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DATA INPUT, PROCESSING AND PRESENTATION

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16. Abstract
The problems of data acquisition, processing and display are investigated in the case of a helicopter rotor balance. The types of sensors to be employed are discussed in addition to their placement and application in wind tunnel trials. Finally, the equipment for data processing, evaluation and storage are presented with a description of methods.

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DATA ACQUISITION, PROCESSING AND DISPLAY

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Introduction /3*

This subject deals with the data acquisition equipment for the rotor testing stand. The necessary measurement quantities will be discussed, how they are calibrated and processed and displayed.

The possibilities of measurement value acquisition and further processing are varied, as is the entire measurement concept. The latter is directed mainly at the object to be measured and the time or frequency range of the processes.

The measurement concept is to be described specifically for the rotor testing stand with its numerous modifications. These modifications were undertaken, on the one hand, because of technical progress (especially in microelectronics), and on the other hand, because some features were insufficient or complete failures. Specifically, the rotor balance construction has been the object of numerous alterations; moreover, the demands placed on the measurement program have also been changed, so that the measurement technology for descending air currents, initially given little attention, has come more and more into the foreground.

1. Sensors for Data Acquisition

The technology for sensors has undergone considerable further development recently because of the great amount of progress in the area of electronics. The miniaturisation of the sensors has become especially significant.

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*Numbers in the margin indicate pagination in the foreign text.

Nevertheless, there are still enough problems in the acquisition of measurement values, specifically when measuring rotating systems as in the case of a helicopter rotor. Especially high acceleration at the rotor blades makes it very difficult, for example, to measure pressure distribution at the blade profile. Problems such as the measurement of blade bending shapes in the rotating rotor or the determination of instationary descending wind field have not yet been satisfactorily solved. /4

The area of measurement technology without contact for determining the flow rate or for measurement of position is still in the initial stage in relationship to the demands at the rotor. It may be expected that substantial improvements will be introduced in further years because of the application of lasers coupled with appropriate optics and electronics.

1.1 Sensors in an On-Board System

All measured value pick-ups and their calibration will be described under this heading, not located in the rotating system. These are the probes to be described in the following with the exception of the sensors for descending winds, to be treated separately.

1.1.1 Measurement of the Angle of the Rotor Mast

The measurement of the adjustment angle of the rotor via the angle of the rotor mast may be correct in a strict sense only for the balanced rotor, i.e. if the pitching and rolling moments are equal to zero, because these moments have an effect on the position of the plane of the blade tips and therefore on the angle of rotor adjustment.

The resulting error for the jointless 4 blade rotor, however, is slight so that the angle of rotor adjustment can be set equal to the angle of the mast. This angle is measured via a path pick-up, mounted at the fixed portion of the rotor stand (Fig. 1). A thin cable runs over a rotary disk with the center point at the point of rotation of the upper section of the column and is attached to a metal rod. This rod is suspended in the path pick-up and the resistance is altered when the rotor is tipped to the front or back.

In wind tunnel tests, attention must be paid that the cable /5
with the metal rod is not exposed to the wind tunnel flow, because vibrations and the distortion of the cable lead to erroneous measurement of the angle of rotor adjustment.

The determination of desired value is undertaken with a potentiometer in the measurement chamber. Regulation is provided that the predetermined desired value is maintained. This is an advantageous procedure because the hydraulic cylinder, utilized for the adjustment and maintenance of rotor angle slowly alters the lifting height under stress. The indication of the actual value (optional adjustment to the desired value is possible) is carried out through a digital voltmeter. If the deviation between actual and desired values is greater than 0.1°, the regulation device reacts such that the accuracy is 0.1 degree.

1.1.2 Rotor Balance

The rotor balance has been subjected to numerous modifications in the past. The reason for this was poor dynamic behavior. This does not mean that the balance was not suitable for measuring rotor components, but only that the initially high expectations were not met.

The stress at the rotor head taken as a basis in the design of the balance led to the dimensions of the pressure gauge. Since the measurements were to be as precise as possible, the pressure for the expected measurement range was selected and multiplied by 1.5 for security. In order to determine the rotor balance statically, six pressure gauges were employed although only five stress quantities were measured, specifically the

longitudinal force, transverse force, thrust, pitching moment and rolling moment. The drive torque is determined via a measurement shaft such that only the positional friction between shaft and balance is measured as moment around the z axis. The version illustrated in Fig. 2 shows the initial configuration. It was demonstrated when putting the rotor into operation that the /6
initially determined stress quantities did remain in the predicted range statically, but exceeded the measurement range of the pressure gauges dynamically.

The next configuration then consisted of four pressure gauges in the z direction with a measurement range of 2000 N each, two pressure gauges in the y direction with 5000 N each, and one pressure gauge in the x direction with 1000 N. Furthermore, the plane of measurement was moved up in order to reduce the lever arm (Fig. 3). The balance is statically overdetermined with the application of seven pressure gauges. The consequences of this static overdetermination in calibration and evaluation will be discussed later. Initial wind tunnel tests have demonstrated that the design of the balance was much too soft so that the high velocity range and extreme rotor stress could not be measured. In a wind tunnel test, the swash plate control malfunctioned because of a defect in the electrical system. Therefore, it was not possible to control the rotor thereafter with the result that almost all pressure gauges were destroyed through overload.

This was the reason for further redesigning of the balance : the measurement range of each pressure gauge was expanded to 5000 N (z and x directions) and 2000 N (y direction). In addition, the pressure gauges now available had a substantially smaller construction height (Fig. 4). The difficulties, however, were still not solved with these measures, because hysteresis effects were added to the limited measurement precision. The static calibrations resulted in the fact that a reverse in sign under stress noticeably altered the calibration factors. This problem was not solved by linearization of the calibration curves, but the errors were still acceptable when measured against demands.

Since the demands on measurement technology have been substantially increased through new research tasks - especially in the area of vibration reduction at the rotors - a fundamentally new measurement principle was introduced for the balance technology.

This principle is based on the separation of dynamic and static portions of the force (Fig. 5): /7

- measurement of the static forces via prestressed force pick-ups
- measurement of the dynamic forces through Piezo-force pick-ups.

1.1.2.1 Prestressed Pressure Gauges

A alteration in stress from push to pull causes hysteresis effects at the pressure gauge, unavoidable because of the measurement principle and the zero passage. If the pressure gauges are prestressed (Fig. 5), however, this effect may be avoided. Two pressure gauges were arranged for this purpose such that an attacking force does not cause a reversal of force at the individual gauge in the entire measurement range. Experiments with gauges prestressed for tension have the smallest error because of an automatic aligning effect. When both pressure gauges have the identical sensitivity, alterations in prestressing have no effect on the characteristic of the double cell. This is of great advantage in the case of variations in temperature.

The principle of prestressing pressure guages is also employed in the DNW ground balance.

1.1.2.2 Piezoelectrical Force Pick-Ups

Piezoelectrical force pick-ups are quartz crystal measurement washers. They convert a force into an electrical charge, because they produce an electrical charge if a disk of a quartz crystal is subjected to pressure. Such a piezo pick-up consists of one or two circular disks of a quartz crystal, an electrode and a housing with a plug (Fig. 6). The force to be measured should act on the circular surface with an even distribution. An electrical charge is generated in the crystalline quartz through the mechanical tension, precisely proportional to the applied force /8 and not dependent on the dimensions of the quartz disks (longitudinal piezoelectrical effect).

The charge generated in this manner is transferred to the electrode and fed to the plug connection. Polarity is selected such that a pressure force generates negative charges, then converted in the so-called charge amplifier into positive voltage. When the pressure is released on the measurement washer, a positive charge is produced if the negative charge previously generated by the stress has been destroyed by a short circuit at the plug connector. The charges of the individual measurement washers are added by connecting several measurement washers in parallel, and the charge amplifier measures the total force. The opposing surfaces at the measurement object must have a finely treated, smooth surface and must be resistant to bending in order to achieve an even distribution of the measurement force on the annular surfaces.

The housing of a measurement washer is tightly welded, but the plug with teflon coating is not completely sealed.

Piezo pick-ups have the advantage of extremely high rigidity and have a dynamic range of up to six decades. There are three component measurement value pick-ups, taking apart the components of a random force, thereby simplifying the construction of multiple component measurement equipment.

Piezoelectrical pick-ups, however, have one large disadvantage: they are not suitable for the measurement of static quantities. When applying a static quantity, e.g. force, the measurement value is first measured correctly, but the value is then reduced of an e function where the time constant τ is situated in a range of seconds up to hours. In order to apply the advantages of the piezo measurement technology to the rotor balance, the static forces and moments are measured with customary DMS force pick-ups.

Ideal piezoelectrical force pick-ups should only transmit an output signal if a force component is acting in the measurement direction of the pick-up. Forces or moments normal to the measurement direction should not generate any output signal. In reality, force pick-ups also transmit an output signal if a force acts normally to the measurement direction. The output signal is identical to that of an actual force acting only in the measurement direction. /9

This phenomenon is designated as cross-talk. The example illustrated in Fig. 7 demonstrates this situation. In the appropriate construction of the piezo elements, cross-talk values of less than 1 % are achieved. The essential prerequisite for this value lies in the treatment of the quartz. The surfaces of the quartz plates for introducing the force must be situated within narrow tolerances normal to the corresponding crystallographic axes.

The problem of cross-talk does not play a large role because of the insulation in the rotor balance, since the transverse forces are absorbed well through the ease of bending of the rods. Fig. 8 shows the total design of the balance with the piezo pick-ups and the DMS pressure gauges. The rotor balance is presently operated in this configuration.

1.1.2.3 Calibration of the Balance, Statically

The calibration of the rotor balance is carried out in the same manner as that of the fuselage balance. The reason for this difference is that the calibration is less complicated and the results are tested for accuracy.

Since the balance is employed both for measuring static and dynamic rotor components, two measurement methods are employed. In the first, the forces and moments are introduced into the plane of the rotor with calibrated weights, while the force is introduced via one or two electrodynamic exciters in the other.

It is assumed in calibration that a linear relationship exists between stress and the measured values of the pressure gauges. This assumption is fulfilled in every case, as the experiments have shown. Since the pressure gauges have a maximum spring path of 0.1 mm under stress, couplings resulting from a shift of the upper plate to the lower plate are not taken into consideration. /10

A very rigid frame with guide rollers is mounted on the base plate of the rotor balance. Forces in the $\pm$ x, $\pm$ y and -z direction are introduced with calibrated weights via a cable attached at the rotor head. A rigid cross is attached at the rotor head additionally for calibrating the moments, also suitable for suspending calibration weights. An equally large calibration weight is attached in the z direction to avoid both a moment and a force being introduced. Through this method, a pure moment is obtained around the rotor head.

Calibration was substantially standardized through the application of a computer. The calibrating weight and the resulting stresses at the pressure gauges are stored in the computer during calibration. After conclusion of a measurement series, a linear regression is undertaken. The rise of the curve is an element a_{ij} of the matrix $\underline{\underline{A}}$, i.e. $a_{ij} = \frac{\partial Z}{\partial F}$ (Fig. 9).

The matrix $\underline{\underline{A}}$ therefore has 7 lines and 5 columns; an inversion is then not possible. Since two equations are linear combinations of the others because of the static overdetermination, the system may be solved by the inclusion of the correction vector $\underline{C}$. /11

$$\underline{C} = \underline{\underline{A}} \times \underline{F} - \underline{Z}$$

$$\begin{vmatrix} Z1 \\ Z2 \\ Z3 \\ Z4 \\ Y1 \\ Y2 \\ X \end{vmatrix} = \underline{A} \cdot \begin{vmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \end{vmatrix} \qquad \text{or } \underline{Z} = \underline{A} \cdot \underline{F}$$

The vector $\underline{Z}$ is determined such that $\underline{C} \times \underline{C}^T$ reaches a minimum. This procedure is designated as the least squares methods with the boundary condition that the square sum of the errors of all seven gauges should approach a minimum. The procedure for calculation of the forces and moments from the display of the pressure gauges may be assumed as known, because this deals in the final analysis with the solution of seven equations with five unknowns. A computer assumes this task for us.

The correction vector $\underline{C}$ indicates how the gauge forces are to be corrected in order to fulfill the equation system $\underline{Z} = \underline{A} \times \underline{F}$. $\underline{C}$ equals zero in the case of complete linearity. As the elements of $\underline{C}$ increase, the error in the calculation of the rotor components also increases. The error threshold may be established up to which a measurement may still be employed. It can be seen that it may be very advantageous to have an overdetermined design statically for the balance i.e. to install more pressure gauges than required for the determination of the rotor components. It is disadvantageous that the rotor components may not be represented on-line, but only result after the solution of the equation system. Since the rotor must be held in certain stress limits during the wind tunnel trials, an immediate display of the rotor components is desireable.

Therefore, a small analog computer was constructed, adding the signals of two pressure gauges. This results in a square matrix $\underline{\underline{A}}$ with 5 lines and 5 columns:

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$$\begin{vmatrix} Z1 + Z2 \\ Z3 \\ Z4 \\ Y1 + Y2 \\ X \end{vmatrix} = \underline{\underline{A}}_{ij} \begin{vmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \end{vmatrix} \qquad \text{or} \qquad \underline{Z} = A_{ij} \cdot \underline{F}$$

This matrix $\underline{\underline{A}}_{ij}$ can be inverted, such that

$$\underline{F} = A_{ij}^{-1} \times \underline{Z}$$

Therefore, the forces and moments at the rotor head result from the pressure gauge displays. The errors resulting from non-linearities are not taken into consideration in this case. This is also not necessary for a quick look representation.

An error resulting in the inclination of the rotor mast must also be taken into consideration. Since the rotor balance provides the forces and moments in fixed coordinates, the balance is also tilted upon inclination of the rotor mast such that the weight component of the constructions above the plane of measurement is included mainly as an x force. This correction is taken into consideration in data evaluation.

