SYNOPSIS

This report describes two planar-motion mechanisms developed at the Shipbuilding Laboratory of the Delft University.

The first one is intended to study forced harmonic motions of a ship model in the vertical plane.

The second one is used to investigate motions in a horizontal plane, particularly with a view on the research of the steering qualities of ships.

Special attention is paid to the measuring system. A mechanical-electronical Fourier-analysis system allows the measurement of the first, second or third harmonics of the hydrodynamic forces and moments as well in amplitude as in phase-relation to the motion of the model.
Mechanical vibrations do not influence the measurements.

1. INTRODUCTION

In 1955 the first forced oscillation experiments to determine added mass and damping of ship motions were carried out at the Delft Shipbuilding Laboratory. A soft spring connected to a Scotch Yoke mechanism was used to oscillate the ship model; the motions of the model and the oscillator were measured by micro-friction potentiometers and recorded by penrecorders [1] .

In 1960 it was decided to build an oscillator according to the planar-motion system published by Gertler [3]. In this system very stiff force dynamometers are used instead of a soft spring and consequently the motions of the model are practically determined by the oscillator itself.

In principle the determination of the forces and moments can be done in the same way as in the soft spring system. By recording the forces as well as the model motions, it is possible to determine the amplitude and the phase-relations of the forces and moments.
However, it is not accurate to measure the phase of two signals from graphical recordings; in addition, there is noise on the recordings as a result of mechanical vibrations of the towing carriage. It is difficult to eliminate this noise by electronical filtering, because the filters cause a phase shift.
To restore the phase relation all the measuring channels have to be equipped with filters having exactly the same characteristics. In practice this requirement is difficult to fullfil with sufficient accuracy.

A very good solution of this problem is given by Tuckerman [2]. His system is in fact a mechanical electronical Fourier-analyser.
The most important feature of this system is the determination of the in-phase and quadrature components of the measured forces. In this way the phase-relation between the amplitudes are easily obtained from readings on stationary meters, thus avoiding the measurement of graphical recordings. This system behaves as a very steep band-pass filter, without phase-shift; vibrations do not influence the measurements. With regard to the system, as described by Tuckerman, the following modifications are made in our apparatus:

1) To improve the stability of the system the integration circuits, given by Tuckerman, are replaced by chopper-stabilised amplifiers.

2) For frequencies higher than .5 cycle per second, the sine-cosine potentiometers had to be replaced by synchro resolvers. Commercial available high accuracy sine-cosine potentiometers are restricted in rotational speed.
By exceeding the maximum allowed r.p.m. (in most cases 100 rev/min.), this potentiometers are very soon damaged.

3) In consequence of the large time-constants in the integration-circuit, which in fact gives the mean value of the signal, another system has to be used for frequencies below .5 cycles per second. For this range the signal is integrated over exactly 1, 2, 3 or 4 periods of the oscillator and afterwards divided by the time of the integration. This modification is designed for low frequency oscillation in the horizontal and vertical plane, which is important for steering problems.

With these modifications an accurate and reliable measuring system is obtained, which operates satisfactorily.

2. THE VERTICAL OSCILLATOR.

The starting point for the design of the vertical oscillator were the following requirements:

1) frequency of oscillation continuously adjustable between .1 [redacted] and 2 c.s.,
2) eccentricity continuously adjustable between 0 and 60 mm ,
3) at the highest frequency a maximum force of at least 50 kg per strut must be possible,
4) the phase between the vertical motions of the two struts must be adjustable,
5) a true vertical harmonic motion of each strut.

The mechanism consists of a heavy bed-plate on which 2 bearing stools are erected. The horizontal driving shaft carries 2 eccentric disks outside the bearings. Around each of these disks a second disk can slide in a yoke. The yokes are guided in vertical direction by 2 rods with linear ball-bushings. When the driving shaft rotates at constant r.p.m., the yokes and consequently the struts will perform a pure sinusoidally motion in vertical direction. The amplitude of this motion depends on the eccentricity of the 2 disks.

The eccentricity can be varied by means of a micro-meter adjustment. Between the yoke mechanisms a phase-shifting device is incorporated in the driving shaft. On one side the shaft is driven by a geared electromotor. This motor is shunt-wound and delivers 1 hp. The motor has an electronic control for constant r.p.m..

On the other side the resolvers of the measuring system are coupled to the shaft by means of a gear. Figure 1 gives a general view of the mechanical part of the oscillator and figure 2 shows the mounting of the resolvers.

3. THE HORIZONTAL OSCILLATOR.

In principle the same apparatus can be used to oscillate a ship model in the horizontal plane. However, at very low frequencies, as used in the research on steering qualities a large amplitude is necessary when a pure yawing motion is desired. The design of this oscillator differs from the first one in two points:

1) the frequency range is 0.01 to 2 cycles per second. The low frequencies are obtained by employing a second gearbox.
2) the eccentricity is adjustable between 0 and 300 mm.

