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ELECTRONIC MEASUREMENT OF VARIABLE TORQUES
IN PRECISION WORK TECHNOLOGY

M. Maehr

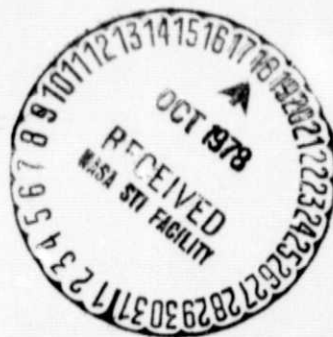
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ELECTRONIC MEASUREMENT OF VARIABLE TORQUES IN PRECISION WORK TECHNOLOGY*

M. Maehr

1. Definition of Problem

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Aside from the classical problems in precision work technology, that is, the measurement of stationary quantities, the measurement of time-variable (dynamic) processes becomes more and more important.

A frequently occurring problem in precision work technology is the determination of the time variation of the torque at rotating parts of mechanisms, such as toothed wheels, couplings, etc. The aim of these measurements is mostly the determination of short-time maxima in the load moments which are crucial in dimensioning shafts, toothed wheel, couplings, and drives.

The knowledge of such load maxima often is the basis for an optimum design of drive controls and for finding the causes of rattles, oscillations, and their elimination. Measuring the reaction moment with the parts of the drive system at rest does not usually

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

lead to correct solutions, although the method has been often suggested; the reason is the fact that the result in general is not correct due to the masses, inertias, and rotational elasticities involved in the problem. The most important results are obtained by directly measuring the torque at the position of interest, say, at a cam plate or a coupling. Thus, this method is preferable in spite of its difficulties.

2. Measuring Torques by Means of Measuring Lengths

2.1. Measuring torques by means of measuring the deformation of shafts

Cam plates are usually placed on a shaft. The most obvious type of measurement would therefore concern the torque at this position and measure the deformation of the shaft without separating the force flux. (By analogy, currents are often measured in electrical engineering through the voltage drop at resistors, without opening the electric circuit for the purpose.) The method is common in engine construction and is shown in Figure 1. The deformation of the shaft due to the torque is measured as a change in the resistance of two wire strain gauges (WSG) oriented along the direction of the principal shear stress; the gauges are simply glued onto the shaft. The connections of these wire strain gauges are made through slip rings in order to make the measurements at a non-movable part of the machine. The variable resistance between the slip rings and the brushes enters the measurement in the form of a disturbance signal, since this resistance is added to the resistance changes due to torsion. Thus, the disturbance amplitude is the larger, the larger the deformation of the wire strain gauge. The limit of these measurements is given by the

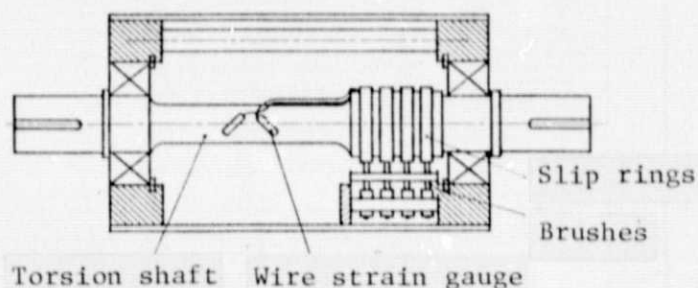


Figure 1. Moment measurement by means of wire strain gauges

departure from linearity of the gauge in use which is, in general, of the order of some 10^{-3} [7]. In the case of engine construction, where the dimension of the units is carried out with the interplay among forces in mind, deformations near that limit are often reached. Figure 2, which is based on a systematic study by Buschmann [1] in Darmstadt, shows that shafts used in precision work technology are heavily overdimensioned by comparison to the classical design of engines, assuming the same amount of torque to be transmitted, and as a consequence they suffer much less torsion.