1.1.2.4 Calibration of the Rotor Balance, Dynamically

The measurement of dynamic rotor components, i.e. forces and moments dependent on time, is difficult because the locations of excitation and measurement are not identical. A transmission behavior therefore results, primarily dependent on frequency and sometimes even dependent on force. If an ideal fixed connection were to exist between the locations of excitation and measurement, the amplitude and phase frequency characteristic would be independent of frequency. Such behavior is usually only achieved in a certain frequency range. The difficulty consists in constructing a balance, not exhibiting any resonance points in all axes at n rotor frequencies (n = 1 ... 8). In order to obtain information /13 on the frequency behavior of the rotor balance, there is possibility of solving the problem with a computer or of determining where the inherent frequencies lie in a stationary vibration experiment. The first method has the disadvantage that the distribution of mass and rigidity in the balance and the upper structures (rotor shaft etc.) must be determined, a very time-consuming process, often only providing estimations. The analytical, however, has the advantage that the effect of modifications (conversions, additions) on the vibration behavior may be determined very rapidly.

The experiment on stationary vibration serves to determine inherent frequencies, inherent forms, the generalized masses of the unattenuated system as well the determination of the actual attenuation of an elastic system. In the standard method, the inherent frequencies are determined by the phase criterium, i.e. the response of the system is compared with the excitation. If the phase angle amounts to 90°, the system is vibrating in its inherent frequency. The system motion is usually determined in this case with several acceleration pick-ups. In order to obtain the most accurate inherent form, the location of attack of the stimulation should be adapted to the individual oscillation shape. In the most unfavorable case, the force of excitation in the vibration node of an inherent form could be initiated with an exciter, so that this inherent form is not stimulated.

Mainly inherent frequency, inherent form and transmission behavior were determined in the stationary vibration experiment with the five-componentrotor balance. The experimental arrangement may be seen in Fig. 10. The balance is connected to a very low adjusted base via screws on a rigid frame. The electromagnetic vibration exciters are suspended on chains and direct the force via push rods to the rotor head, represented here by a substitute mass. Short extensions are connected by screws to /14 the substitute mass to permit additionally the initiation of moments. The exciters function in counter-phase in this configuration. The balance motion is measured with a total of 24 acceleration pick-ups. The signals are divided into the real and imaginary part in vector component meters and then processed by a computer for further application. The representation of the transmission behavior of the balance in the real and imaginary part has the advantage of better mathematical processing than in a phase and amount representation.

Fig. 11 shows the results from sweep tests. Two differing configurations were examined. Configuration 1 differs from configuration 2 in a greater distance between the plane of the rotor head and the measurement plane. The shift of the inherent frequencies to the right in the range of 10 - 15 Hz in configuration 2 can be clearly seen. Of course, in this type of test, the transmission behavior of the balance is not yet determined; however, the sweep test provides a good overview of the dynamic behavior of the balance.

A pressure gauge is inserted between the electro-dynamic exciters and rotor head for dynamic calibration, providing the amount and phase of the input signal. Output signals are amount and phase of the pressure gauges. For the balance configuration 1, Fig. 12 provides an example of the ratio of the input signal (force FY) to the output signal (pressure gauge 1 to 7) in amount and phase. Since the rotor is operated with a constant blade tip Ma number ($Ma_{tip} = 0.62$), other speed and therefore other harmonics are also produced with temperature and/or pressure changes. This means that the transmission functions of the balance must be constant in at least a certain frequency range ($\Delta f = \pm 0.5$ Hz) to avoid the necessity of too many calibration matrises.

Calibration matrises up to the 5th harmonic have been prepared for the real and imaginary part of the balance at the rotor testing stand.

In the case of 5 forces and moments and 7 pressure gauges, this results in 70 calibration factors per frequency, i.e. a total of 350 up to the 5th harmonic. It can therefore easily be seen how much data must be processed if the amplitude and phase in the range under consideration did not remain constant. /15

Parallel to the measurements, a mathematical model of the balance with upper structures was prepared. Fig. 13 provides a short overview of the point-mass distribution employed for this purpose. For reasons of simplification, only the transmission elements of the pressure gauges are considered as spring elements, while other elasticities are not taken into consideration. A comparison between calculation and measurement provided satisfactory results, so the mathematical model is an aid in alterations at the rotor balance for estimating the new inherent frequencies.

In order to achieve the required precision, however, the experimental determination of transmission function should not be neglected.

1.1.3 Torque Measurement Shaft

The torque measurement shaft is located between the upper plate and lower plate of the rotor balance. A DMS full bridge is attached on a shaft determining the torsion of a measurement shaft (Fig. 14). There is a linear relationship between torque and torsion such that the moment may be indicated directly in analog. The speed is determined from a sequence of rectangular impulses and therefore is available in digital and analog form. The product of speed and torque is indicated as output in analog form.

1.1.4 Measurement of Speed

One of the important quantities for data processing is speed, because this establishes the reference for almost all further measurement values. Especially the dynamic processes are related to speed. A total of four sensors of differing types are employed at the rotor testing stand for determining the speed: /16

- speed from the torque measurement shaft
- direct voltage speed transmitter
- electro-optical angular coder
- annular potentiometer.

The direct voltage speed transmitter is employed for measurements at the blade tip drive, because the torque measurement shaft does not supply any signal then.

The angular coder indicates the momentary rotor blade position with relation to a defined zero position ($\Psi = 0°$), in addition to the indication of rotating frequency. The coder transmits a digital signal to be directly processed in the computer. Resolution is situated at 512 scannings per 360°, i.e. the rotor position is indicated with the precision of 0.7°. This accuracy is necessary for the adjustment of higher harmonic signals, because a phase-accurate excitation is necessary for vibration reduction at the rotor.

The ring or ramp potentiometer supplies a linear function over time to be reset to zero after each rotation (saw-tooth ramp). This signal serves for setting the cycle of the data acquisition equipment and permits the temporal correlation of the measurement signals.

1.1.5 Measurement of Control Angle

There are two possibilities for determining the control angle: one consists in measuring the alterations in voltage at the blade rotary joint with the potentiometer; voltage and blade angle are dependent in a linear relationship on one another. The other possibility leads to the control angles via the position of the swash plate.

The swash plate is adjusted by the three electro-hydraulic positioning elements corresponding to the predetermined control angles at three desired value potentiometers. The conversion of control angle in the positioning path is carried out via a solidly wired analog computer. Inductive path pick-ups are attached to the positioning elements, indicating the actual values of each positioning element. The return report is carried out through an inverse analog computer, calculating the actual values of the control angles. The actual and desired values of the three control angles are displayed at digital voltmeters and recorded by a computer. Since the translation ratio of both rotors differ between positioning path and blade angle, a separate circuit must be provided for each rotor. /17

1.1.6 Measurement of Temperature and Static Pressure

Corrections in speed are necessary for the maintenance of the Ma number at the blade tip when temperature and air pressure vary. In the range of $0° \text{ C} \leq t_\infty \leq 30° \text{ C}$ and $980 \text{ mbar} \leq p_\infty \leq 1040 \text{ mbar}$, the velocities are situated in the range of approx. $1000 \text{ rpm}^{-1} \leq n_{Ro} \leq 1080 \text{ rpm}^{-1}$. These quantities clearly show that it is necessary to monitor temperature and air pressure. Ordinarily, variation in air pressure is slight so that this value must be measured only once or twice on each measuring day.

In contrast, the temperatures in the wind tunnel are altered very rapidly, especially when high flow speeds are employed. It is therefore important to display the temperature in the control chamber and to record this or to provide the value for the desired speed.

1.2 Sensors at the Rotor in Motion

Measurement pick-ups in the rotating system of the rotor are usually subjected to multiples of the load. Moreover, the wind forces are strong, varying greatly at high tunnel speeds, while the direction of flow at the sensors is constantly changing. It can be seen that these measurement value pick-ups must be of especially high quality. /18

The cables and plug connectors presented us with the most difficulties, often not sufficient for the alternating forces from the flow. It should be especially emphasized that the greatest care is necessary when laying laced wiring harnesses and plug connections, because errors assumed to stem from the sensor are usually caused by contact defects in the electrical lines. This is almost always the case if the sensor functions faultlessly at rest or with a slowly rotating rotor, but the signal is defective as soon as the rotor reaches the prescribed speed.

1.2.1 Measurement of the Blade Angle

The course of the blade angle in time may be determined with a precision potentiometer. The control angles may be calculated from this course through an harmonic analysis. It is important in this case to be able to correlate the angle of circulation of the blade to the local adjustment angle of the blade.

The potentiometer is connected by screws at the rotary joint of the rotor. A gear is located on the shaft, meshing in a gear segment. The relative motion between gear and gear segment is proportional to the blade angle. The potentiomenter weighs 20 g and is therefore well suited for the rotor. The disadvantage of this measurement set-up is that the play between the gear and gear segment distorts the results, since only a very small measurement range of the potentiometer is utilized when setting the blade angle so that the gear play has excessive influence. Therefore, another measuring principle will be employed in the future. A resistance element (see Fig. 15) will be fastened directly to the rotary joint and the alteration in tension when setting the angle measured via a slip ring. The entire measurement range can be utilized because the length of the conductor path can be adjusted precisely to the rotor relationships. Unfortunately, we cannot yet report on the success /19
of this measurement principle since no continuous trials have been undertaken up to now.

1.2.2 Measurement of the Impact and Pivotting Moments

It is especially difficult in a jointless rotor to define measurement points for determination of the impact and pivotting moments. In contrast to a rotor with joints where impact and pivotting joint are clearly anchored and the moments are measured via the angles, a fictitious joint must be employed in the case of a jointless rotor for impact and pivotting. Since no angle may be measured in this case because the transitions are continuous, strain gauges are employed. Since the rotor blade does not only vibrate in the first inherent form, all strains are measured, resulting from higher blade bending shapes at the location of the strain gauge. In calibration, of course, these effects may not be taken into consideration. These difficulties are the basis for equipping all four blades with DMS at exactly the same measuring points. Therefore, it should be possible to obtain information on the accuracy of measurements.

Couplings between impact and pivotting result when setting the blade angle; the couplings increase with size of the blade angle. These couplings are again separated in evaluation through coordinate transformation, so that the moments are situated in a rotor-fixed coordinate system.

DMS full bridges were fastened at the top and bottom (for impact moments) as well as at the back and front (for the pivotting moments) on the blade neck, wired such that only blade bending is measured.

The blades are calibrated as follows. The blade is inserted vertically to exclude strains from the weight of the blade. The forces are introduced via a defined lever arm. The relationship /20
of applied moment is proportional to the electrical voltage of the strain gauge. Hysteresis effects caused by an alteration in sign of the bending moment in the impact or pivotting direction can be neglected. If it is demonstrated during calibration that couplings exist between impact and pivotting or vice versa, the

blade must be turned around the axis of torsion until the couplings have disappeared.

1.2.3 Torsion Measurements

The torsion may not be measured directly at the blade because of the form and inhomogeneity of the blade neck. Rather, the strains of the circulating control rods are taken as a measure for the torsion of the blade. This measuring method is also not free of defects, since the bearing friction and the reset forces from the torsion spring elements in the rotor head are included in the measurement. In the case of centrifugal force of 1×10^4 N, however, this is certainly not a large value. The signal/noise ratio is not very high because of the slight strain on the control rods, so that the results can be evaluated only with loads ≥ 5 N.

1.3. Equipment for Measuring Descending Wind

Much energy has been devoted to the area of descending wind measurement technology in recent years for comparisons between calculation and measurement as well as for researching the rotor-induced flow adjacent to the rotor. Pneumatic 5-hole probes were employed for initial studies, later supplemented by hot-wire probes.

Positioning the probes via a shifting device was limited to the y coordinate (see Fig. 16). This shifting device is replaced in the next wind tunnel trials by a system covering a field of /21 5 m x 6.2 m, thereby reaching any random point below the rotor circular area (see Fig. 17). Therefore, blockage in the wind tunnel flow will greatly increase in an enclosed measurement path, so that free flow measurements may have to be carried out where the shifting device can be mounted almost completely outside of the wind tunnel flow. Since the descending wind of the entire downwind cylinder of the rotor is to be measured, the probe must also be positioned in the vertical direction.

Strong forces are applied to the descending measurement equipment through the blowing action, such that the individual components must be strong, in turn disadvantageous for dynamic behavior. Therefore, studies on the dynamic behavior of the equipment were previously carried out since amplitude size and the position of the inherent frequencies may greatly distort the descending wind measurements. Especially when instationary flow measurements are to be carried out, the vibration characteristic of the probe mount must be known, because it cannot be seen from the signals of the hot-wire probes which speed portions originate from the probe vibration. For this purpose, the probe mount is provided with acceleration pick-ups for measuring the additional speeds after integration.

The adjustment device is moved in the x-y plane via step motors, permitting exact positioning. The z adjustment is carried out pneumatically. The lifting height amounts to approximately 1 m. After successful signal recording, the probes are automatically driven into the next position.

1.3.1 Distance Measurement

The distance of the probe to the blade is especially important for measuring the flow field, because a correlation with theoretical values is otherwise erroneous. Generally, the measurements are related to the plane of the rotor and not to the /22 plane of the blade tip, leading to greater deviations only in the range of the blade tip, amounting to up to 0.2 m for the 4 blade rotor. A simple possibility for determining the distance from the blade to the probe is provided with a device consisting of a very thin rod of low mass, travelling very slowly in the plane of the blade until the blade and rod touch. An impulse is triggered in this case, fixing the position of the rod and the downwind probe. The plane of the rotor is applied as reference quantity. Condition for this measuring method is that the distance is always related to the same blade; however, this assumes a good track accuracy of the blades.

Another possibility for determining distance is presently under study. In this case, an opto-electronic principle is employed. A laser beam hits a blade and is reflected. A photo cell is driven until the reflected light is caught. The distance between photo-cell and laser beam is a measure for the angle of reflection and therefore a measure for the local bending of the blade. The accuracy of the measurement increases with distance of the plane of the blade and plane of the measurement.

