted with two strain gauge load cells and one piezo-electric force transducer as shown in Figure 6. The two strain gauge load cells are mechanically biased to operate at the middle of the characteristic curves to eliminate the hysteresis error which occurs around zero force. The electrical outputs of the cells are combined to form one signal whose voltage level is proportional to the acting force. Calibration test have shown that the linearity error in case of static load is better than 0.1% of full range of 5000 N.

Generally a strain gauge load cell is able to measure static and dynamic loads. But in this case of application the range of the dynamic forces is very small in contrast to the static forces. To achieve a good sensitivity to dynamic loads a piezo-electric load cell is installed. In Figure 7 typical frequency response curves of a strain gauge and a piezo-electric load cell are recorded. It shows the very good accuracy of the piezo-electric load cell while the strain gauge signal is distorted over the tested frequency range.

One problem in the design of multi component balances is the decoupling of the particular force and moment components. For the dedicated balance, flexible beams are fitted between the strain gauge and the piezo-electric cells. In this way the influences of shear forces are eliminated because they are smaller than the resolution of the load cells.

For proper measurement results it is necessary to calibrate the balance in the frequency range of interest. The complex transfer functions for each force transducer are obtained by a freqency response test with swept sinus signals. Figure 8 shows the typical arrangement for the x-force calibration. An electrodynamic exiter generates harmonic force oscillations with a maximum amplitude of 240 N. With a piezo-elctric force transducer attached to a dummy hub, the acting force is measured to obtain the system input. The dynamic response of the balance, measured by the individual force transducers, is resolved into real and imaginary parts with respect to the system input by means of vector component meters.

The advantages and disadvantages of the dedicated balance can be summarized as follows:

Advantages:
- high resolution and accuracy to static forces and moments
- high resolution and accuracy to dynamic forces and moments

Disadvantages:
- time-consuming calibration procedure
- very expensive

4. THE DIGITAL QUICK-LOOK AND CONTROL SYSTEM

The data obtained from the measurement equipment are sampled by a PCM-system as shown in Figure 9. The two subsystems, Rotor-PCM and Ground-PCM, work independently and asynchronous. The Rotor-PCM is equiped with thirty-two analog input channels, amplifiers, antialiasing filters and independent power supplies for strain gauge bridges. After the analog to digital conversion with a resolution of ten bits the serial bit stream is sent via slip rings to the ground unit of the Rotor-PCM. Here the digital data are converted back into analog signals smoothed by filters. In this way the sensor signals from the rotating hub and from the stationary part of the rotor test stand have the same features.

The second PCM, called Ground-PCM, acquires all signals by multiplexing the analog inputs. It samples each of the sixty-four channels with a rate of 781 Hz and ten bit accuracy. At this time all sensor signals are timed synchronously to a reference signal generated by a high precission ramp function potentiometer which is turned directly by the rotor shaft.

Further data processing and analysis is performed by a mini-computer system as shown in Figure 10. Its three major tasks are:

- data acquisition and storage for offline data analysis
- quick-look at the most important signals, like the blade pitch angles and the quality criterion
- wave form generation for moving the swashplate in order to control the blade pitch angle by higher harmonics

These tasks are performed by three independent parallel working process computers /5/.

4.1 THE QUICK-LOOK PROCESSOR

For the visual monitoring of the important states of the test stand, the sensor signals must be analysed online. This is a high performance task which requires high speed mathematical operations like the FFT, high data transfer rate and high resolution graphic displaying. To obtain the realtime analysis including the eighth rotor harmonics a special computer system must be configured, see Figure 11. The data input and demultiplexing is performed by a programmed interface called Communications-Element. It has its own processor, a small program memory and direct access capabilities to the host memory. The maximal practicable data transfer rate is the bus tranfer speed of the host processor but the maximum actual transfer speed is 50,000 words per second which is determined by the Ground-PCM system.

A second co-processor which operates in conjunction with the host minicomputer is an array processor. Its high operating speed of arithmetic computation enables the realtime analysis of twelve channels simultaneously.

The individual functions which are performed are

- FFT of the reference signal
- FFT of the blade pitch signal
- Transfer funtion of the reference to the blade pitch
- Power spectra of the seven balance signals
- computation of the quality criterion

Some difficulties can occure if the period of the FFT is different from the period of the signal. In this case, the values at the beginning and the end of the FFT period are different, and the transform into the frequency domain is not correct. One preventive measure is the application of a window funtion like the Hamming window or Hanning window in this case. In addition, proper results can be achieved by the calculation of the transfer function, the complex ratio of the dedicated sensor signal to the reference signal. If the amplitudes of the reference signal are scaled to the value one (1.0), the transfer function is the correct linear spectrum. A digital simulation of this analysis technique has shown a very good accuracy of the results. In this way the effective blade pitch angle is analysed and then displayed in the frequency domain on a graphic display, Figure 12.

The quality criterion is obtained from the seven piezo-electric force transducers. After the FFT application the vibrational power spectras are calculated and continously averaged with an exponential decay. The scalar value of the quality criterion is then determined by the total vibrational power. Both calculations, the resulting power spectra and the quality criterion, are graphically displayed.

To achieve efficient synchronization between the different operations the software is divided into self-contained tasks as shown in Figure 13. The basis of event-driven task sheduling, which is used in this application, is the software priority assigned to each activ task. When a significant event is declared, the executive interrupts the executing task and searches for a task capable of executing. The highest priority task that has all the resources it needs to run will be the task that gains the CPU.

A task switching procedure with such capabilities requires a real-time operating system which supports multi-tasking.

4.2 THE CONTROL PROCESSOR

The control processor provides the sine waves for the actuator control, each with a different amplitude and phase shift, in order to control the blade pitch angle at higher harmonics. The momentary amplitudes of each actuator are dependent on the following seven parameters

- azimuth angle of the rotor
- amplitude and phase shift of the 3 Ω control
- amplitude and phase shift of the 4 Ω control
- amplitude and phase shift of the 5 Ω control

Whereas the amplitudes and phase shifts are slowly manual controlled via potentiometers, the azimuth angle alternates very quickly. This requires short response times from the computer to provide the appropriate control inputs for the hydraulic actuators. To achieve these features the sine wave generation is performed by a table-look-up procedure. For each actuator the sine wave is stored in the processor memory. They will be updated if the parameters amplitude or phase shift alter. The read out cycle of the table values starts if an interrupt occurs from an azimuth encoder which is attached to the rotor shaft. With a resolution of 256 points per revolution, at every 1.4 degree of azimuth or every 223 µs an interrupt activates a data output for the swashplate positioning.

Figure 14 shows the configuration of the controlling part of the rotor test stand. For the higher harmonic control the incoming data are the azimuth angle of the rotor and the six control values of the amplitudes and the phase shifts. Outputs are the three sine waves which are transmitted to the servo system of the electro-hydraulic actuators. For the right strategy in vibration reduction, the operator can be supported by the optimization algorithm which was introduced in /6/. This software package is implemented in the control processor, but at present it is not capable of altering the control values immediately.

The following program parts are used for implementing the optimization procedure (Figure 15):

- The bloc named quality criterion computes a scalar value QC representing the performance of the system to be optimized for a given set of control inputs. The quality criterion may comprise several different performance indexes, added together with appropriate weighting parameters. In the case dealt here the design objective consists in minimizing the hub vibrations.

- The program part 'static optimization algorithm' has to drive iteratively the control inputs to values minimizing the quality criterion. A very simple optimization program is used, which comprises less than 100 FORTRAN-statements /7/. Basically the algorithm stores at each iteration the value of the quality criterion and compares it with values previously determined. This comparision triggers a new selection of the values of the control inputs in a particular way. The process is repeated until the performance index QC ceases to change. Constraints may be taken into account either by adding penality functions to the quality criterion or by introducing boundaries directly into the search space over which the nonlinear programming algorithm operates.

- The bloc 'control inputs' consist of two parts, the graphic display and the board with the control potentiometers. At this time there are no hardware/software connections between the two parts and therefore it is a so called open loop control. The operator is therefore required to provide this connection manually.