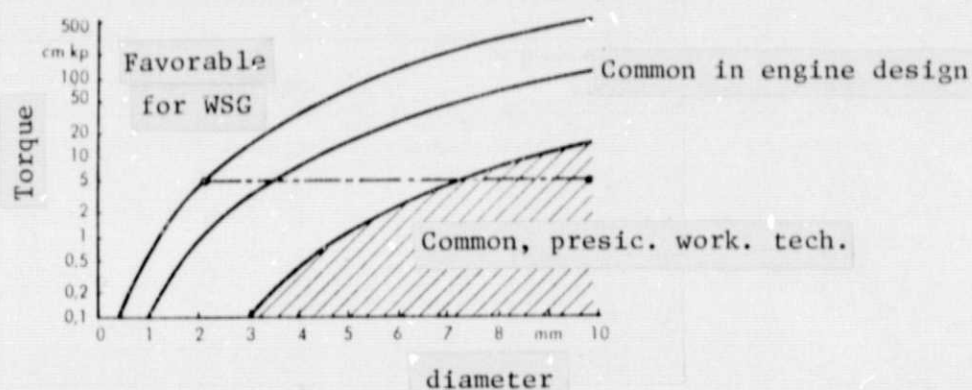


Figure 2. Dimensioning of shafts in engine design and in precision work technology; from [1]

A numerical example may illustrate the situation.

A steel shaft 30 mm long and 10 mm in diameter suffers a torsion of $0.66'$ under a load of 5 kpc. That corresponds to $0.22'$ per cm, corresponding approximately to the length encompassed by the wire strain gauge. The gauge suffers a torsion of $1.6 \cdot 10^{-5}$, which is less by two orders of magnitude than the possible deformation. Even if the disturbance voltages at the slip rings could be completely eliminated, the measurement with this method does not allow for high accuracy, since the resolution of the gauges is only of the order 10^{-4} [2]. In order to utilize the permissible deformation of the gauge to full extent, the torsion angle would have to be about $22'/\text{cm}$ or about 1° for the entire length of the shaft (which had been assumed to be 30 mm). For this purpose, the torque of 5 kpc is too small.

One might consider dressing the shaft; however, this makes the shaft less resistant to bending, and there would be less space to attach the gauges. Another possibility is the use of a hollow shaft with the same exterior diameter. This, in turn, leads to wall thicknesses which are hard to realize. In addition, the portion of the shaft which is used for the measurement becomes much softer than the piece it replaces. In particular in the case of impact processes, the results may be quite inaccurate [3]. Figure 3 shows that the initial pulse of a coupling process does not reach its full amplitude. In addition, there are low-frequency oscillations. /62

2.2. Known suggestions
for measurements
in precision work
technology

We have seen that the methods of engine design cannot simply be applied in precision technology by means of miniaturization.

Let us now review the measurement methods for torques that have been developed in precision work technology.

2.2.1. Wire strain
gauge torque
indicators
according to
Buschmann

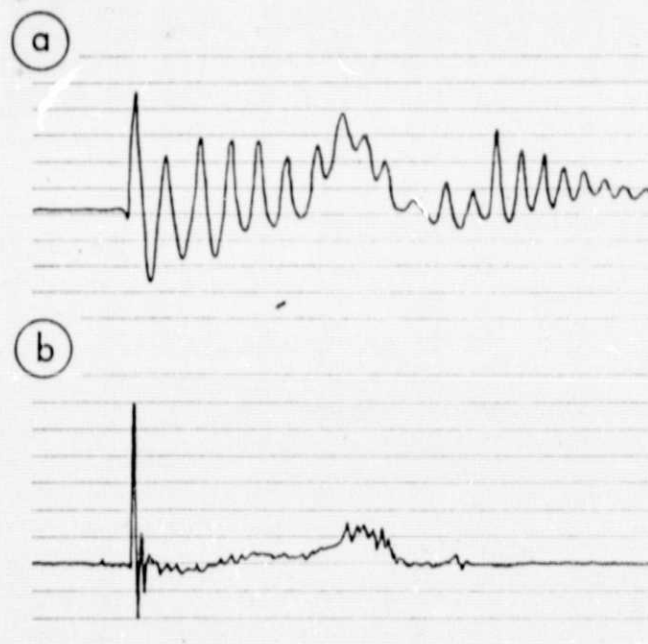


Figure 3. Erroneous measurements due to soft acceptors; from [6]

a) with an intermediate spring;
b) "pathless" measurement with a quartz pickup;
1 division corresponds to about 2.5 kpcm