1.3.2 Downwind Measurement with a Pneumatic Probe

Most downwind measurements have been carried out up to now with a pneumatic 5-hole probe (see Fig. 18). This probe is especially suited for measuring average values, because the long hose lines (between probe and measured value acquisition) provide excellent attenuation for the system. The probe may be guided into the main flow direction because of the large measurement error with blowing action at an angle, but only the adjustment is possible and also necessary. The measured values α are therefore only acquired if the pressure is equal between hole 2 and 4. This measurement principle has proven excellent because it is very accurate, hardly subject to malfunctions and easy to operate. The measured values are recorded with a customary camera. The level of liquid in the glass tubes is photographed, representing a measure for the pressure relationships at the probe. /23

Only those signals are evaluated with the β angles situated in the range $-20° \leq \beta \leq +20°$, because the error is otherwise too great. The average values obtained with the 5-hole probe are suitable for checking results from simple computer models such as the impulse method or the blade element theory. Calculations based on a turbulance model may not be correlated with sufficient accuracy to the measurements, because the dynamics of the flow away from the rotor, especially the position and distribution of velocity of the blade tip turbulance may not be measured by this probe. Nevertheless, it is not possible to dispense with this type of downwind measurement if it is necessary to monitor signals from other probes, such as hot-wire probes, for measurement accuracy.

1.3.3 Downwind Measurement with a Hot-Wire Probe

The hot-wire anemonetry has gained considerably in importance in recent years, because measuring flows with high velocity gradients is especially important in instationary aerodynamics. The disadvantage of this measurement principle is that it does not permit non-contact measurements, such that induction takes place from the sensor to the flow (Fig. 19).

The principle of the hot-wire measurement technology consists in the fact that a thin tungsten, platinum or platinum-iridium wire with a diameter of 1 to 15 m is heated electrically. When this heated wire is introduced into a flowing medium, a certain amount of heat is drawn off per time unit, corresponding to the flow rate.

The heat drawn from the hot wire is a direct measure for the amount of the flow rate in the simplest case of an incompressible flow at constant air temperature. Usually it is not taken into consideration that the condition of the flow around the measuring wire is altered in various Re number ranges, thereby producing another heat dissipation and also another temperature distribution over the wire cross-section. /24

The alteration in condition of the flow around the measurement wire as a function of the Re number is an explanation for the fact that the hot-wire characteristic does not have a purely exponential character, but rather has sharp bends in the characteristic at certain Re numbers. The temperature distribution along the hot wire of finite length attached at the probe mount (prongs), a function of the flow rate, is also not taken into consideration.

A zero point adjustment undertaken before the experiments should be repeated often during measuring and compared with the originally adjusted value for checking the measuring probe with respect to contamination , damage or alteration in the air temperature.

The measuring instrument consists of a single or multiple wire probe with the appropriate electronics, accomodated in an 19" push-in unit. Each hot wire is connected with the electronics via a cable of defined length. Amplifier, linearization stage, rectangular generator, digital voltmeter and power supply are required for each hot wire.

The best results are obtained with a probe having wires of tungsten core with platinum coating and a diameter of 5 m as well as a cold resistance of 4-8 ohms. This wire is superior in strength to pure platinum wires. The permissible velocity range depends on the shape of the hot wire arrangement and amounts to approximately 110 m/sec in our case. The maximum wire temperature amounts to 300° C. Generally, the highest possible wire temperature should be employed to achieve high sensitivity of the instrument and to reduce the effect of air temperature alterations. Nevertheless, the temperature alteration of air, especially large at high velocities in the wind tunnel, must always be taken into consideration when calibrating the probes. Therefore, a small wind tunnel was constructed (V_{max} = 80 m/sec) and provided with a cooling and heating device (temperature range: 0° - 50° C). This tunnel was designed such that the temperature deviations over the cross-section of the beam are negligible. The possibility of turning the probe in the beam also makes it possible to estimate interference effects especially well, playing a role particularly in multiple-wire probes. Calibration curves are determined for various temperatures and flow rates (U[V] = f(t[° C], V_∞ [m/sec]). /25

These curves are available as measured values. With the aid spline interpolations, intermediate values of temperature and tunnel velocity may be determined, then taken into consideration in evaluations.

Up to now, downwind measurements were carried out below a 4 blade rotor and the 2 blade reaction rotor with a single-wire or a double-wire probe. The results will be reported at a later time.

2. Data Processing and Evaluation

Data processing (signal recording, transmission, preparation and display) has achieved great importance in modern experimental technology. The main reason is that much data is to be measured simultaneously in most cases and that these data depend greatly on time, i.e. they are not static. Moreover, the demand is presented that a decision may already be made at the experimental location on the quality of the recorded measurement data, so that experiments need not be repeated. Monitoring numerous sensors /26
also belongs to the area of data processing just as does the most rapid possible display of conditional quantities (quick look display). Since the amount of data in extensive experiments is especially large and therefore difficult to interpret, the data are presented on a display screen in easily understandable representation after appropriate preparation. For example, time sequences are better represented immediately in frequency range and stress quantities not indicated as number, but rather as columns of variable length with the appropriate limit value.

Efforts were also made in recent years at the rotor testing stant to evaluate and present important measurement data during the experiments. Fig. 20 shows data acquisition and evaluation as they exist presently at the rotor testing stand, as well as the new data processing equipment, available in hardware but still in the preparation stages in the software packages. The old equipment consists of three components:

component 1: evaluation of static and dynamic signals from the rotor head and rotor balance (optional) Evaluation duration of an experiments: approximately three minutes.

component 2: recording the experiment, presenting rotor quantities. Evaluation duration: approximately 10 sec.

component 3: storage of all measurement values on magnetic tape for evaluation at the large-frame computer.

While the old equipment required only pdp 11/45 computer, the new data acquisition and processing equipment already need three computers.

Computer 1: control and monitoring of the rotor testing stand.

Computer 2: presentation of the data on a display screen (refresh rate: one per second).

Computer 3: data storage and monitoring. /27

This extensive expansion of the data processing equipment is based in future research tasks. The higher harmonic control cannot be carried out without a high-capacity control and monitoring computer unit.

2.1 PCM Unit

Data acquisition is carried out alm st exclusively via the PCM unit. The digital signals are stored on an analog tape together with other auxiliary signals important for subsequent evaluation at the large-frame computer.

On the basis of the spatial separation of the rotor testing stand in the measurement path of the wind tunnel, on the one hand, and the data recording equipment in the measurement chamber, on the other hand, a high-performance telemetric instrument had to be created. The time-multiplex procedure (PCM, pulse code modulation) is superior to the frequency-multiplex procedure because of fewer disruptions and defects in comparison to the analog data transmission systems.

Analog signals may already be disrupted by slight external voltages. The disturbing effects act in analog procedures - caused by the system or externally - on the entire measurement chain including the transmission path. Digital procedures, working with binary code, i.e. only with two different electrical states, for example pulse or no pulse, or in voltage levels, for example 5 volts or 0 volt, remain uncritical as long as the disturbing effects are situated at least 6 dB below the useful signal. Signal regeneration at the receiving point compensates for distorsions in impulse shape as well as differences in level of 20 % and more. The analog processing of acquired input signals is concluded with the analog/digital conversion.

While the continuous analog representation permits infinitely /28
many values within the range of presentation, there is a finite and defined number of discrete values differing from one another in the digital presentation, determined by the number of the smallest ranges of digitalization. The quantization or conversion error necessarily occurring in this case is precisely known and can be maintained so small that it is situated far below the customary inaccuracies of analog measurement technology and instrumentation. A resolution of 10 bits, i.e. $2^{10} = 1024$ amplitudes steps) then signifies an accuracy of 1 $^{o}/oo$, i.e. one volt signal level is resolved with 1 mV. Further noticeable errors do not occur in transmission, storage, etc.

The analog measured values of the sensors situated in a parallel position in the rotating system are scanned sequentially in time in the commutator (multiplexer) and converted via an A/D converter into a bit parallel data flow (Fig. 21). In order to correlate the signals correctly later, a synchronous word is added to the data flow in the encoder in equal intervals. Digital information may also be added. The transmission of the pulse flow, now serial, is carried out via a slip ring, since a wireless transmission proved insufficient because of the many possibilities for disruptions causes by reflections in the wind tunnel. Then follow the bit synchronizer (bit cycle is extracted), frame synchronization and serial/parallel, digital/analog conversion and quick look representation of the analog signals.

Serial bit flow from the rotor head PCM equipment as well as the base PCM equipment are written together with the periodically recorded synchronous words on a track of the magnetic tape. A third track is required for recording the experiment number (language track).

During playback, the signals stored on tape are read by the /29
playback head and amplified. The frame and word synchronization as well as the regeneration of the serial PCM signal is carried out with the aid of the synchronization character added during recording (as well as circulation impulse and start impulse). The digital/analog conversion follows the serial/parallel conversion. The data of measured values are available in digital form at the exit of the PCM decommutator and, provided with word addresses and transfer information, are processed directly in a computer.

Up to now it was possible to process the signals from 32 channels when the PCM equipment on the rotor head and at the base had 16 channels each (15 free channels, one channel for the synchronous word). The new equipment processes 34 channels each. The main errors, occurring in the application of the PCM equipment, are caused by the amplitude resolution (10 bit) and the scanning rate per measurement channel, resulting at a defined bit rate (scanning or aliasing error). Up to now, 16 channels with 62.5 kbit/sec each were scanned, so that only vibrations up to the 5th rotor harmonic could be evaluated in the recommended 5 times scanning.

With the new PCM equipment, signals up to 140 Hz can be reproduced with a maximum bit rate of 500 kbit/sec, corresponding to the 8th rotor harmonic. Maintaining this value was considered an important requirement in the definition of the new rotor head PCM equipment. It was possible to reduce size and weight of the equipment substantially althrough 32 filters were added, not present in the old equipment. No battery is necessary because the power supply is carried out via a slip ring, and this fact makes itself noticeable especially in weight.

2.2 Signal Processing in the Downwind Measuring Equipment /30

The signal flow of the downwind measuring equipment is presented in Fig. 22. The command to move to a certain position where the downwind is to be measured is carried out manually or by a computer (LSI-11) according to a previously determined measurement program. The alignment of the probe in the averaged main direction of flow through variation in the adjustment and shifting angle (α ,β) is carried out via a regulator, also giving the signal for recording the data from the three hot-wire anemometers. An immediate evaluation of the measurement signals is carried out in the computer via the PCM equipment. Mainly position and velocity components are to be recorded immediately and plotted.

2.3 Presentation of the Results

The experiments in the wind tunnel are carried out in accordance with a previously defined experimental program. This essentially contains variations of the control angle, adjustment angle and wind tunnel velocity.

Adjusting these parameters requires constant monitoring of the rotor loads, thrust and moments being the most important quantities in the 4 blade rotor. In the case of the double-blade rotor, it is better to monitor the forces at the rotor. Monitoring is carried out through simple analog display instruments with scaled load limit range.

All other sensors measuring the load quantities also require monitoring. For example, the static and dynamic signals from the pressure gauges are presented on small monitors. A possible overload of the rotor balance is indicated in time by limit value signals. All measurement channels from the PCM equipment may be called for in sequence in order to obtain information on possible sensor defects. These signals may also be viewed at the monitor on a double-channel frequency analyzer in the time or frequency range. /31

A completed experiment is recorded on tape. Several selected quantities are plotted and later joined to an experimental series - in the case of one determined parameter each (specifically, wind tunnel velocity and angle of rotor adjustment). Very simple tendencies or trends may be determined then from the sum of the measurement points.

3. Measurement Container

The rotor testing stand is controlled and monitored from a container. Radio communications exist between the container and measurement chamber of the wind tunnel in order to exchange necessary information on the course of the experiment rapidly. At least three persons are required in the container itself:

- for steering the rotor
- for supervision
- for recording the data.

Since almost all control and monitoring components in the container are supported on vibration metals, only slight work is required to secure the equipment for transport. This is especially important for the mobility of the equipment.

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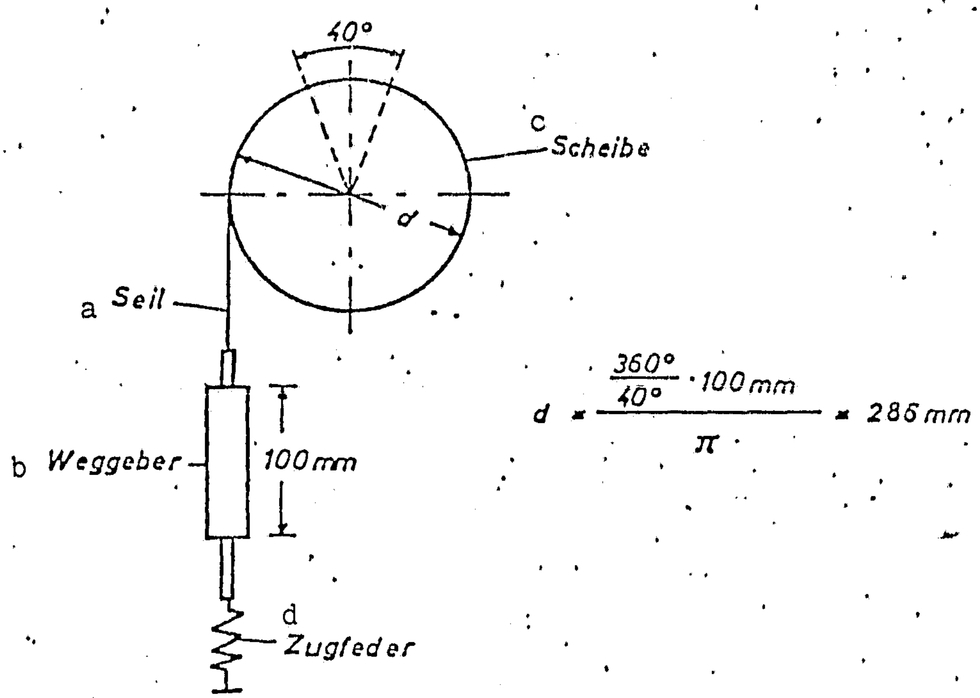


Fig. 1: α_{Ro} Adjustment - Linear Pick-Up of the Angle of Rotation.