The main advantage of the described optimization strategy consists in its simple and flexible application. The method can be easily used because the orginally dynamic optimization problem is solved by a given static search algorithm which needs not to be adapted to the task considered. The method is very flexible because the different program parts are independent from each other. This means that the model under test or the quality criterion or the structure of the input commands may be changed without the obligation to modify accordingly the other parts, as it is often the case when using more difficult optimization methods.

4.3 THE DATA RECORDING PROCESSOR

The third processor system performs the data acquisition and storage for offline data analysis. For this task the system is built up as shown in Figure 16. The same programmed interface as introduced at the quick-look processor connects the processor to the PCM data bus. It works with the PCM data rate of 50,000 words per second and transfers the data into the host memory via direct memory access. A small program, running in the computer, stores the data on the magnetic tape. Each data file contains a file header with all important test parameters. All sensor signals which are picked up by the Ground-PCM system follow the header. The file length is dependent on the test aim, but if necessary a continous data recording is possible.

5. THE ELECTROHYDRAULIC ACTUATOR SYSTEM

The rotor test stand uses a conventional swashplate for standard and higher harmonic rotor control. Three hydraulic actuators mounted on the upper plate of the six component balance as shown in Figure 14, move the swashplate. For the higher harmonic control the specifications for the actuators are very precise. As shown in the chapter DESIGN CRITERIA the operating frequency is seventy Hertz. The smallest sine wave amplitude which must be performed is nearly 0.1 mm. This is a value obtained from the theoretical investigations. In practical application it is probable that the required amplitudes are greater. Therefore the maximum amplitude which can be provided by the actuators is three millimeters.

Extensive frequency response tests have shown that many parameters influence the transfer function. The results are different transfer functions of the three actuator systems. An illustration is given in

Figure 17. With such behaviour, a proper higher harmonic control is not possible.

To avoid the effects of hydraulic oil temperature and pressure, static piston stroke, effective mass, dynamic control amplitudes and several unidentified interferences a new closed loop control system must be evaluated. The block diagram in Figure 18 illustrates this phase shift and amplitude control system. Each actuator system is fitted with such circuit arrangement to achieve equal system performances.

The principle of operation is that the phase of the system inputs will be corrected until the differences between the reference waves and the system outputs are zero. A similar principle is used for the amplitude correction. Differences between the reference and piston stroke amplitudes are corrected with manipulation of the system input amplitudes. Results of such improvements are clearly shown in Figure 17.

With this improved hydraulic system static and dynamic swashplate positioning are possible with good accuracy and therefore a successfull higher harmonic control can be achieved.

6. CONCLUDING REMARKS

In the present paper a computer based data processing and control system is introduced. The development of this system was determined by the aims of the HHC research at the DFVLR. Many particular problems must be solved in such a complex system but the result is a high performance tool to control the rotor test stand in various HHC applications.

Some characteristics of the processor units which makes it possible to obtain this range of application are :

- modular design, by which changes in the test specifications are performed by simple hardware modifications
- modular software, resulting in small and self-contained program modules
- simple modification of the hard- and software

The versatility allows the application of this system to other dedicated tasks than the HHC. Each module can be used independently, whereas for fail-safe systems a redundancy can be achieved. The consequent use of common hardware modules provides a good performance/cost ratio and also inexpensive maintenance.

The six component balance for static and dynamic force measurements introduced in this paper is a high precision instrument. Its present configuration is a result of various pilot tests and trials under windtunnel conditions. The application of the two rotor systems has also provided important inputs to the improvement of the balance. A modularity is achieved by seperate measurement systems. Depending on the application both force transducer systems can be used together, or each can be used independently.

The hydraulic actuator system is a part with largely unknown system characteristics. One method of eliminating their influences is shown in the present paper, but the use of such closed loop control is restricted to cases with harmonic motion.

7. LIST OF REFERENCES

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/2/ G. Lehmann, Entwurf einer rechnergestützten höherharmonischen Steuerung für den DFVLR Rotorversuchsstand. DFVLR, Report No. IB 111-81/13 (1981)

/3/ G. Lehmann, Ermittlung des optimalen periodischen Verlaufs des Einstellwinkels eines Hubschrauber-Rotorblattes. DFVLR, Report No. IB 154-78/12 (1978)

/4/ H.G. Jacob, G. Lehmann, Optimization of Bade Pitch Angle for Higher Harmonic Rotor Control. Paper No. 77, Seventh European Rotorcraft and Powered Lift Aircraft Forum, Garmisch-Partenkirchen, September (1981)

/5/ G. Lehmann, Systemanalyse zur Meßdatenerfassung und -verarbeitung am Rotorversuchsstand. DFVLR, Report No. IB 154-80/10 (1980)

/6/ H.G. Jacob, An Engineering Optimization Method with Application to STOL-Aircraft Approach and Landing Trajectories. NASA TN D-6978, Washington , D.C. (1972)

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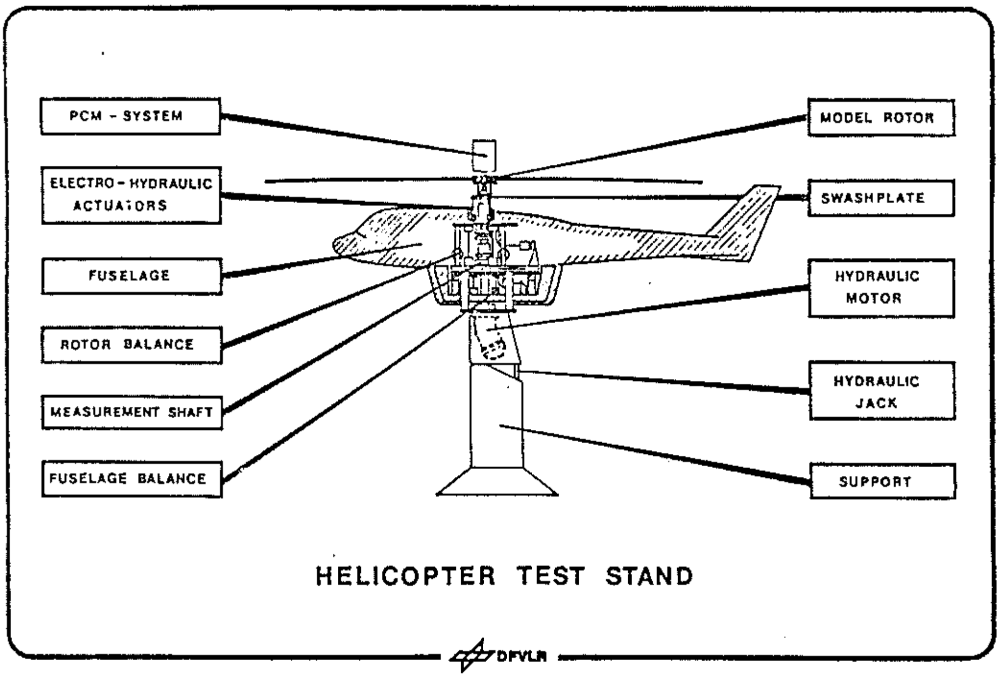