Figure 4a shows an arrangement with a wire strain gauge as measuring device; by contrast to the arrangements discussed so far, this one can be realized [1]. Nevertheless, in order to fully

utilize the gauge, a torsion of up to 3° is required, whereas the torsion of the comparison shaft was only $0.66'$. Figure 4b shows a more recent development by Buschmann. In this case, the torque to be measured is transformed into a tangential force on a strain tape whose deformation is then measured with a wire strain gauge. The torque indicators that have been constructed on the basis of this principle reach a significant strength. Depending on the dimensions, torsion angles between only $15'$ and $3'$ were reached with a torque of 5 kpcm [1].

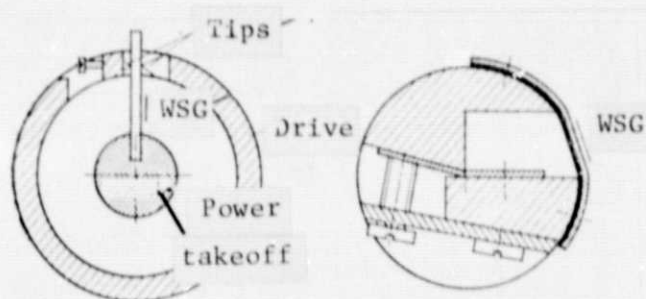


Figure 4a/b. Wire strain gauge indicators according to Buschmann [1]

2.2.2. Electric measurement of the torsion angle

Another possibility is shown in Figure 5 [3]. Here the measurement of the torsion angle of a shaft was carried out either by a capacitive or by an inductive method [4]. Again we have a typical length measurement, and we assume that the measured part must be soft as was the case with the deformation measurement making use of the wire strain gauge (WSG) in order to obtain significant initial signals.

Torque indicators that make use of this measuring scheme are industrially produced. Figure 6 shows an example [5]. According to information from the manufacturer, the torsion angle at nominal torque must still be between 0.3° and 1° , whereas the comparison shaft had $0.66'$; nevertheless, the torque indicator is elegantly

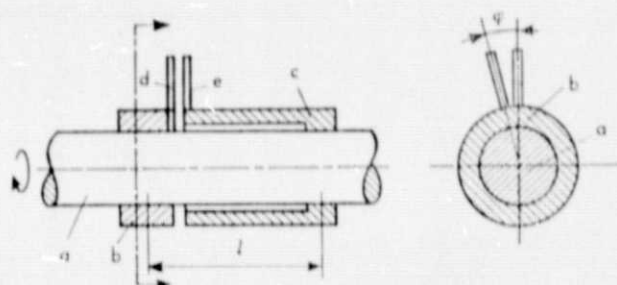


Figure 5. Torque measurement by means of a torsion measurement along a significant length

a — round bar spring; b, c — jackets; d, e — indicators

produced. In the most favorable case, the indicator is stronger by a factor of 10 in comparison with the wire strain gauge indicator, but it is still too soft by a factor of about 30 in comparison with the comparison shaft.

2.2.3. Measurements of the torsion angle by means of measuring the phase angle between two ac voltages

Figure 7 shows a solution which should be of interest for electronics [3].

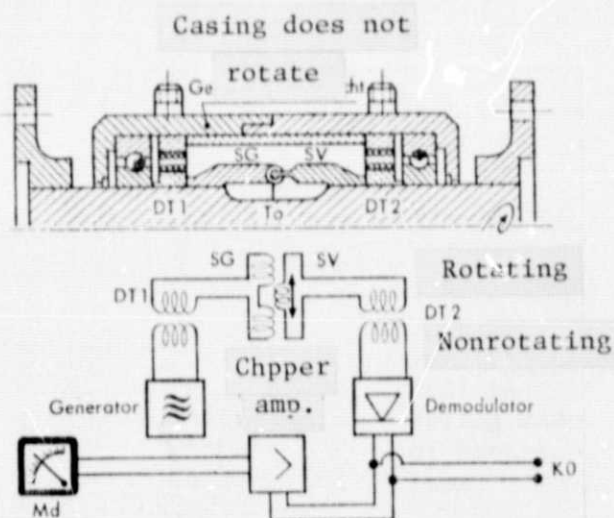


Figure 6. Inductive measurement of the torsion angle (Dr. Stai-ger, Mohilo and Co., manufacturer's diagram)

as discussed above. The originality of the solution is due to the electronic measurement of the torsion angle in the form of a phase angle between two ac voltages. The generators consist of audio tapes and pickups glued to the unit and fed by closed sinusoidal waves.