Key: a. cable
b. path transmitter
c. disk
d. tension spring

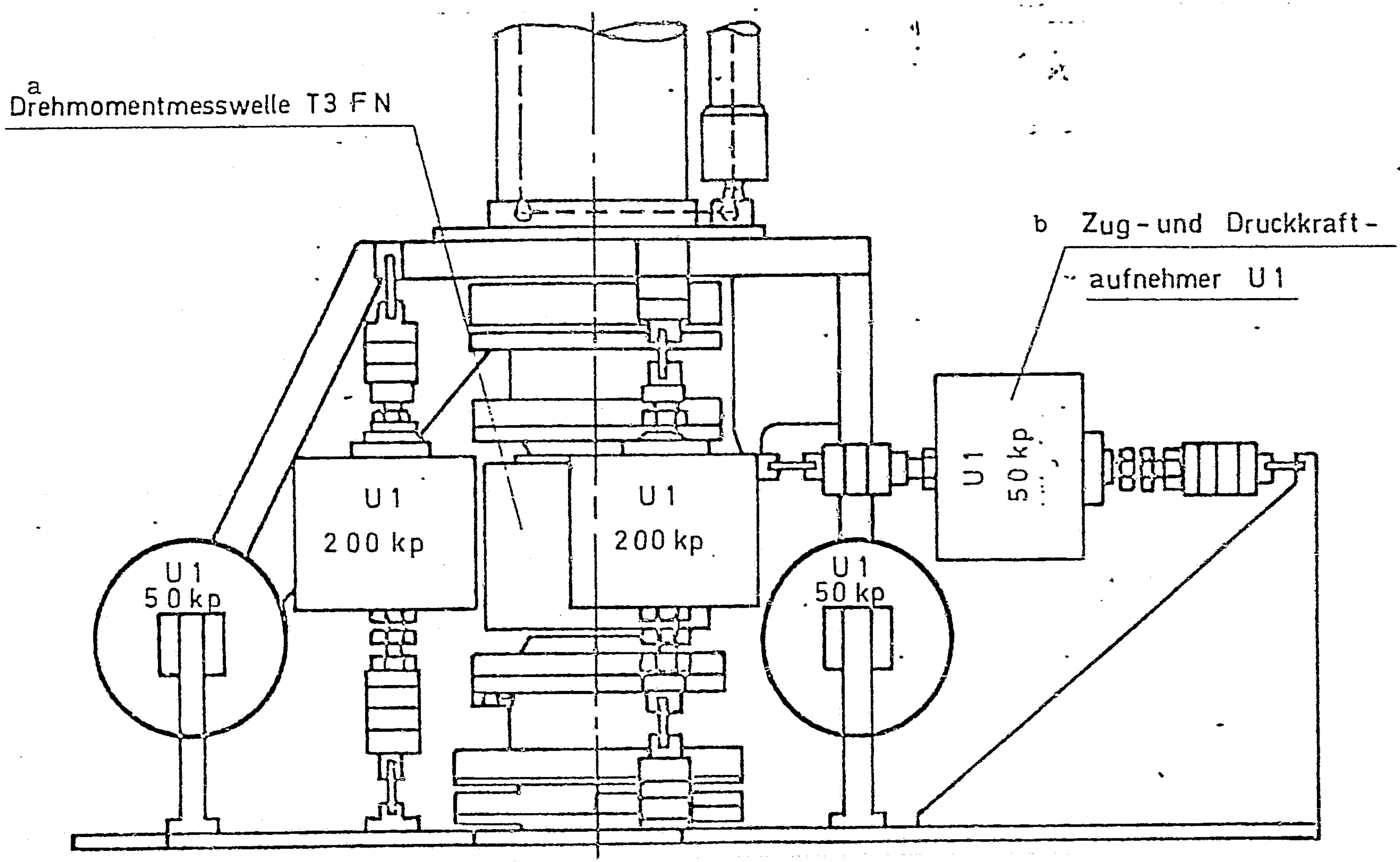


Fig. 2: Rotor Balance - First Version.

Key: a. shaft for measuring torque

b. pick-up for pushing and pulling forces.

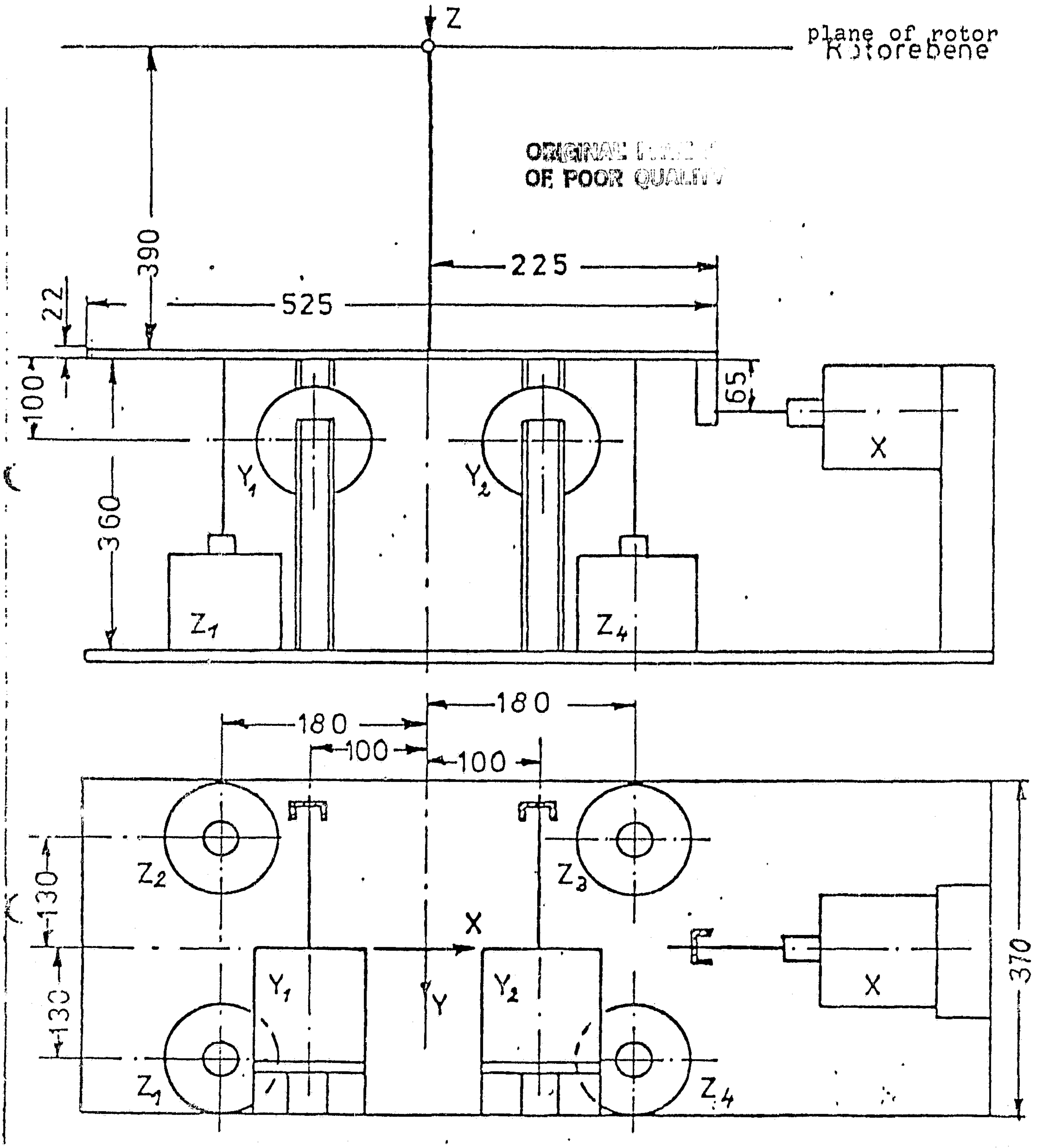
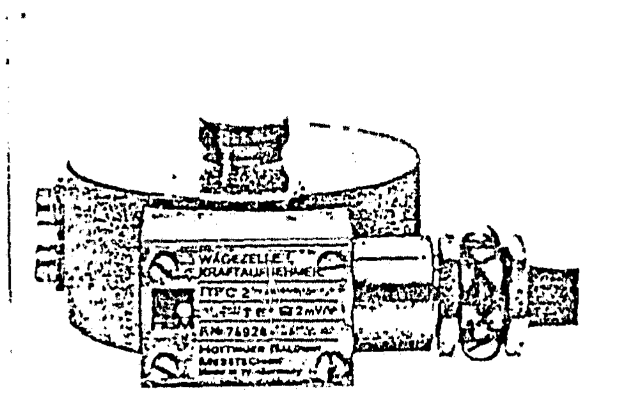
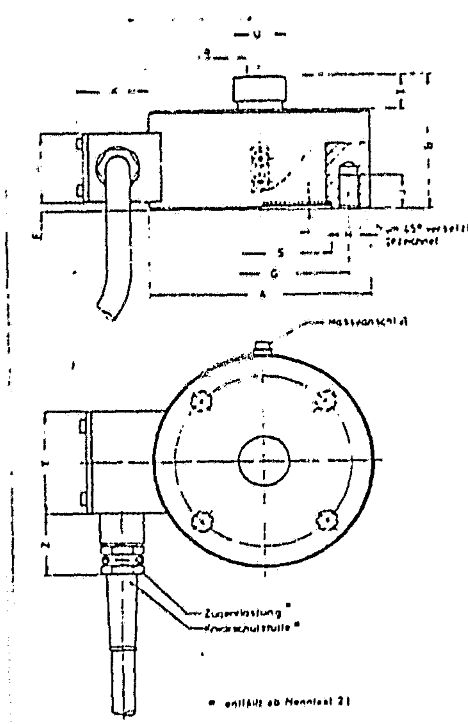


Fig. 3: Modified Rotor Balance.





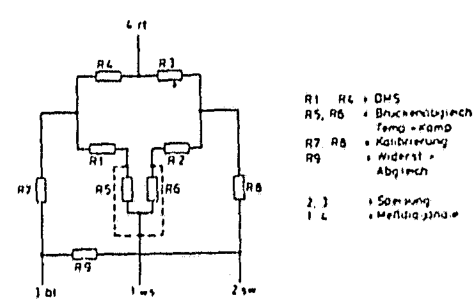
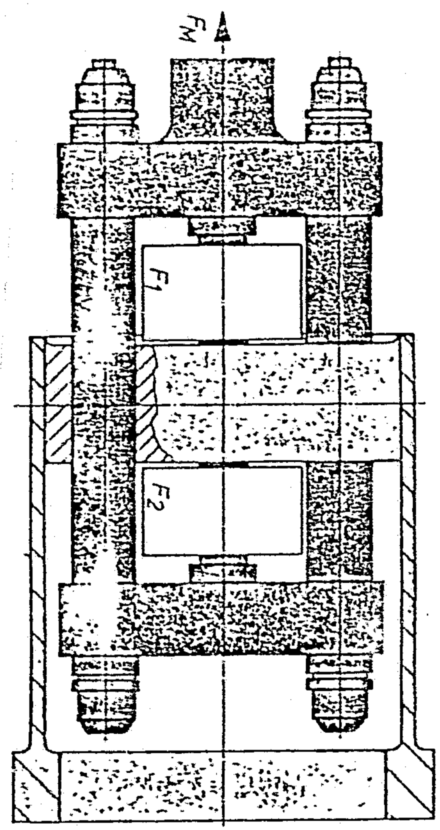


Fig. 4: Strain Gauge (DMS) - Force Pick-Up.



Dual Load Cell Force
Measuring Unit

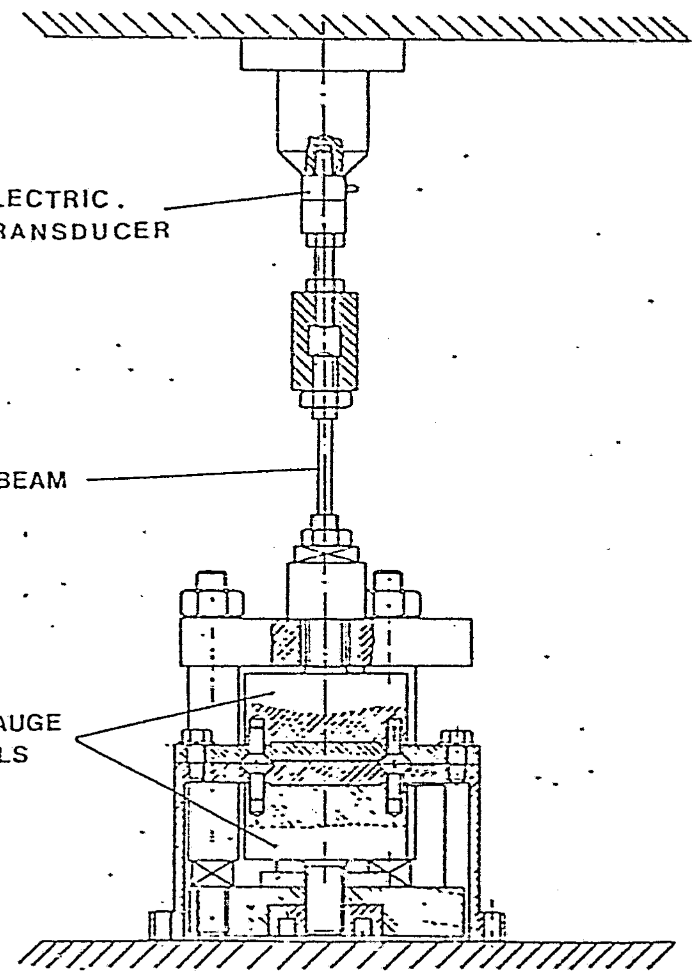


Fig. 5: Prestressed Strain Gauges.