Figure 1. DFVLR-Rotor Test Stand

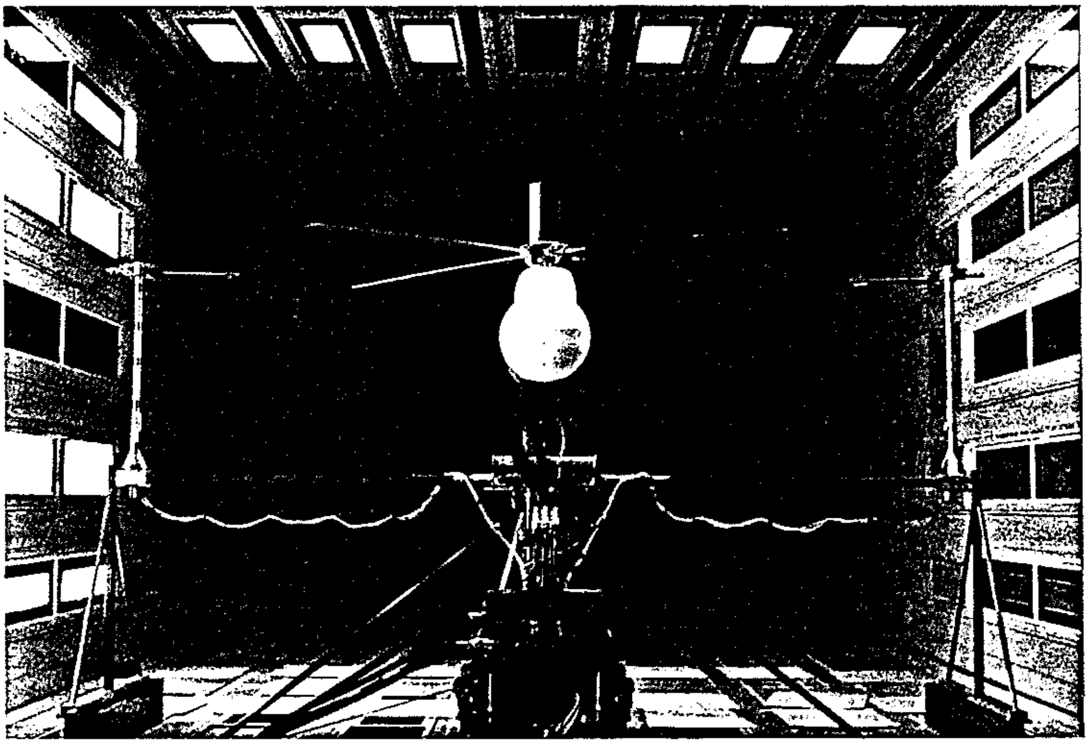

Figure 2. Rotor Test Stand in German-Dutch Wind Tunnel DNW

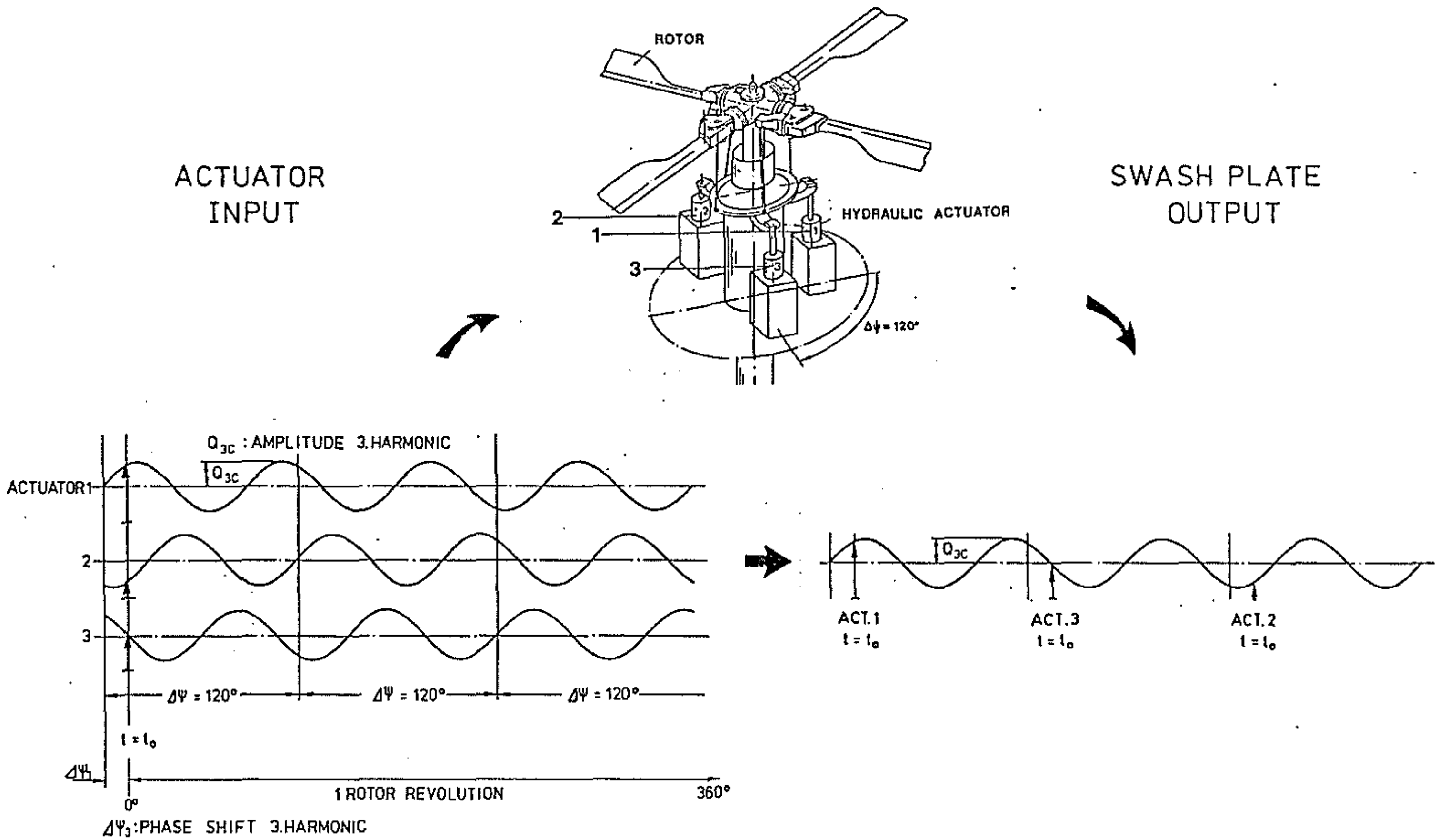

Figure 3. Interpendence of the Actuator Input and the Swash Plate Moving

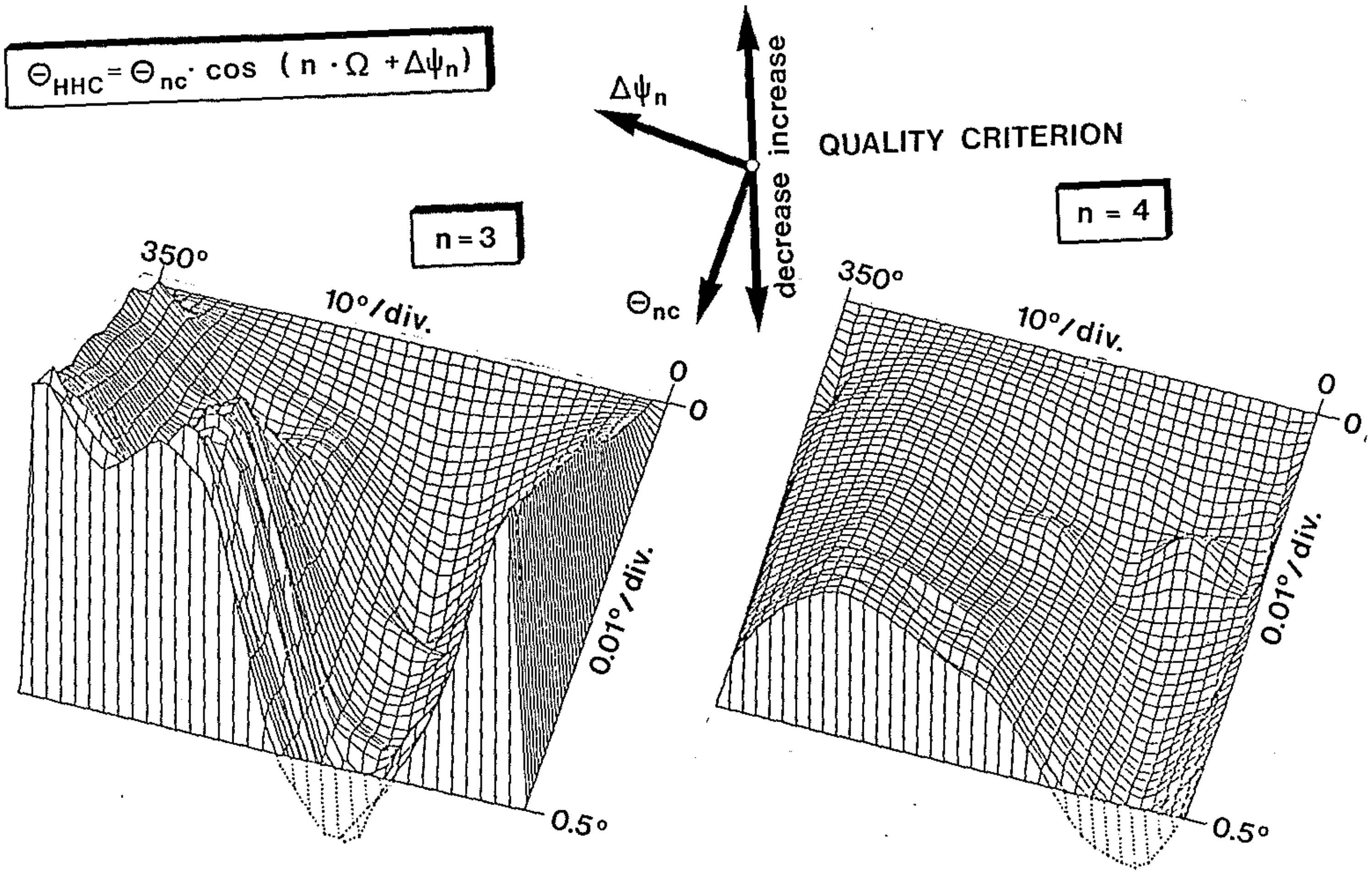