3. Torque Measurements by Means of Force Measurement

All the methods we have discussed so far use distance sensitive

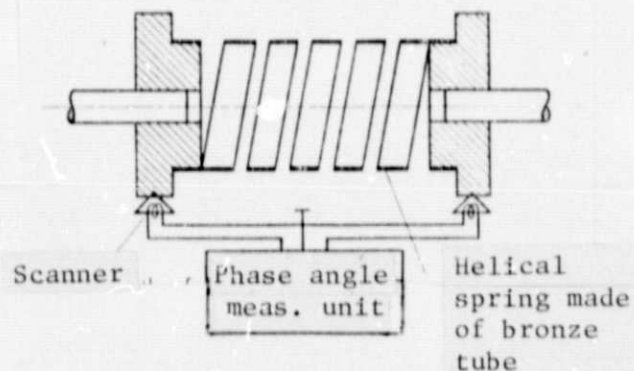


Figure 7. Measuring the torsion angle through the phase angle between two ac voltages [8]

For a dynamical measurement of the torque, the device does not appear to be very useful due to the softness of the spring,

pickups. We have pointed out that in precision work technology the deformation distances are too small in comparison with the sensitivity of the usual distance pickups, so that the signal does not get sufficiently above the noise level.

The required high signal level even in the case of small distances indicates the desirability of force-sensitive pickups. Piezoelectric systems are almost ideally suited for the purpose. They combine a maximum deformation sensitivity among force-sensitive pickups with an extremely high resolution of 10^{-6} [2]. The required high strength is evidenced by the very high limiting frequency which in general is above 100 kHz.

The following considerations may serve to show that quartz crystals are indeed useful for this purpose: a 5 kpc/cm torque with a 1 cm radius causes on the quartz a deformation of about 0.5μ , according to a simple approximative calculation; this corresponds to a torsion of about $0.2'$. The steel shaft which we use for comparison, as before, responds at the same load with a torsion of $0.66'$. Thus, it is in principle possible to produce a torque indicator of the required strength.

3.1. Piezoelectric quartz crystal — measuring shaft

3.1.1. Pickup according to Kuntzl

In principle it is possible to transform the torque into a force by means of a scale balance. Figures 8 and 9 show a version which has actually been produced and which makes use of two quartz crystals in push-pull operation; we shall discuss them in more detail as far as the electronic arrangement is concerned.

3.1.2. Piezoelectric quartz crystal

A piezoelectric quartz crystal is an active source, Mechanical forces are converted into electrical charges. Thus, we have a charge source. A charge source is not something easy to imagine, and for this reason, we show in Figure 10 a substitute schematic.

Due to the internal time constant, a charge that had been affixed suddenly at time zero has essentially disappeared after about 30 minutes.

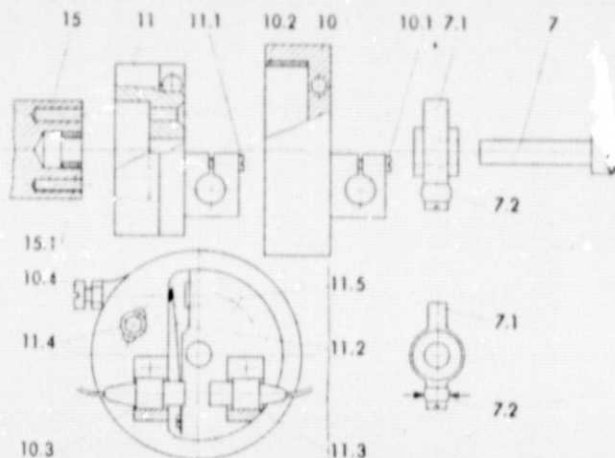


Figure 8. Piezoelectric quartz crystal torque indicator; from [6]:

Details: 7 — drive shaft; 7.1 — drive lever; 7.2 — transmission ball; 10.11 — quartz pickup halves; 10.3, 11.3 — quartz crystals; 10.4 — screw to adjust the preload; 11.2 — leaf spring; 11.4 — stop screw; 11.5 — rubber spring; 15 — drive shaft; 15.1 — teflon socket

The lower limiting frequency of a piezoelectric crystal is above zero [7], as is the case with all active sources; however, this is only of minor importance for dynamical measurements. But it is important that a piezoelectric quartz crystal is in principle not very useful for measuring stationary situations.