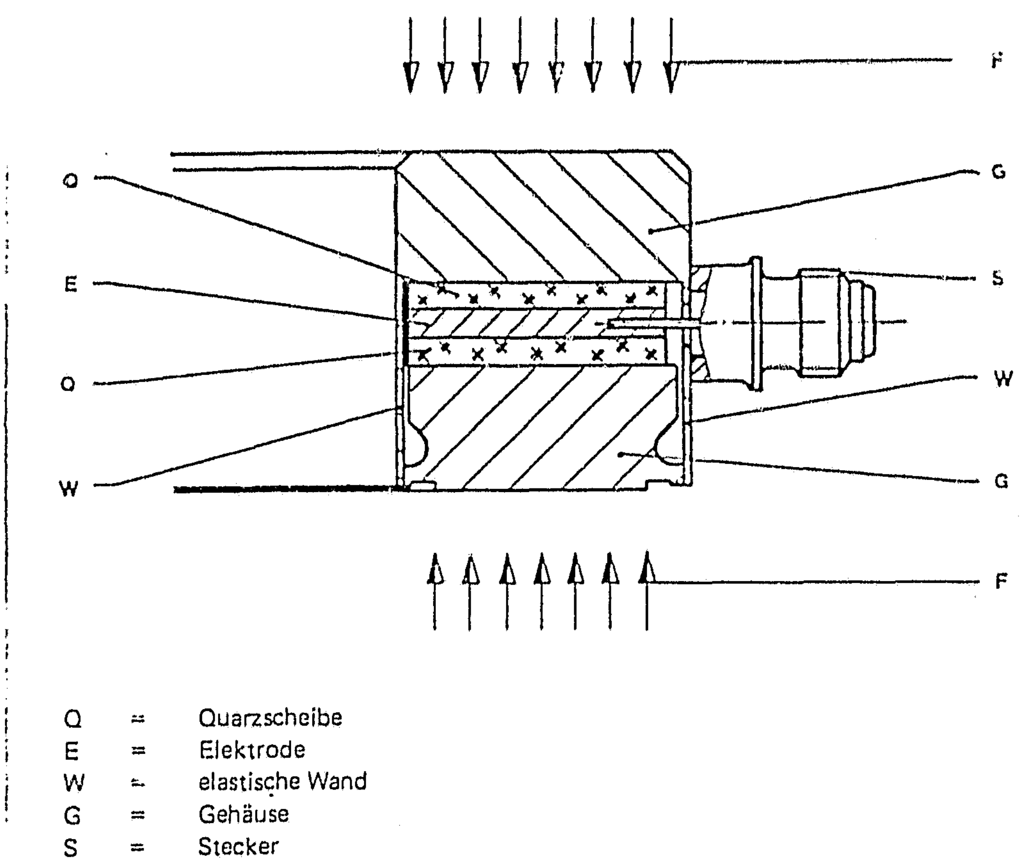


Fig. 6: Diagram of the Cross Section of a Quartz Crystal Measurement Washer.

Key: Q = quartz disk
E = electrode
W = elastic wall
G = housing
S = plug

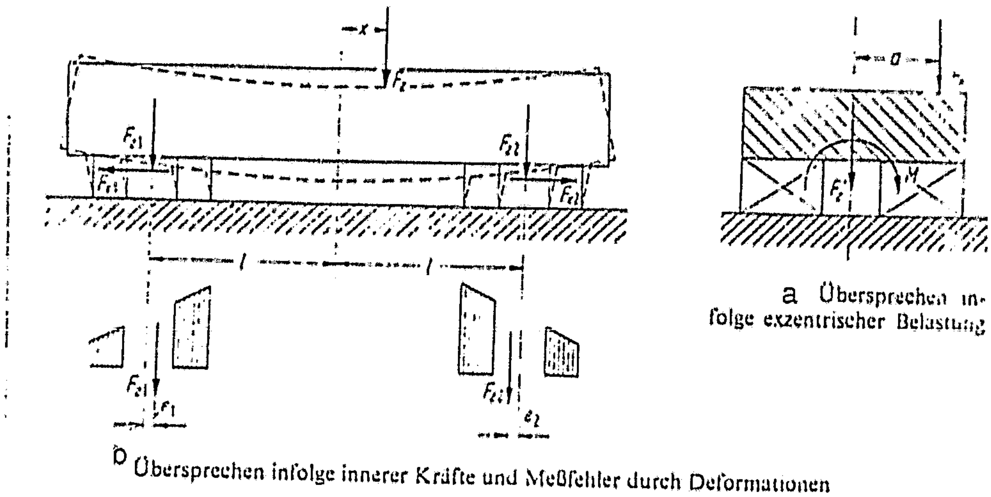


Fig. 7: Measurement Error Through Erroneous Load at the Piezoelectric Pick-Up.

Key: a. cross-talk as a result of eccentric load
b. cross-talk as a result of inner forces and measurement error through deformation

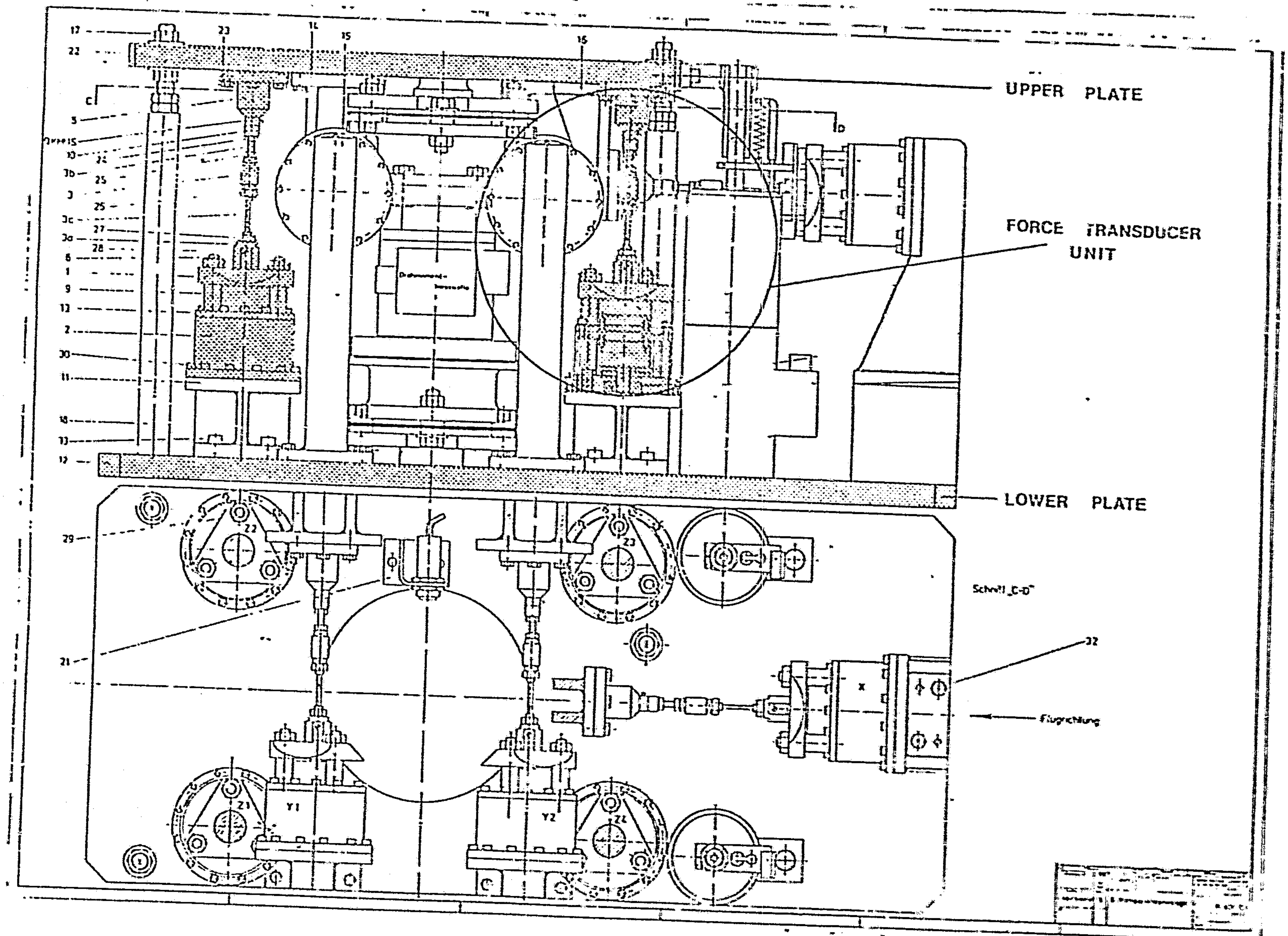


Fig. 8: Six-Component Balance, Side View and Top View

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Abb. 8: Sechs-Komponenten Rotor-Waage in der jetzigen Konfiguration

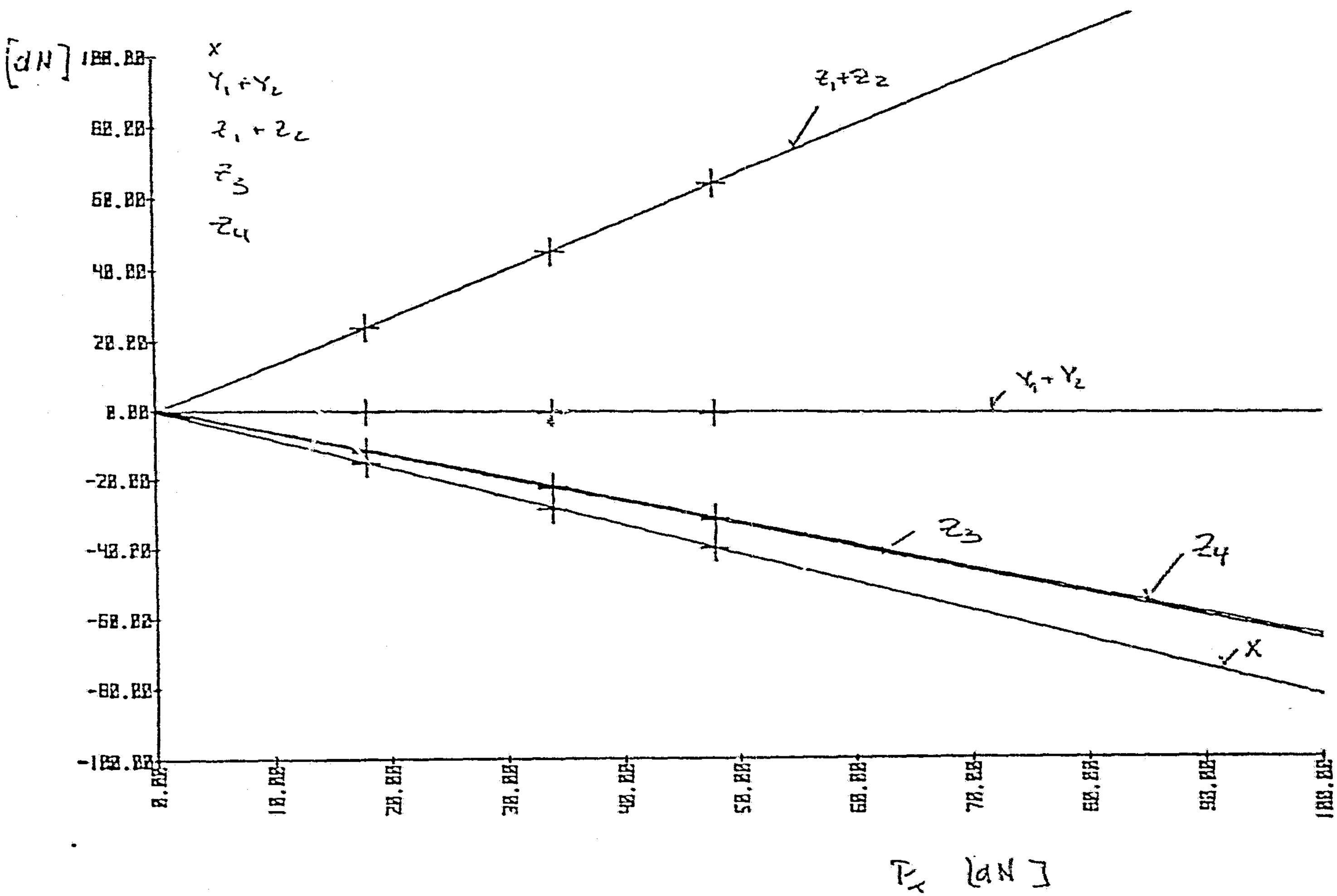

Fig. 9: Calibration Diagram for the Rotor Balance (static).

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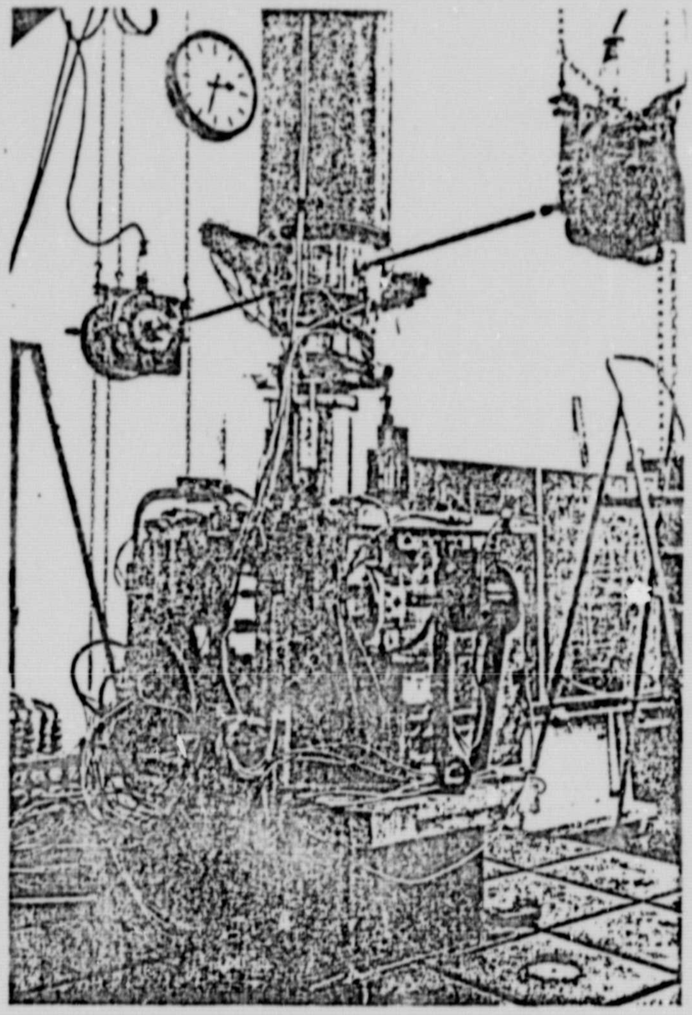
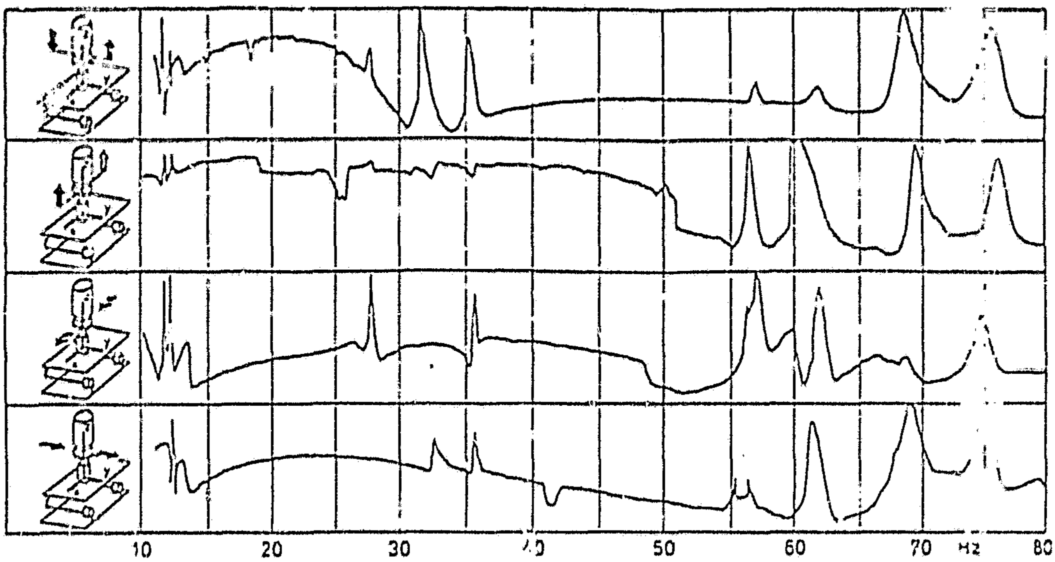