Figure 4. Sensitivity of the Quality Criterion

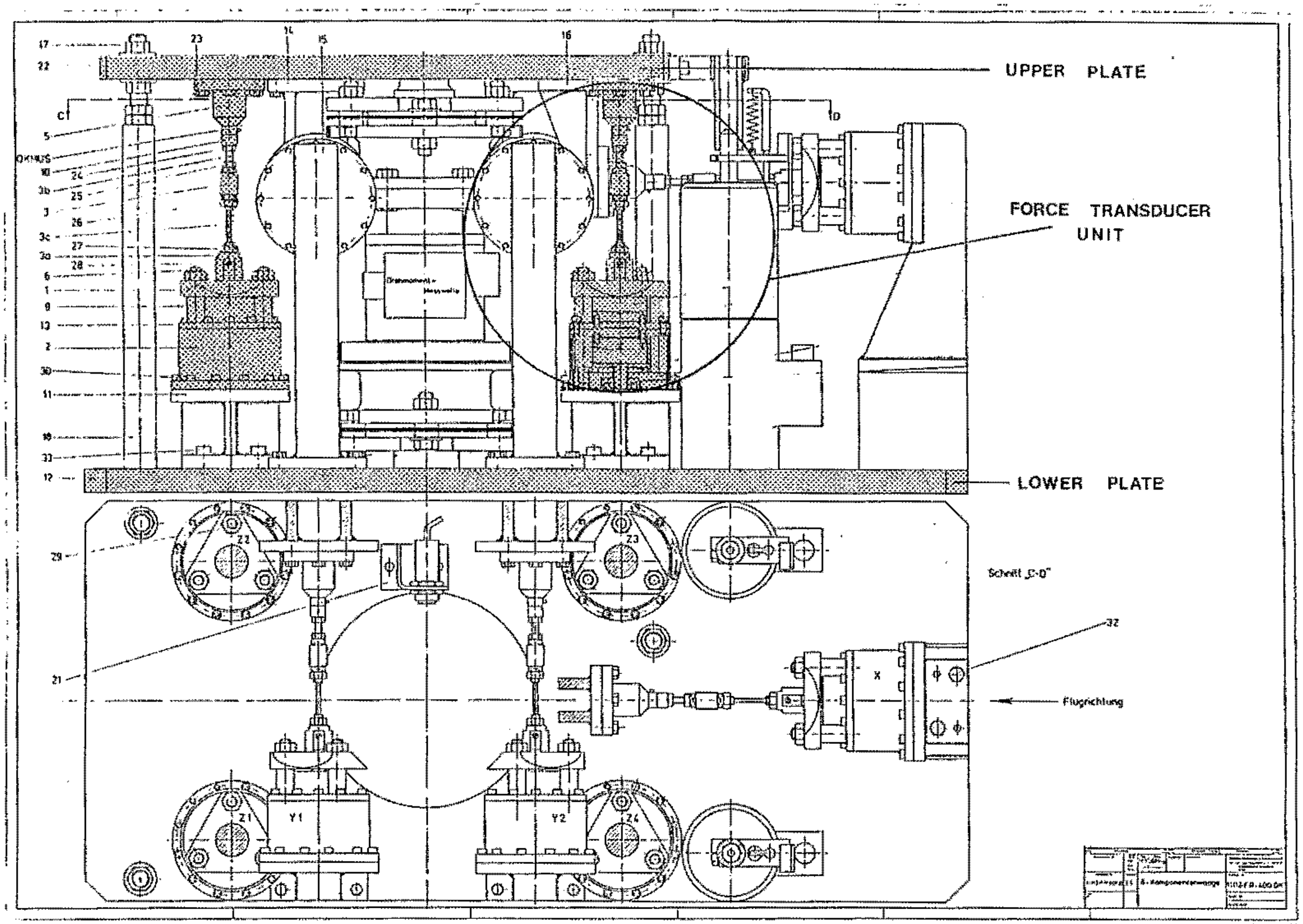

Figure 5. Six-Component Balance, Side View and Top View

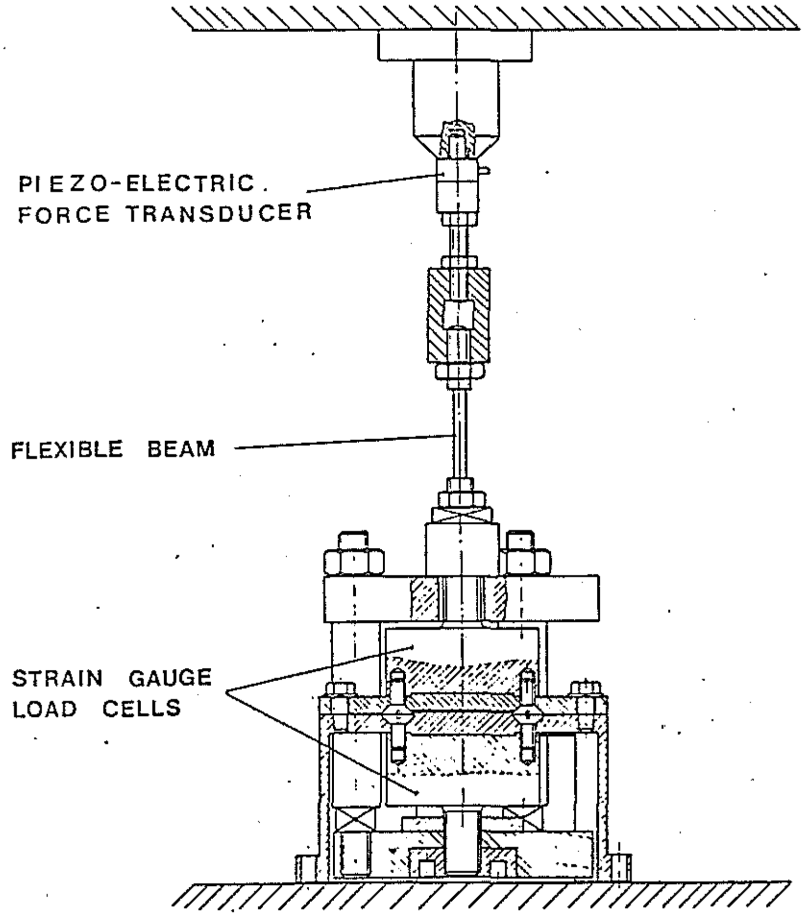

Figure 6. Force Transducer Assembly

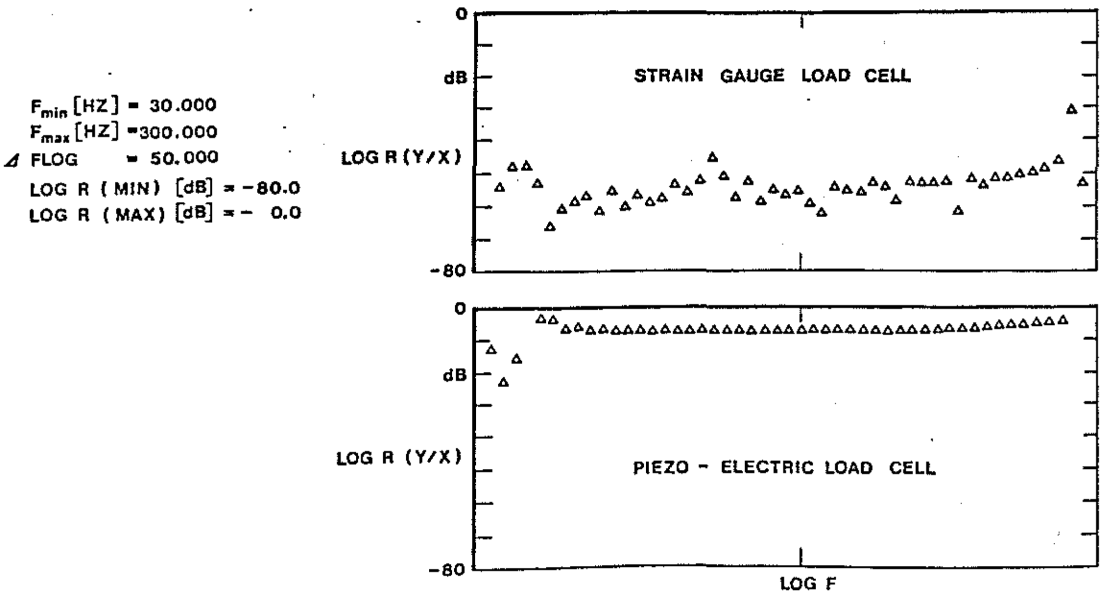