The charge affixed to a quartz crystal is a quantity which is very difficult to handle as far as the electronics engineer is concerned. Since even very large forces cause minute deformations of the crystal, the exchanger takes on only tiny mechanical energies. In addition, the efficiency is low, and as a consequence this charge

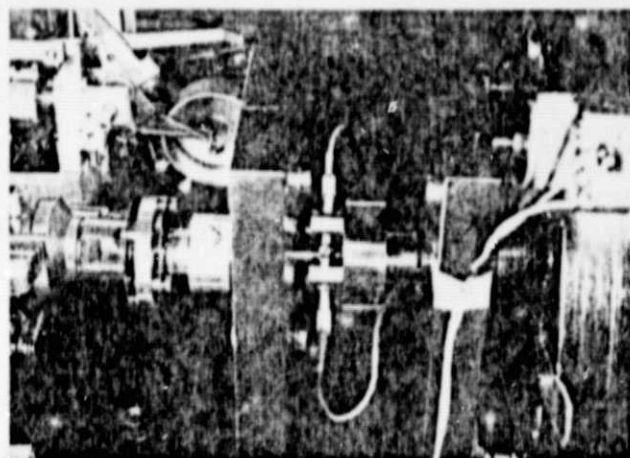


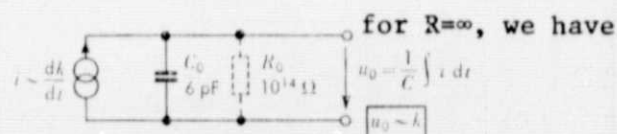
Figure 9. Piezoelectric quartz crystal torque indicator during a measurement with a telex instrument

Charge source is the piezoelectric quartz crystal

$$\text{Force } k \rightarrow q \text{ Charge}$$

$$\frac{d\lambda}{dt} \rightarrow \frac{dq}{dt}$$

Schematic diagram



Internal time constant:

$$\tau_i = R_0 \cdot C_0$$

$$\tau_i = 6 \cdot 10^{12} \cdot 10^{14}$$

$$\tau_i = 600 \text{ s}$$

$$\tau_i = 10 \text{ min}$$

Figure 10. Schematic diagram of a piezoelectric quartz crystal

source can only transmit small amounts of electric energy to the consumer. As a consequence, the source must be adapted through a very high resistance, including optimum insulation resistance, and in turn this requires optimum screening measures. The extremely high voltages present near the crystal add to the problems, if semiconductors are used in the electrical system.

3.1.3. Charge amplifiers

It is suggested that the charge be converted into a proportional voltage. This can be done with the aid of a system of the type shown in Figure 11. This system is called a charge amplifier, even if the name is not really quite correct.

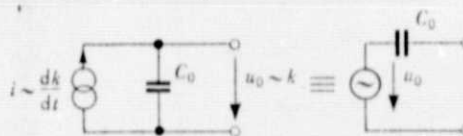
Real operational amplifiers with FET input are indeed very similar to the idealized assumptions:

Input resistance and neutral amplification are extremely high. Values such as $R_e = 10^{11} \Omega$ and $v = 10^5$ are quite workable.

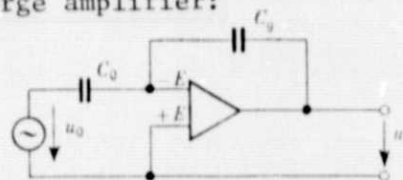
It is similarly possible to achieve sufficiently small values for input current and output resistance, for instance $I_e = 10 \text{ pA}$ and $R_a = 100 \Omega$. In the form of an IC, this unit has an extremely small mass and is very small.