Fig. 10: Dynamic Calibration of the Rotor Balance in Longitudinal Direction.



Sweep Tests of the 6-Component Balance (Configuration 1) with Differing Exciter Configurations.

Sweep Tests of the 6-Component Rotor Balance (Configuration 2) with Differing Exciter Configurations.

Fig. 11: Dynamic Behavior of the Rotor Balance for Two Different Configurations.

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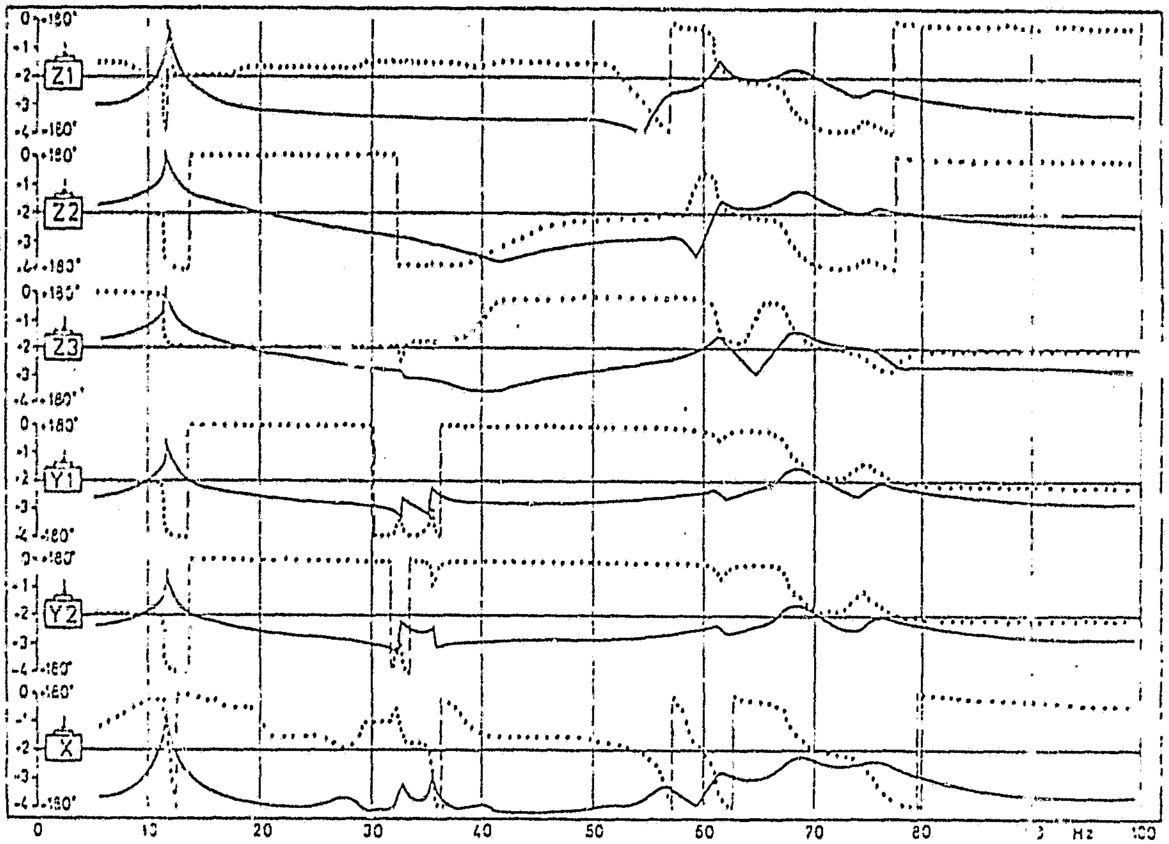


Fig. 12: Amplitude and Phase Frequency Characteristic of Individual Signal Doses in Relation to the Stimulation in the y Direction with Balance Configuration 1. The Numbers of the Amplitude Scale Indicate the Exponent for Base 10. The Scale is Selected such that the largest Signal Occurring has a Size of 1 x 10°.

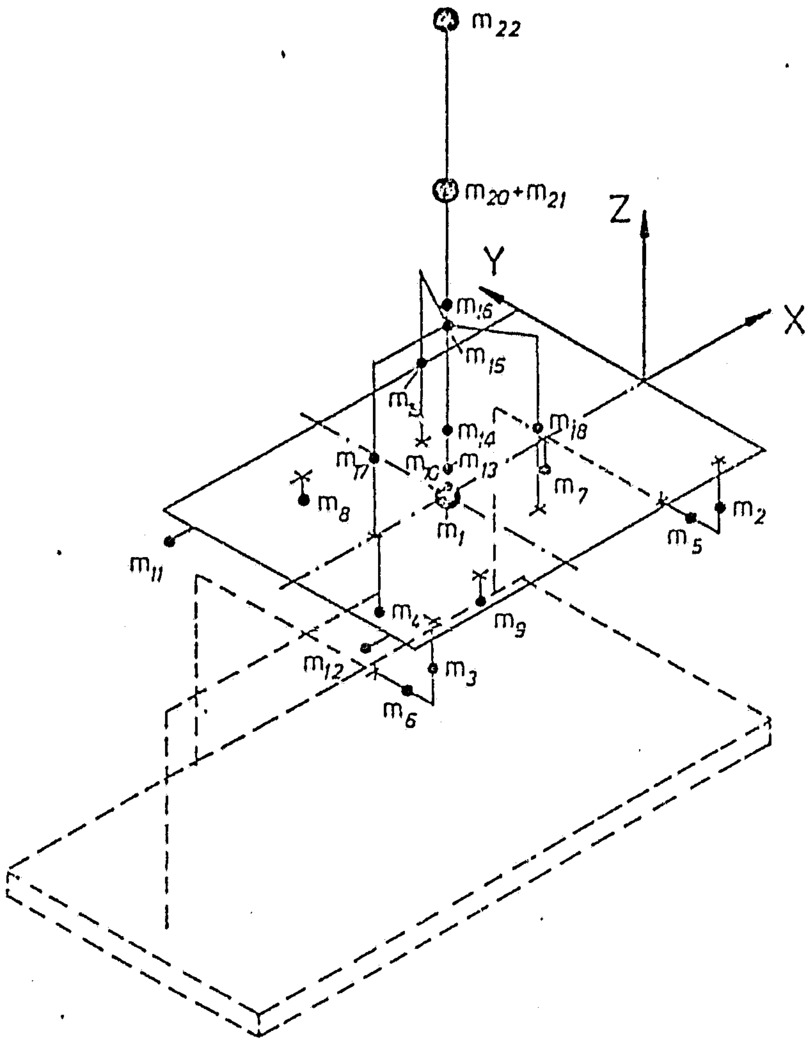


Fig. 13: Substitute System for Configuration 2.
The Point Masses are Connected with Infinite,
Rigid Rods With No Mass.

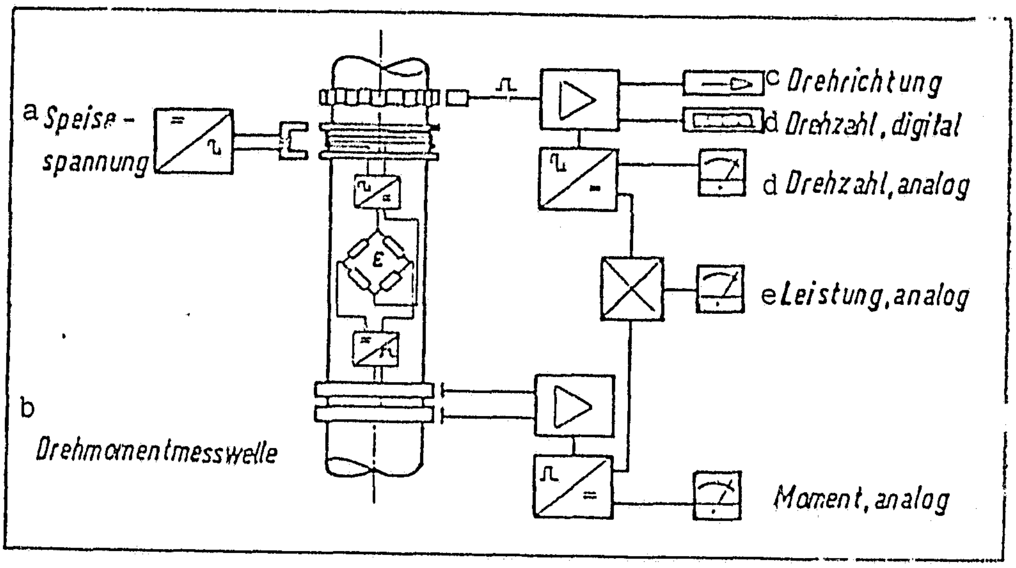


Fig. 14: Function Diagram of the Measurement Device for Torque-Speed Output.

Key:
a. supply voltage
b. measurement shaft for torque
c. direction of rotation
d. speed
e. output

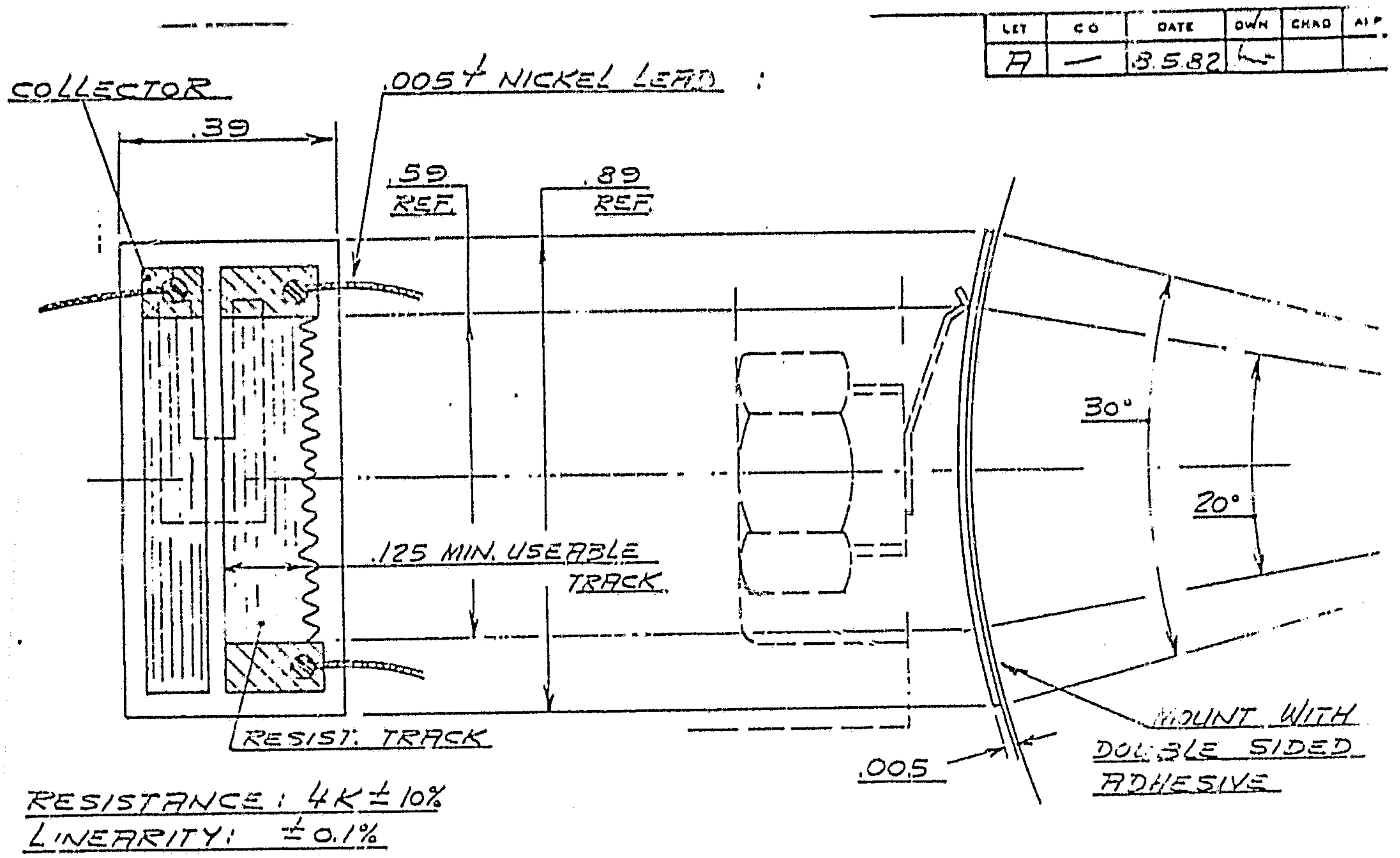


Fig. 15: Sensor for Measurement of Blade Angle.