Figure 7. Frequency Response of the Force Transducers at 10 N Dynamic Loads

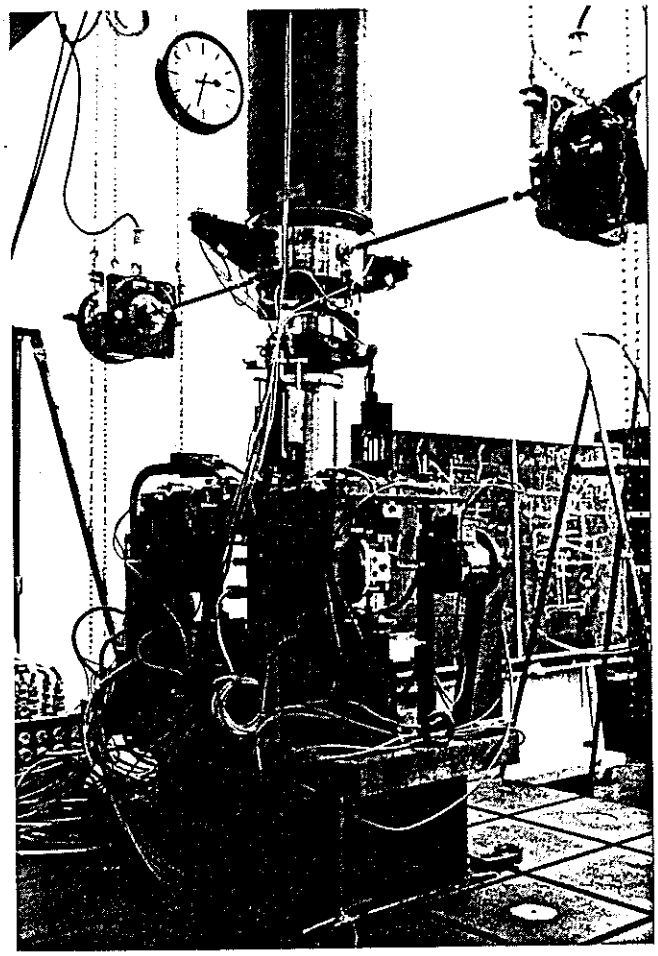

Figure 8. Arrangement at X-Force Calibration

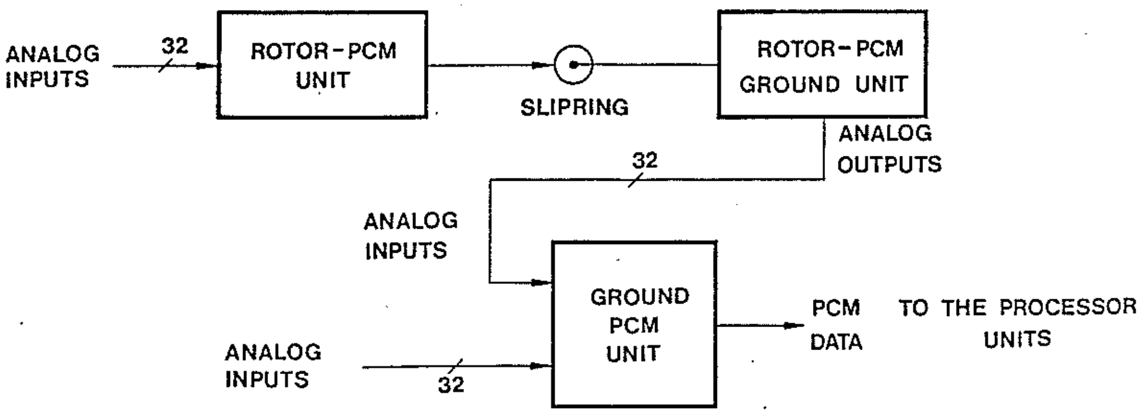

Figure 9. PCM Configuration

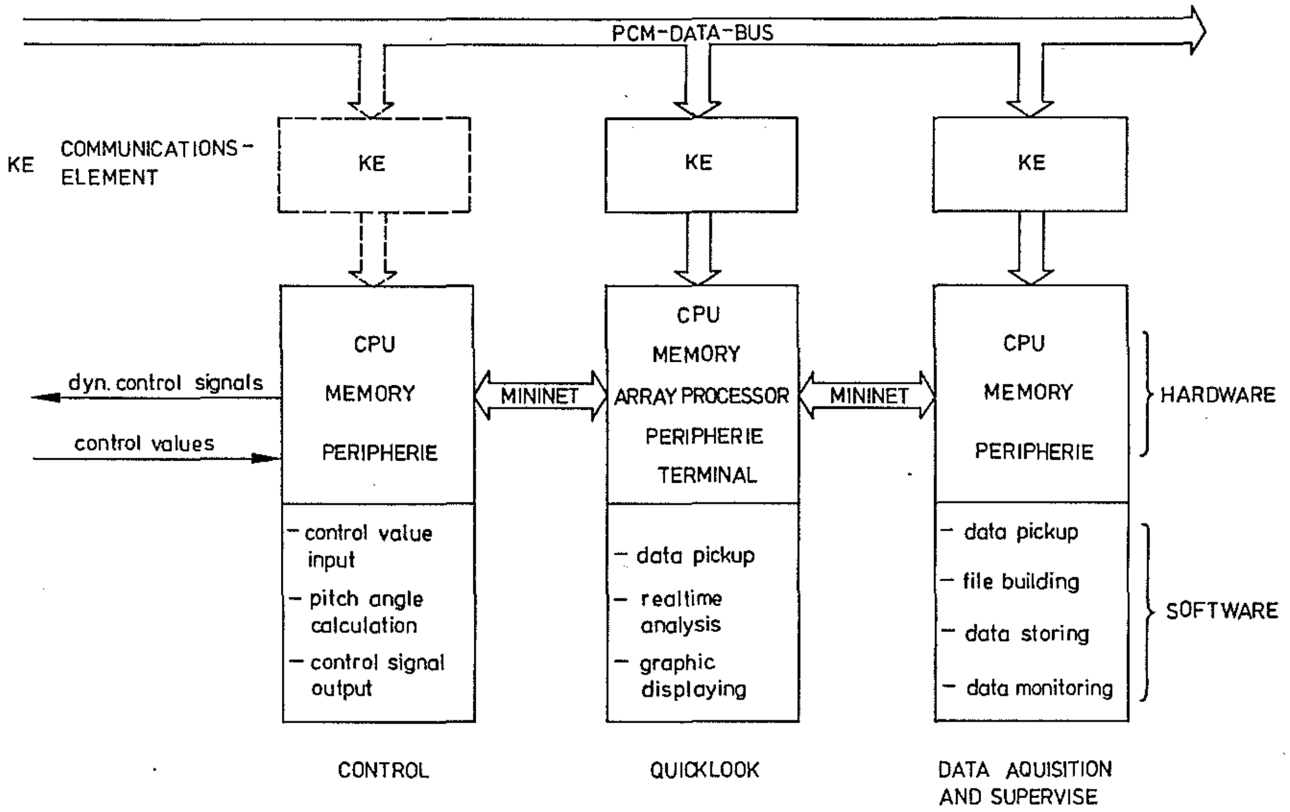