Since even in the FTE case the input current is not zero, a current path is used to channel the small, but finite current. The inverse-feedback resistance may be very large due to the small amount of current. However, a

Piezoelectric quartz crystal:



Charge amplifier:



Ideal operational amplifier: $R_e = \infty$ ($I_e^* = 0$)
 $R_a = 0$
 $v = \infty$
 $B = \infty$

$$U_a = -\frac{Z_g}{Z_0} U_0$$

$$u_a = -\frac{C_0}{C_g} u_0 \quad C_0 \cdot u_0 = q_0$$

$$u_a = -\frac{q_0}{C_g}$$

$$u_a \sim k$$

$$q_0 \sim k$$

Figure 11. The principle of a charge amplifier

compromise will have to be found, since large resistances cause larger zero drift. Even if dc quantities cannot be measured in principle, dc components should decrease relatively fast.

The operation shown in Figure 9 for two quartz crystals requires symmetrical inverse feedback of the type shown in Figure 12.

3.1.4. Transmission of measured values from the rotating shaft

The charge amplifier produces an input voltage which is proportional to the torque. At this point we have to consider the problem of the transmission of measured values on non-moving parts of the instrument. There are four basic possibilities available:

galvanic: slip rings,
inductive: rotational
transmitter
capacitative: cylinder
condenser
telemetric: emitter and
receiver

Slip rings always produce voltage disturbances and unnecessary frictional torques. Mercury transmitters which are available on the shelves are usually too large for applications in precision work technology; they are also very expensive. Rotational transmitters are admittedly sometimes in use; however, they cannot be manufactured in as small a size as cylinder condensers. They were chosen for the instrument since telemetry receivers, due to the necessarily missing screening along the transmission path, accept much more noise.

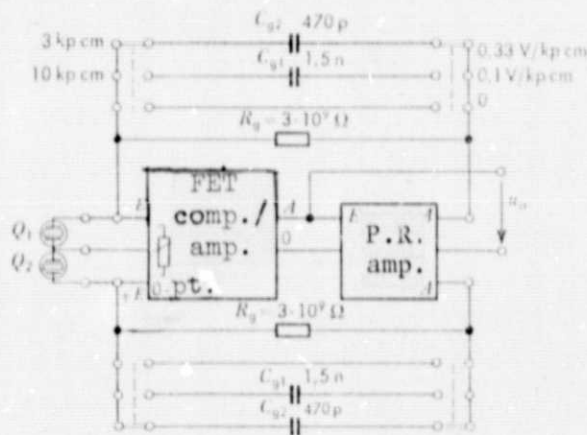


Figure 12. Charge amplifier
for two quartz crystals

comp./amp. — computer amplifier;
P.R. amp. — phase reversal amplifier

Another criterion in deciding the type of transmission method is analog or digital transmission of the signal. Digital transmission is in general much more accurate; in addition, its requirements as the noise level is concerned are much less. On the other hand, in particular on the emitter side where the smallness of the elements is important, analog transmission requires much less effort. The modulation method is easy to choose. Eccentricities of the system to be transmitted cause by necessity an amplitude modulation under rotation; as a consequence, the information must be packaged in the dimension "time". This results in a decreased amount of disturbances. In the case of analog transmission, this requires frequency modulation, whereas in the case of pulsed processes, for instance, pulse duration modulation is to be chosen. /65

The design for the laboratory instrument uses a 10.7 MHz oscillator which is frequency modulated with the aid of a capacitive diode. There is a separator stage behind the oscillator in order to avoid feedback from the output to the oscillator frequency.

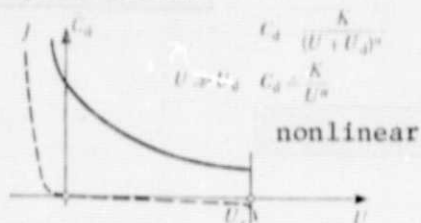
Figure 13 shows the principle of frequency modulation by means of a capacitive diode.

Figure 14 shows the wiring diagram of the emitter.