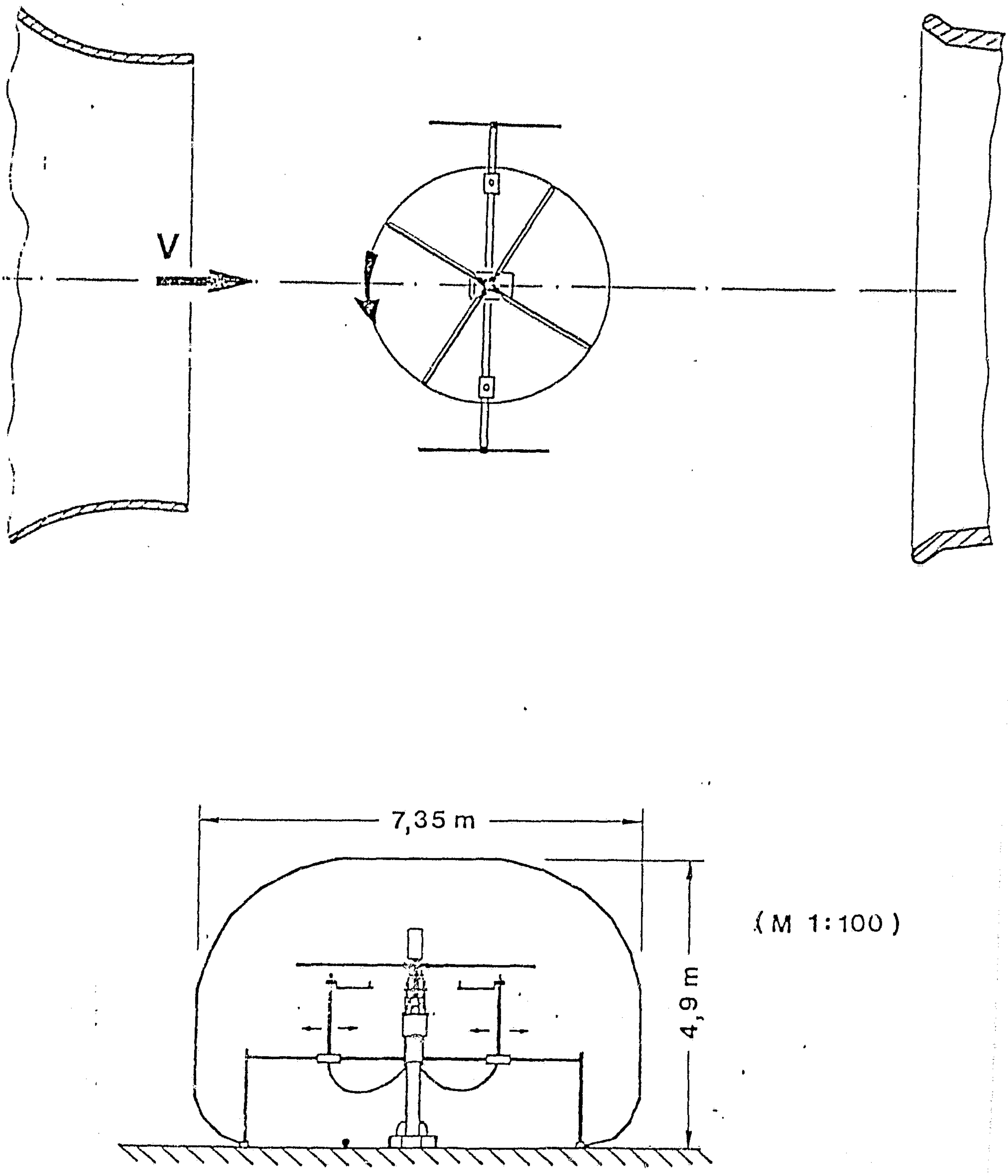


Fig. 16: Downwind Measurement Equipment in the DB Wind Tunnel.

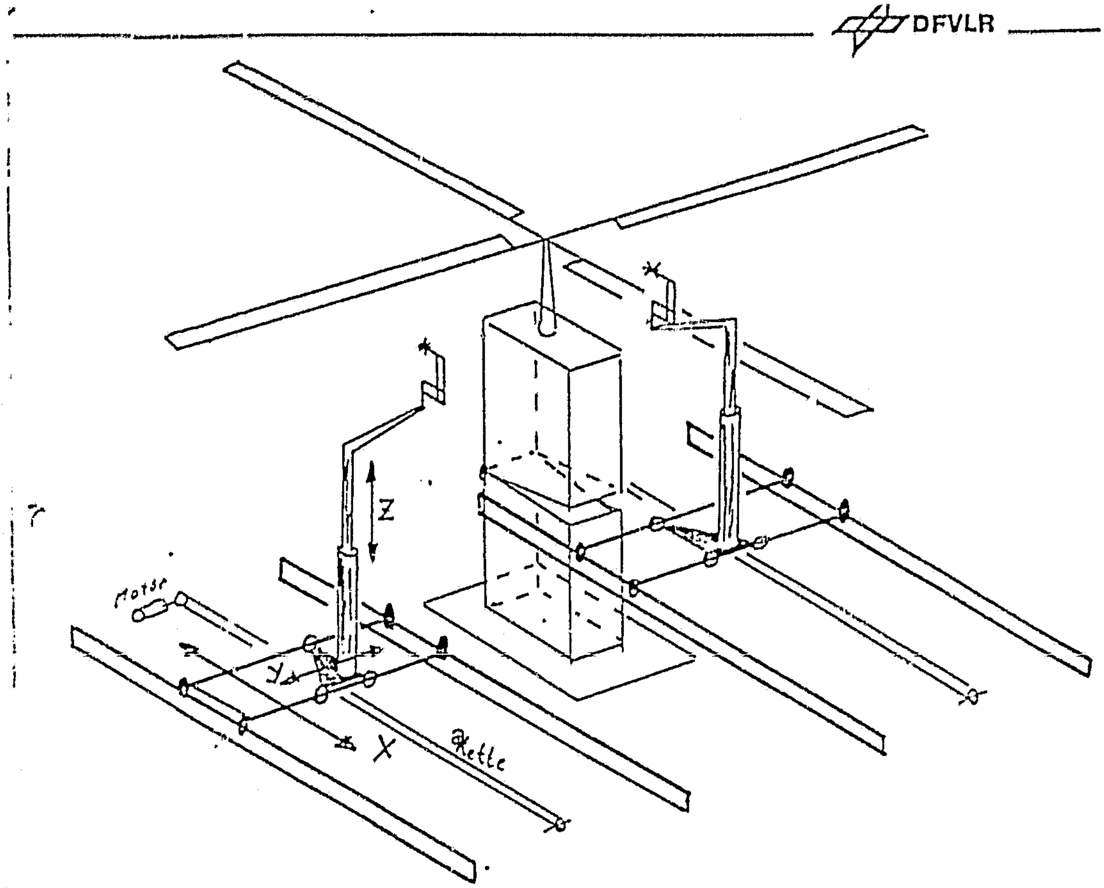


Fig. 17: Downwind Measuring Equipment.

Key: a. chain

The adjustment device for positioning the probe is moved in the x-y plane via step motors. The z-adjustment is carried out pneumatically. The triple-wire hot-wire probe is aligned in the local average direction of the downward flow around the y or z axis at the α and β angles. After a successful signal recording, the probes are automatically moved to the next position. A field of 5 x 6.2 may be covered with the two devices. Below the rotor, measurements from the plane of the rotor to 1.0 m from this plane are possible.

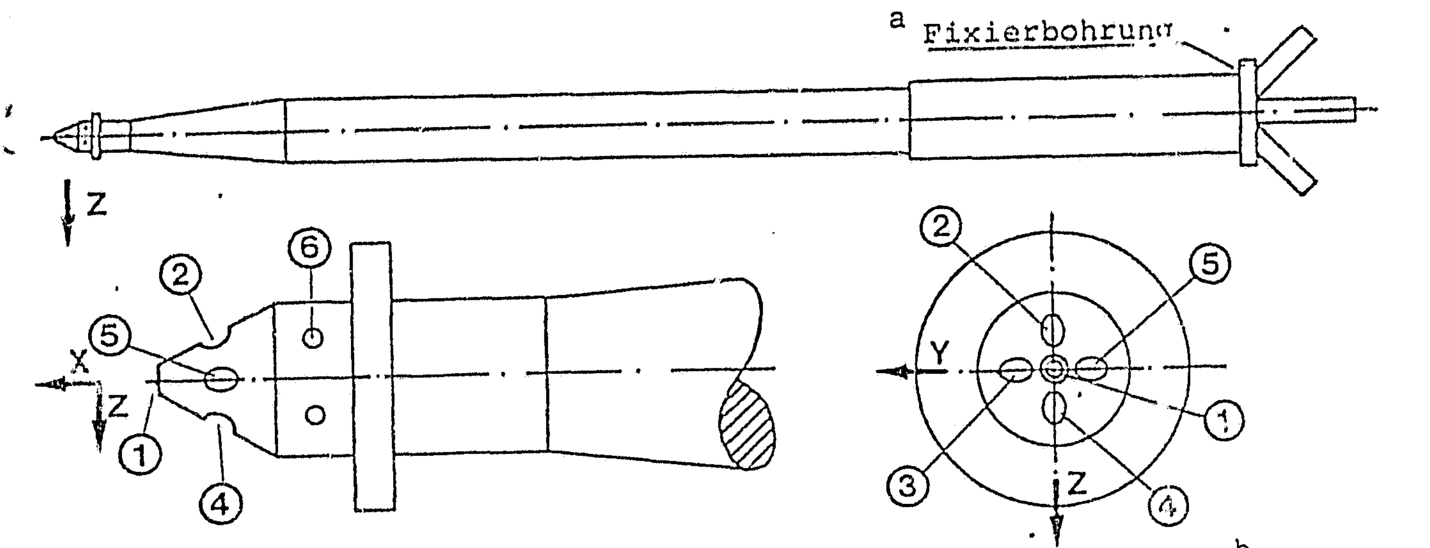


Abb. 18: Pneumatische Strömungssonde nach Conrad

② + ④ α-Messung [b]
③ + ⑤ β-Messung
① Gesamtdruck [c]
⑥ stat. Druck [d]

Fig. 18: Pneumatic Flow Probe according to Conrad.

Key: a. positioning hole
b. measurement
c. total pressure
c. static pressure.