Figure 10. Digital Data Processing and Control System, Block Diagram

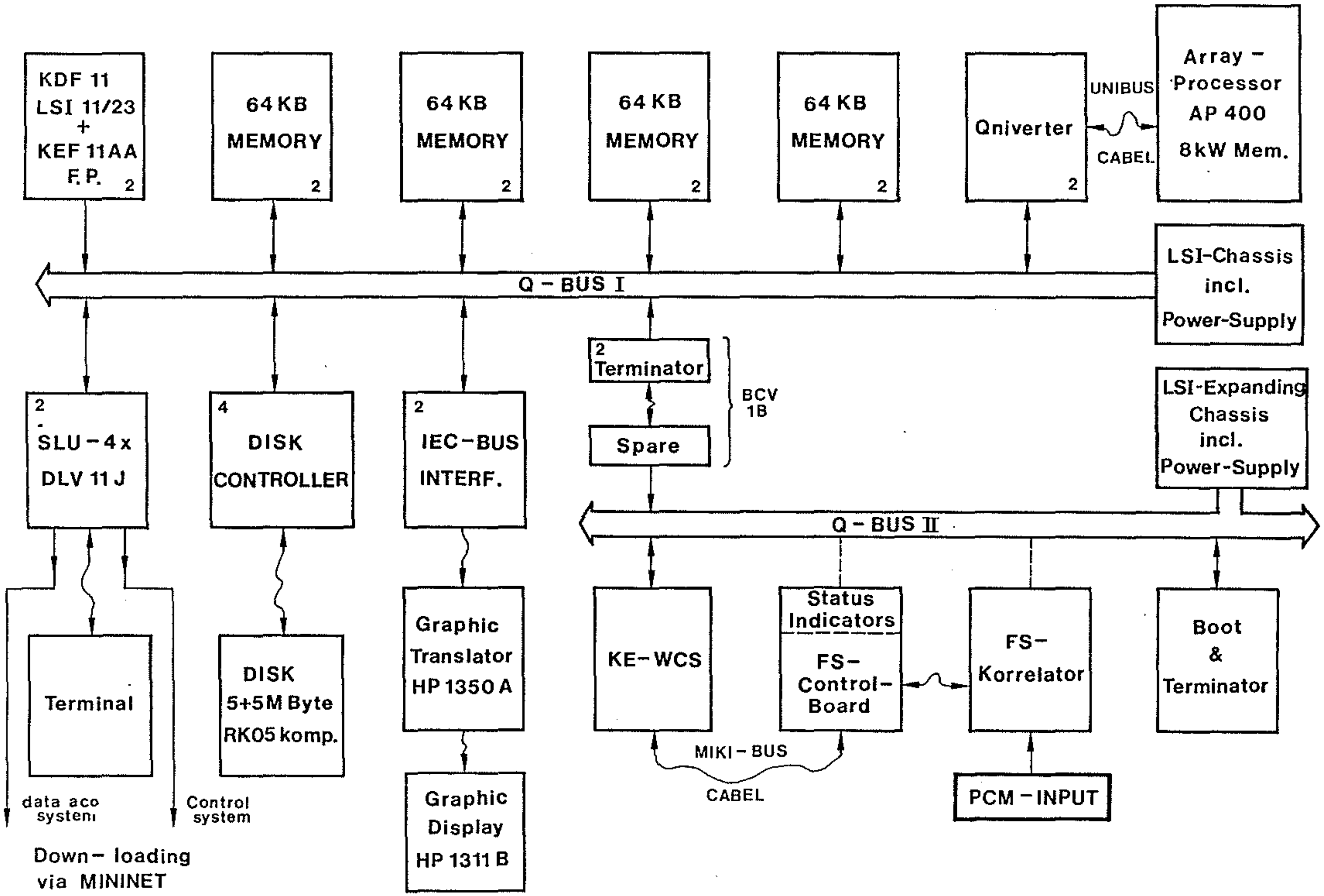

Figure 11. Quick-Look Processor System Architecture

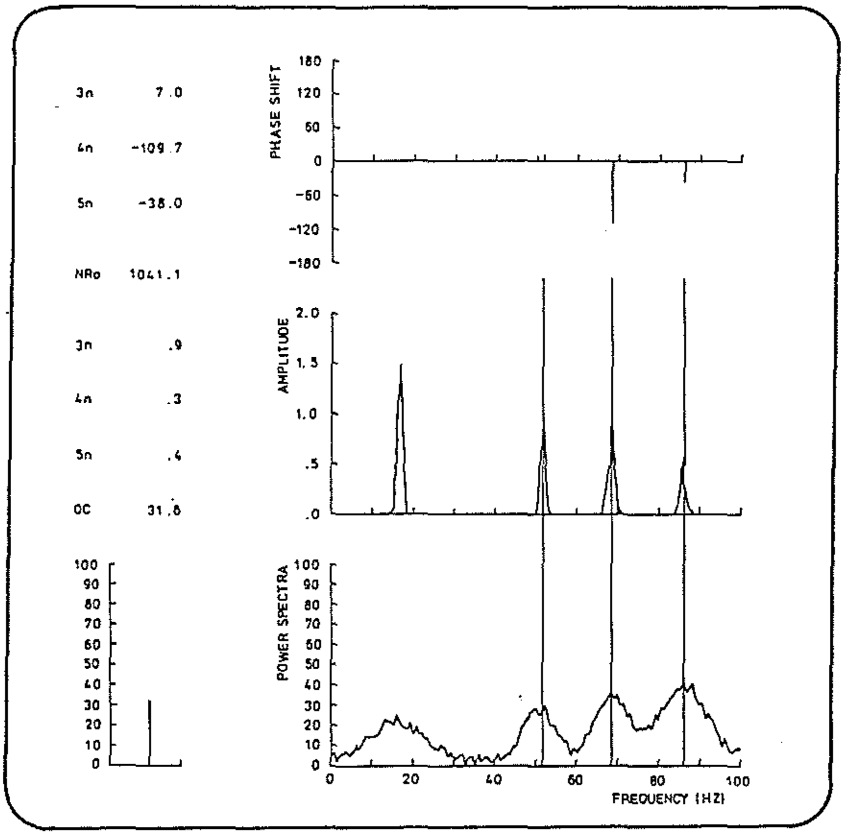

Figure 12. Quick-Look Display

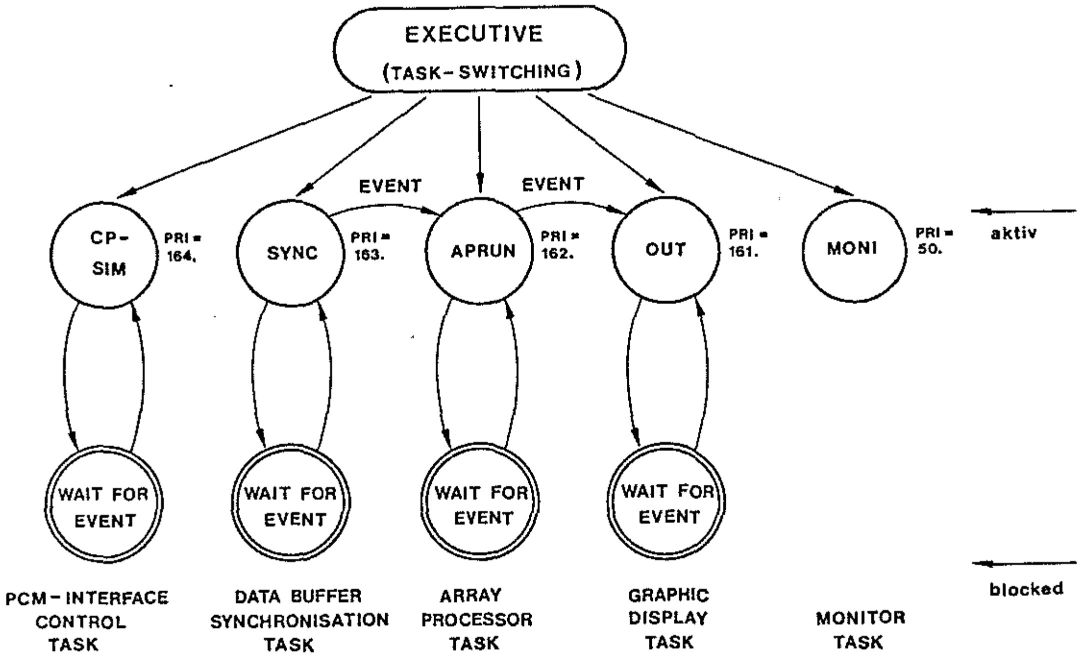