The initial signal of this emitter is coupled to the receiver by means of the above-mentioned cylinder condenser with one of the layers rotating, the other fixed. The receiver consists of an intermediate frequency amplifier unit with discriminator and dc amplifier behind it. The dc amplifier should have a bandwidth limitation, so that remaining frequencies and the higher-frequency noise and similar disturbances are cut out.

The transmission characteristic may be brought to optimum linearization by wobbling with its own oscillator; at least, there is a three-point contact with the straight line.

Capac. diode:



Linearization via bias volt.:

$$U = U_0 + u_1 \quad U_0 \gg u_1$$

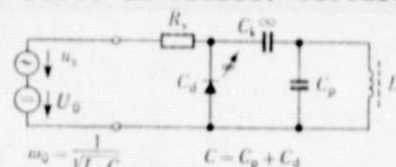
$$U = U_0 \left(1 + \frac{u_1}{U_0} \right)$$

$$C_d = \frac{K}{U_0^\alpha} \left(1 + \frac{u_1}{U_0} \right)^{-\alpha}$$

$$C_d \approx C_{d0} \left(1 - \alpha \frac{u_1}{U_0} \right)$$

$$\frac{dC_d}{C_{d0}} = -\alpha \frac{du_1}{U_0}$$

Capac. diode in oscill. circuit



$$\frac{d\omega_0}{\omega_{0m}} = -\frac{1}{2} \frac{dC}{C}$$

$$\frac{d\omega_0}{\omega_{0m}} = \frac{\alpha}{2} \frac{C_{d0}}{C} \frac{du_1}{U_0}$$

Figure 13. Frequency modulation by means of a capacitive diode

If the screening is complete and the bandwidth properly limited, the noise level can be reduced to values that are at least comparable to that of good FM receivers in good reception areas. The quality of transmission of the FM unit is thus in any case better than that of slip rings.

Figure 15 shows the wiring diagram of the entire measuring chain.

3.1.5. Power supply for the rotating measuring electronics

The measuring electronics rotate together with the shaft; they can be made in very small size. This, however, make sense only if the power supply for the electronics which are also placed on the rotating shaft can be produced with a similarly small size.

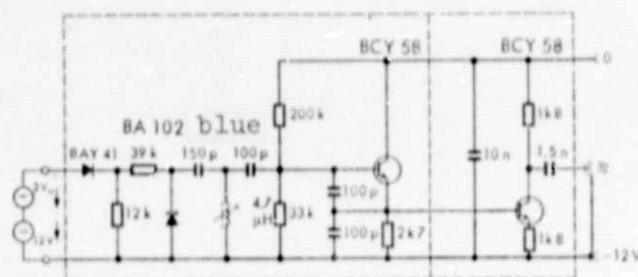


Figure 14. Emitter for measuring values

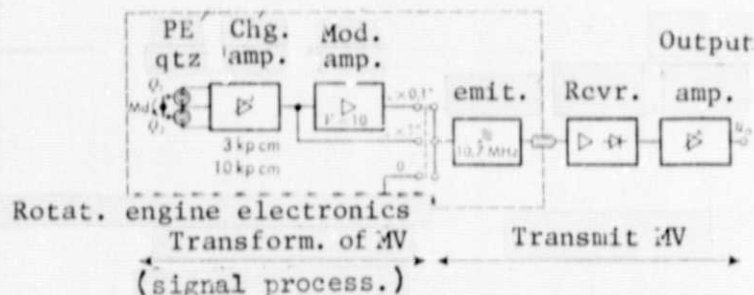


Figure 15. Piezoelectric measuring chain

PE qtz — piezoelectric quartz crystals; MV — measured values

For this reason, batteries are in no case useful. In principle it would be possible to transmit the already stabilized operational voltages to the shaft by means of slip rings; there, they are stabilized once more, and this step does not require a large amount of additional effort. In a laboratory, the slip rings are always carefully tended, and this solution is indeed practical under such conditions. If the unit is used in a plant, however, the existence of a possible spark emitter next to a high-frequency transmitter is dangerous.

3.1.6. Error estimates

The total error consists of a mechanical and of an electrical component.