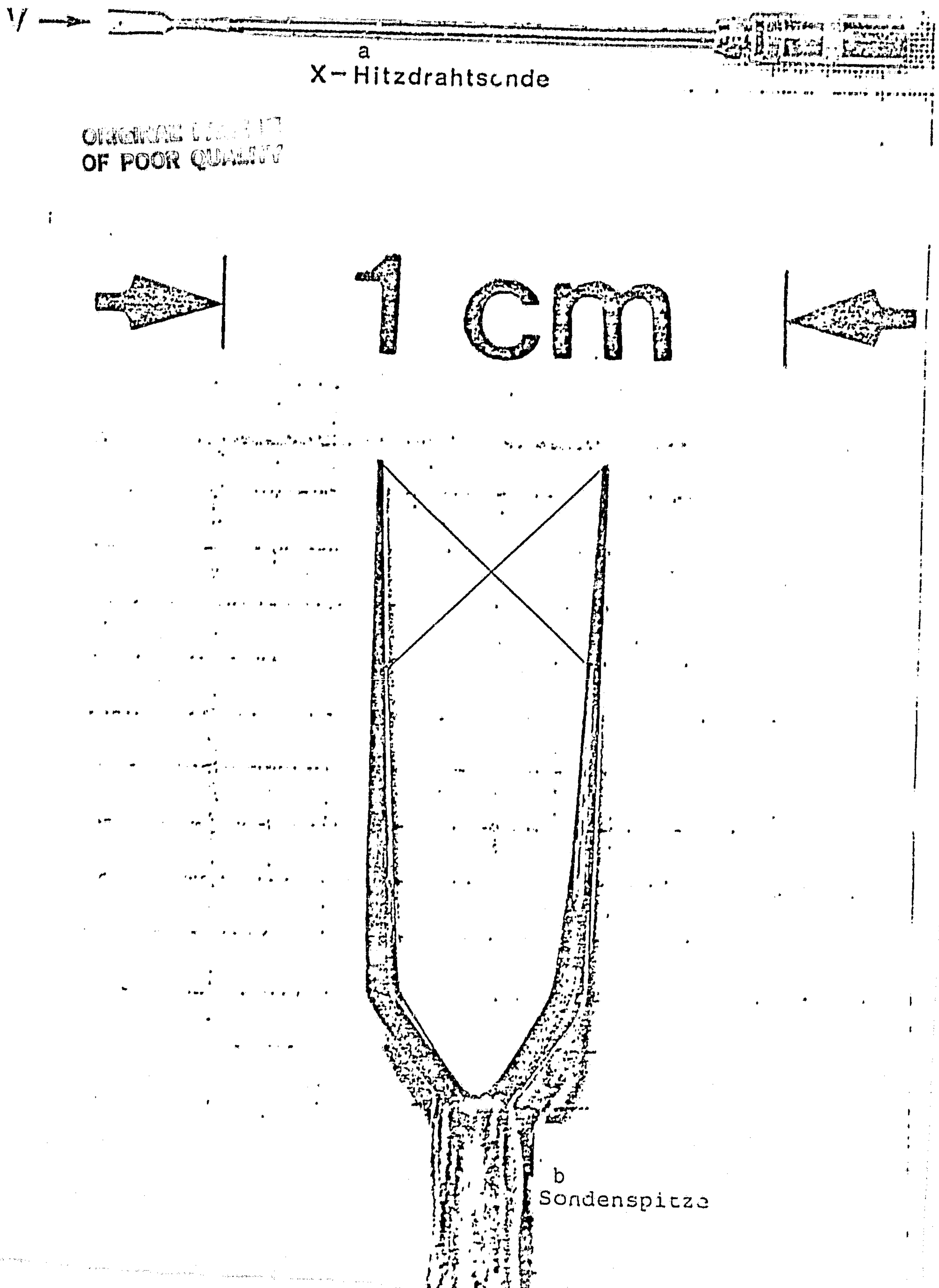
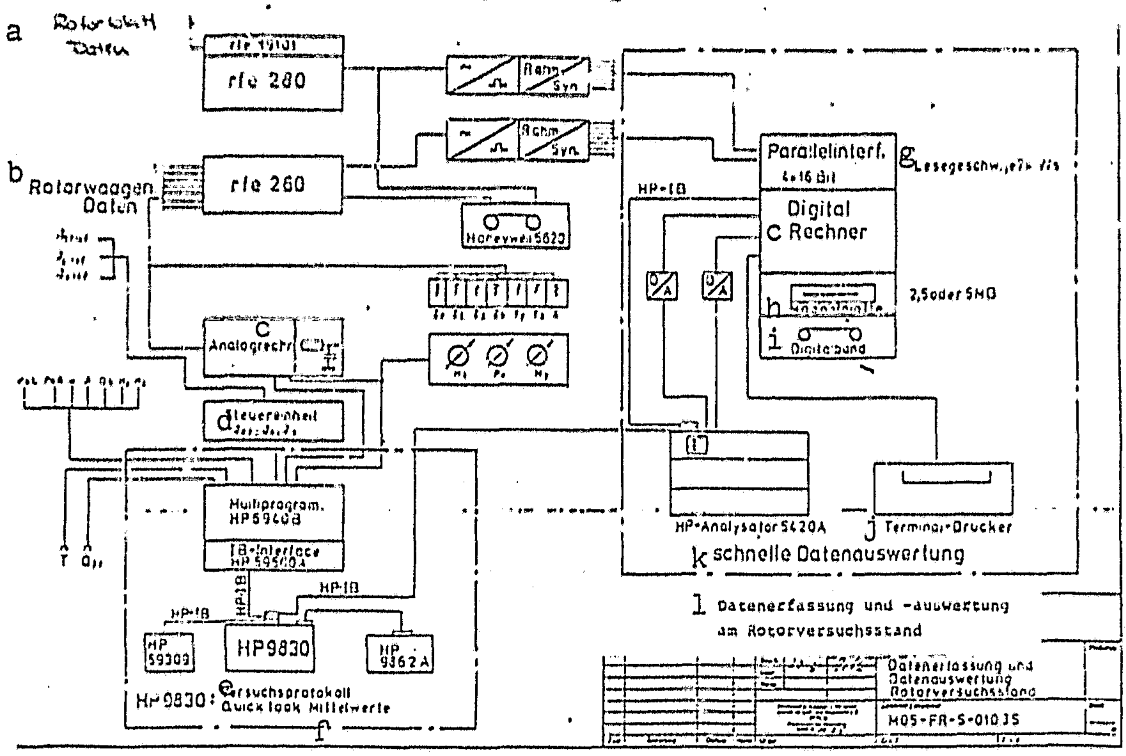
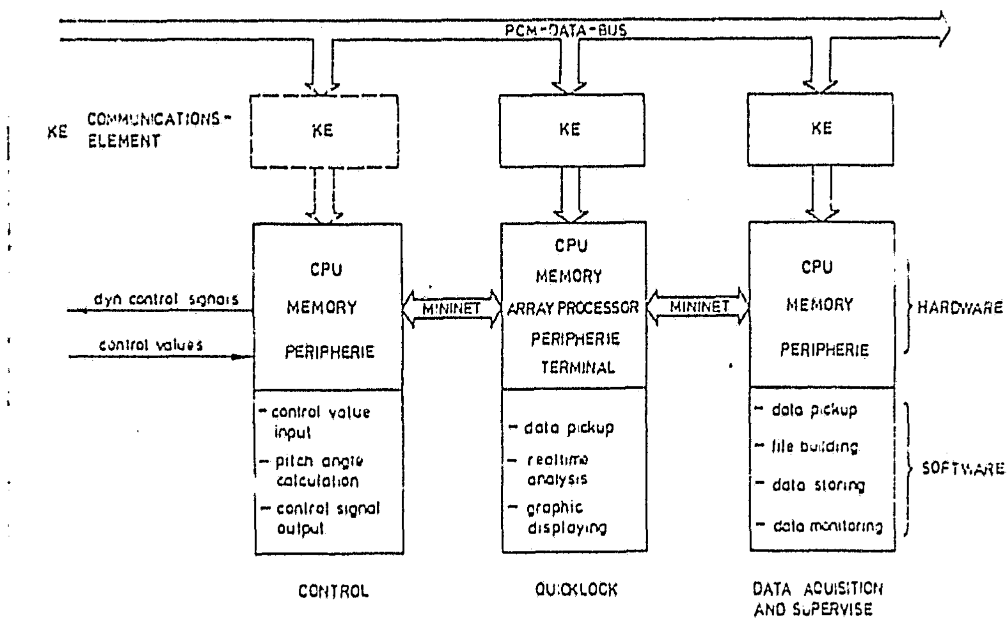


Fig. 19: Hot-Wire Probe in Double-Wire Construction
(X - hot -wire probe).
Key: a. hot-wire probe b. probe tip



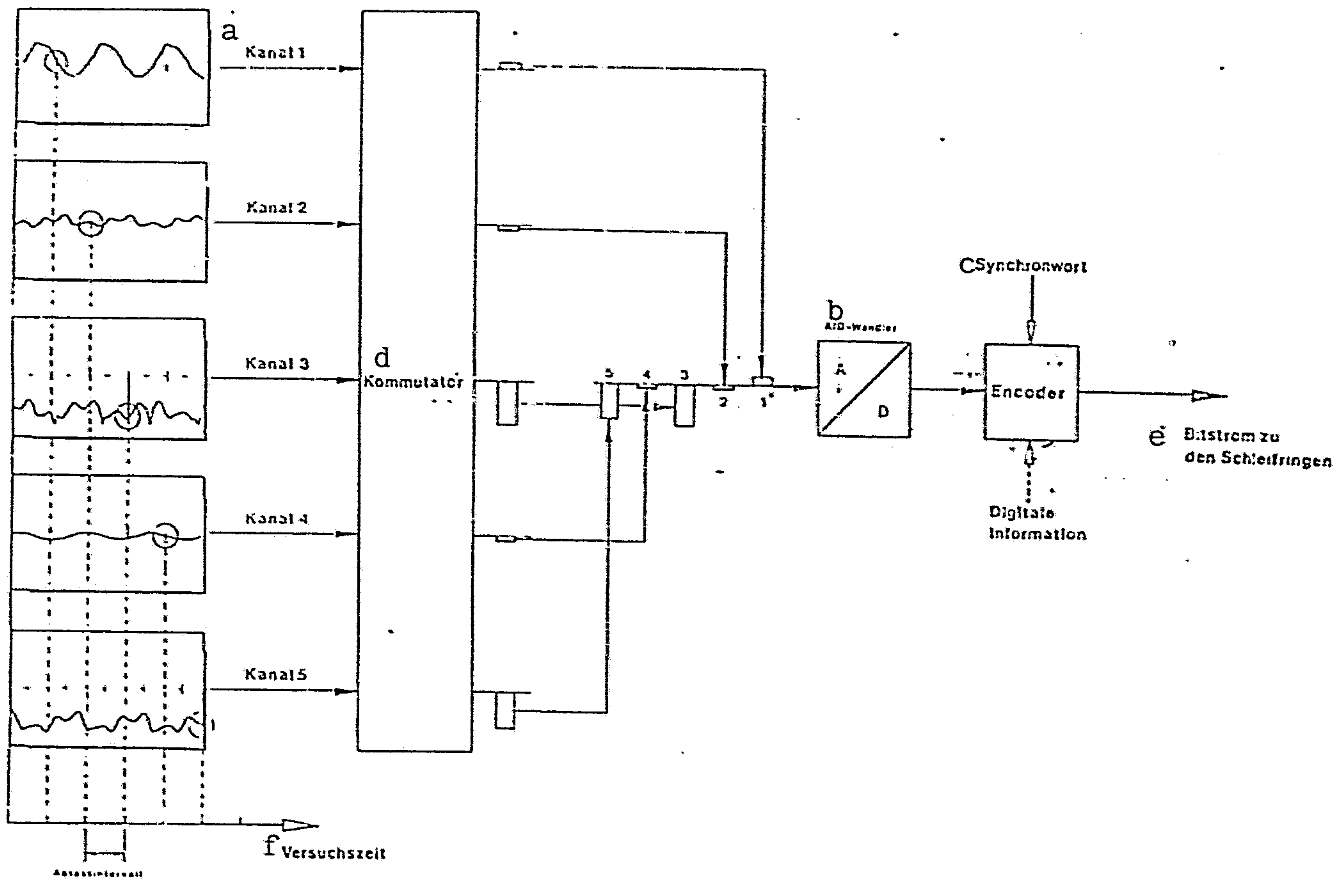


Digital Data Processing and Control System, Block Diagram

Fig. 20: Data Acquisition and Processing an the Rotor Testing Stand.
(see following page for key)

Key for Fig. 20:

a. rotor blade, data
b. rotor balance, data
c. computer
d. control unit
e. record of experiment
f. average values
g. reading rate
h. magnetic plate
i. digital tape
j. terminal printer
k. rapid data evaluation
l. data acuisition and evaluation
   at the rotor testing stand



g Prinzip der Meßwerterfassung

Fig. 21: PCM Signal Processing.

Key: a. channel b. A/D converter c. synchronous word c. commutator
e. bit flow to the slip rings f. trial time g. principle of measured value input

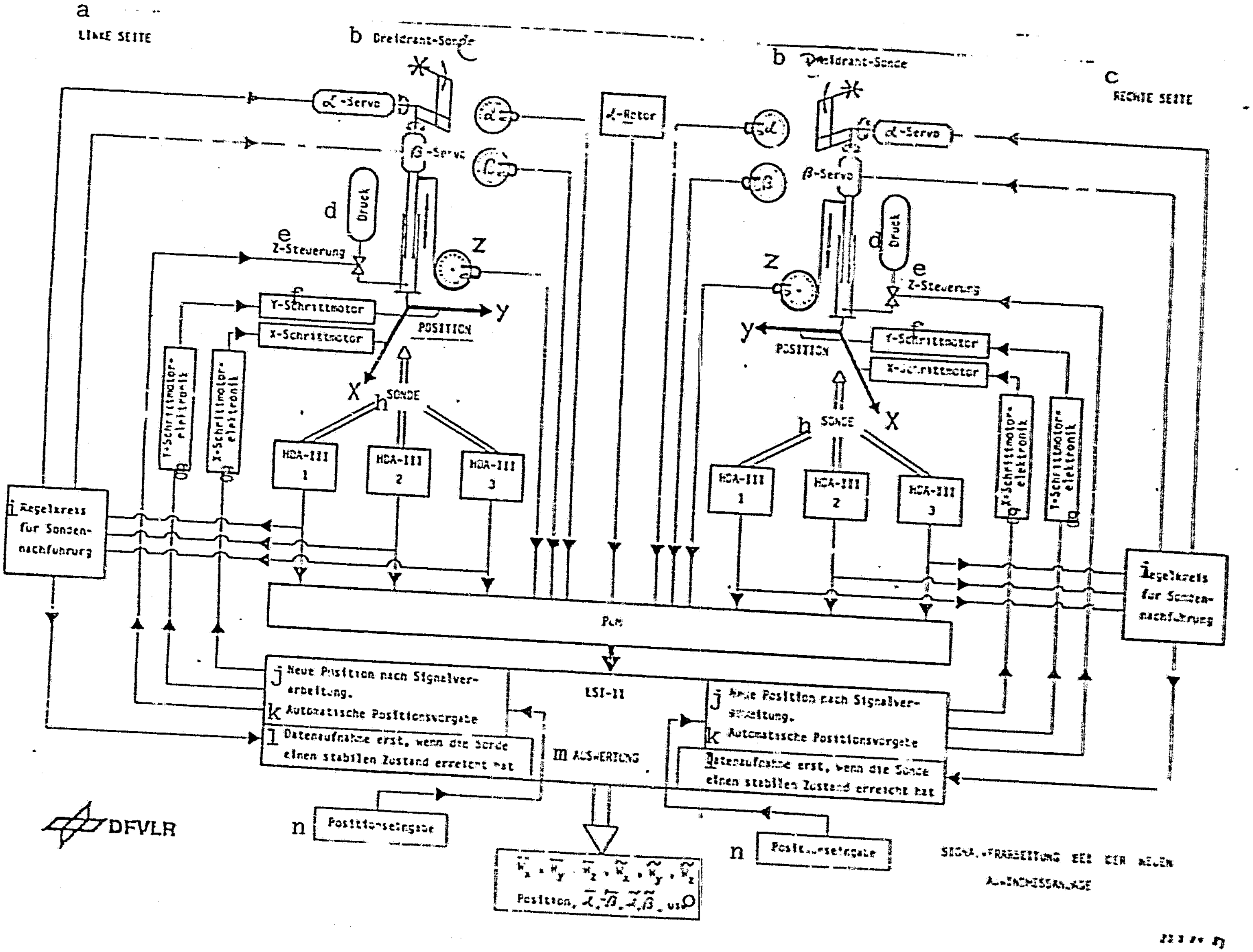


Fig. 22: Signal Processing for the Downwind Measurement Equipment.
(see following page for key)

Key for Fig. 22:

a. left-hand side
b. triple-wire probe
c. right-hand side
d. pressure
e. control
f. step motor
g. step motor - electronics
h. probe
i. closed-circuit for probe guidance
j. new position after signal processing
k. automatic positioning determinal
l. data input only when the probe has achieved a stable condition
m. evaluation
n. input for position
o. etc.