Figure 13. Software Configuration in the Quick-Look Processor System

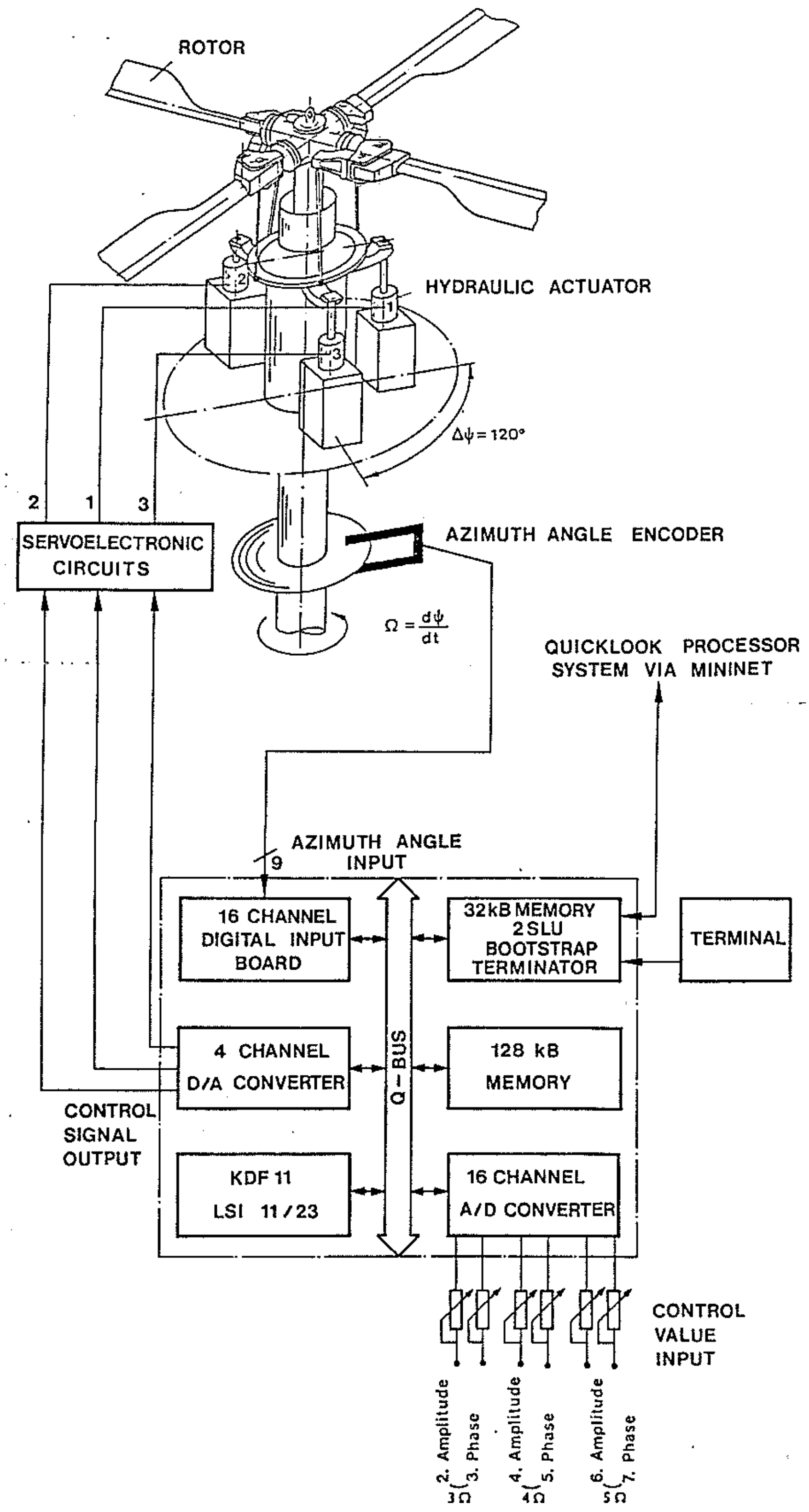

Figure 14. Control Processor Configuration

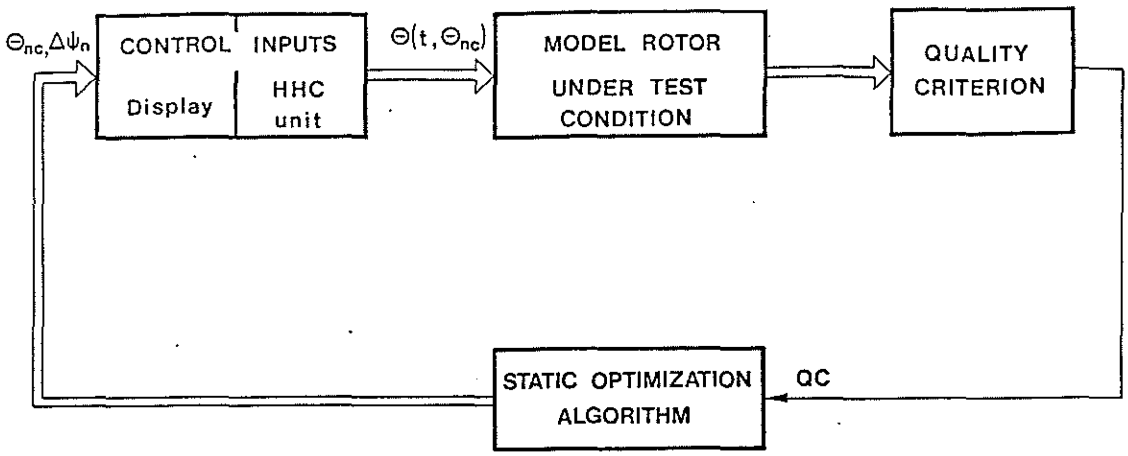

Figure 15. Principle of the Optimization Procedure

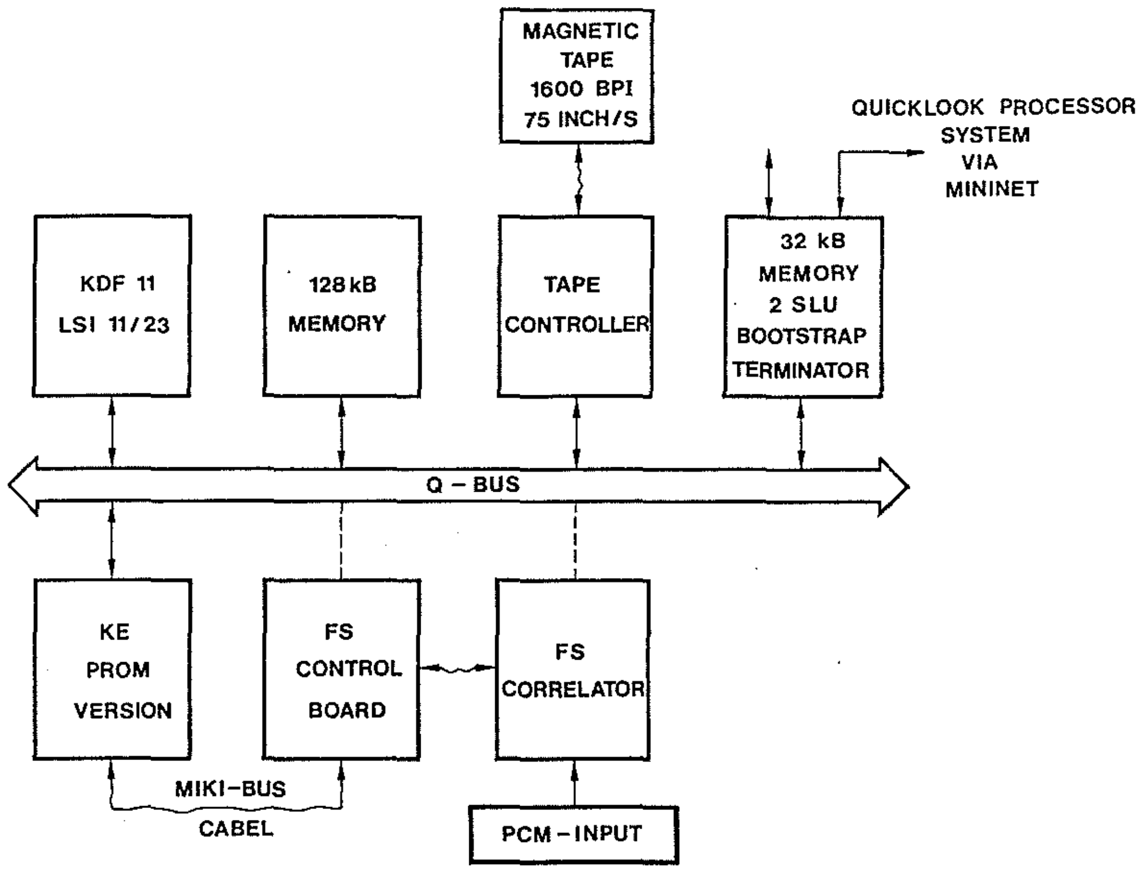