The mechanical error consists of misalignments and bearing friction errors. Both errors can be kept below 1% by careful manufacturing. In the case of collisional processes of the type occurring during discontinuous coupling of two masses, where theoretically the bearing relative velocity is infinite at the moment of impact, the bearing friction error may be as much as 5%.

/66

The electrical error is the sum of the errors of the single units of the measuring chain.

The linearity of the quartz crystal pickup is guaranteed by the manufacturer to within $\pm 0.3\%$. The eigenresonance frequency is near 100 kHz. Additional frequency errors are thus not expected even in the case of impact processes.

In the case of the charge amplifier, the ohmic inverse feedback results in a lower limit frequency. It is permissible to assume that the low-frequency processes have the repeat period of the rotation number; the lowest frequency should have the value:

$$f_{\min} = \frac{n \text{ (U/min)}}{60} \text{ Hz}$$

This makes it possible to state a minimum time constant of the inverse feedback, so that the damping of this lowest frequency is not more than 0.1%.

The error due to the finite voltage amplification of the operational amplifier is, in the case under consideration, practically the same as the reciprocal of the neutral amplification. The latter varies with frequency, as shown in Figure 16, so that the error shows up in the case of impact processes; but even here it should not exceed 0.1%, assuming that frequencies above 1 kHz are not transmitted in any case by the mechanical system.

The transmission characteristic of the 10.7 MHz line can be made sufficiently linear without particular effort. Measured statically, the departure from linearity of the entire line was nowhere more than $\pm 2.5\%$. The RC component formed by the initial resistance R_v of the capacitative diode and the coupling capacitance of the oscillatory circuit shows low bandpass behavior as far as the modulation signal is concerned. Choosing a sufficiently small time constant, $\tau = R_v \cdot C_k = 7 \mu s$, one can limit the frequency error at 1 kHz to less than 0.1%.

Only in the case of impact loads does the bandwidth limitation of the output amplifier cause a noticeable error. This additional error can be kept below 1% by choosing the appropriate dimensions at 1 kHz.

Figure 17 shows in graphic form the maximum components of the total error due to the single units. The numbers are chosen very conservatively. In addition, it is unlikely that in practice

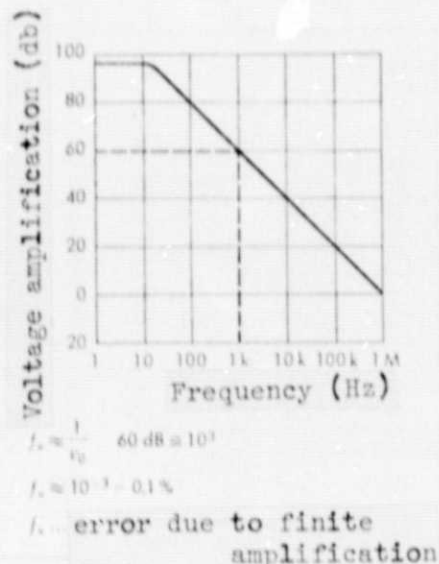
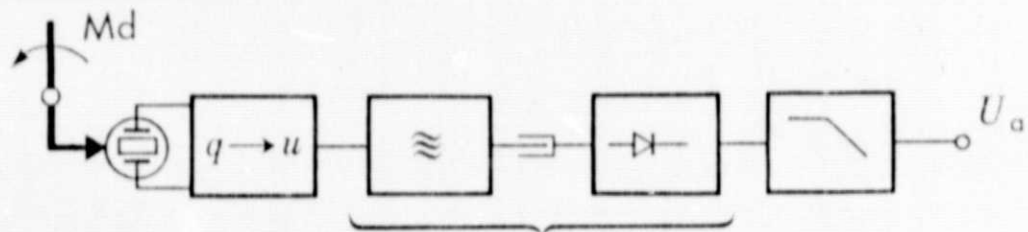


Figure 16. Frequency behavior of an open operational amplifier



w.o. collision :	2 %	0,3 %	0,1 %	2,5 %	0,1 %
w. collision :	6 %	0,3 %	0,1 %	2,6 %	1 %

Figure 17. Error estimate of the single members of the measuring chain

all error components reach their maxima at the same time, and then with the same sign. The quadratic error sum is 3.2% for measurements without impact processes, 6.6% — in the case of impact loads.

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