Figure 16. Data Acquisition and Supervise System Architecture

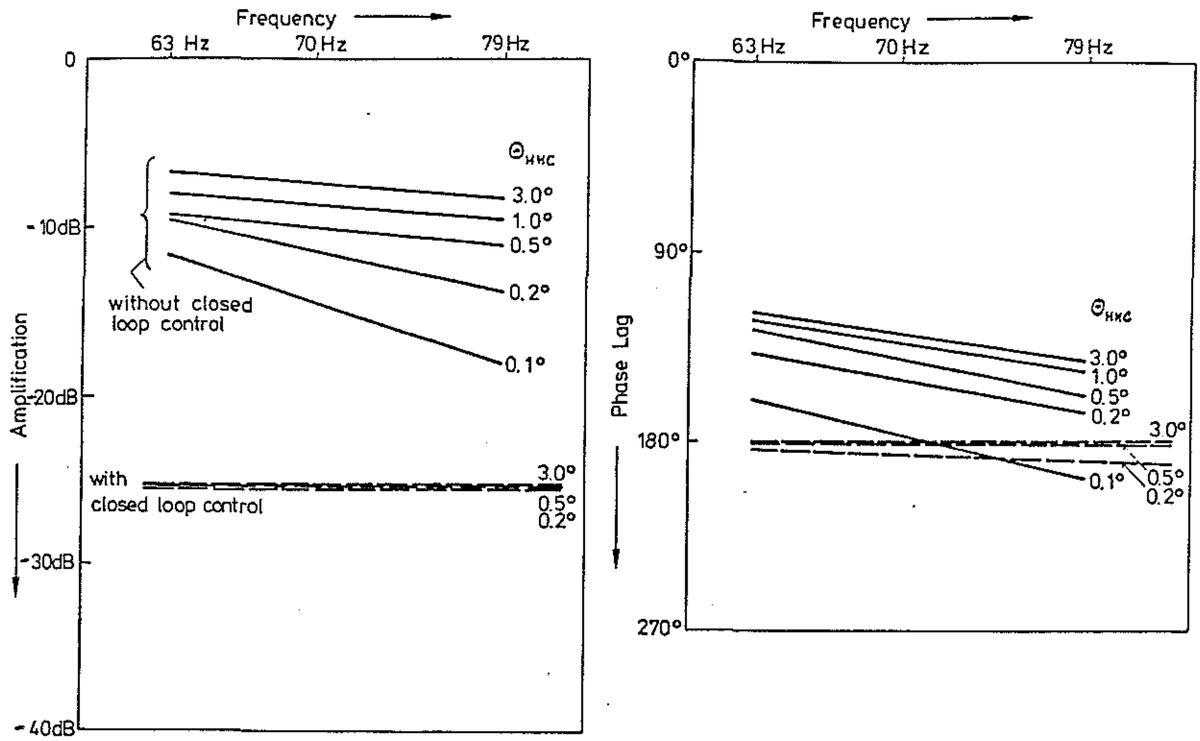

Figure 17. Frequency Response of an Actuator System, with and without Closed Loop Control

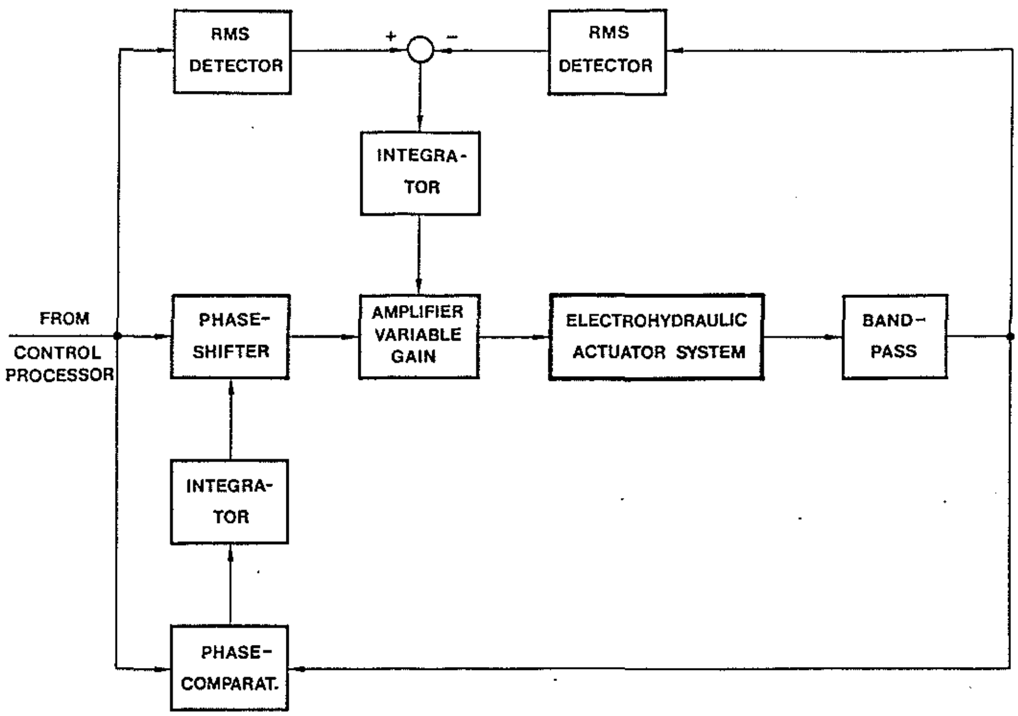

Figure 18. Closed Loop Control, Block Diagram