A crankshaft-slider mechanism is used to obtain a harmonic motion. Between the gearbox and one of the Scotch-Yoke mechanisms a phase-shifting device is incorporated. The outer-side of the drum of this phase shifter is used as a tooth-wheel to drive the resolvers of the computing system.
A photocell is used to give a pulse for every cycle of oscillation. These pulses trigger the gating circuits of the integrating system and are used to measure the period of the oscillation on an electronic time-interval counter. The complete mechanism is inserted in a very stiff frame. This frame can be mounted under the carriage.

The oscillator is shown in Figure 3; Figure 4 gives some details of the Scotch Yoke mechanism.

4. THE MEASURING SYSTEM.

The force, necessary to give a harmonic motion to a shipmodel, is a periodic function of time. The period of this function is equal to that of the motion. The first harmonic of the force function differs in phase with the motion. The higher harmonics can be of interest and the evaluation of these seems of interest in a number of cases. Two force dynamometers are used to measure the forces. These dynamometers connect the struts of the oscillator to the model.

The dynamometers have the same shape as those described by Gertler [3] although strain gauges are used in stead of differential transformers as sensing elements. Heavy top- and bottomplates connect four flexures. The bending of these flexures is measured by eight strain gauges, connected in a Wheatstone bridge. The dimensions are 50 mm cubed and they are machined from a solid block ARMCO 17-4-PH stainless steel.

To perform the analog Fourier analysis, the signal $E(t)$. proportional to the force, has to be multiplied with sin $n\omega t$ and cos $n\omega t$, where ω is the circular frequency of the oscillation and $n = 1$, 2 or 3 to find the first, second or third harmonic of the force. The time-average values of these products represent the in-phase and quadrature components of the force. A more detailed discussion of these formulae and their electronic representation is given in the appendix.

The carrier frequency of the strain gauge bridge is 1000 cycles per second. Representing this carrier by $e_c \sin\omega_c t$, the output of the strain gauge bridge will be $E(t) . e_c \sin\omega_c t$, $E(t)$ representing the time function of the force. This signal is amplified in an a.c. amplifier.
The bridge supply oscillator, balancing circuits of the bridge and a.c. amplifier are incorporated in a "Peekel" strain gauge meter, type 540 DNH. After amplification the signal is fed into the rotor winding of a resolver, which is linked to the drive shaft of the mechanical oscillator. The output of the stator windings are proportional to:

$$E(t) \,.\, e_c \sin\omega_c t \,.\, \sin n\omega t$$

$$E(t) \,.\, e_c \sin\omega_c t \,.\, \cos n\omega t$$

These signals are phase-sensitively rectified, giving voltages, proportional to:

$$e_x = E(t) \,.\, \sin n\omega t$$

$$e_y = E(t) \,.\, \cos n\omega t$$

By integrating these voltages over exactly one period, the mean value is found from:

$$e_{x_o} = \frac{1}{T} \int_o^T e_x \, d\,t \quad \text{and} \quad e_{y_o} = \frac{1}{T} \int_o^T e_y \, d\,t,$$

when $t' \gg T$ the following approximation may be accepted:

$$e_{x_o} = \frac{1}{t'} \int_o^{t'} e_x \, d\,t \quad \text{and} \quad e_{y_o} = \frac{1}{t'} \int_o^{t'} e_y \, d\,t.$$

Differentiating these equations with respect to time we find:

$$e_{x_o} + t \frac{d\, e_{x_o}}{d\, t} = e_x$$

$$e_{y_o} + t \frac{d\, e_{y_o}}{d\, t} = e_y$$

These equotations can be solved with the aid of analogue computer techniques. (See fig. 5). The transfer function of the circuit, given in figure 5, is:

$$-\frac{e_o}{e_i} = \frac{R_o}{R} \frac{1}{1 + \rho R_o C p}, \quad \text{or}$$

$$e_o + \rho R_o C \frac{d\, e_o}{dt} = - \frac{R_o}{R} e_i$$

By means of the potentiometer in the feedback path, the time constant of the total circuit is adjustable between 0 and $R_o C$. The time constant, necessary to get a reasonably stationary condition of the voltmeter which is connected to the output of the circuit, has to be at least 1,5 times the period of the signal. It can be shown that not until a period of 4,6 $R_o C$ seconds after the start of the measurement, the output of the integration circuit reaches its steady-state value. A block diagram of the complete circuit is given in figure 6.

When the oscillation period exceeds 2 seconds, difficulties arise due to the large time constant which should be needed in the integration circuits. Therefore another integration system is used in case of oscillation in the horizontal plane. Instead of the mean value of the multiplied and rectified signal, an integration is performed over exactly 1, 2, 3 or 4 periods. By dividing this value afterwards by the time interval of the integration, the mean value is found.

Between the output of the a.c. amplifier and the input of the resolver a gating circuit is inserted. This gating circuit is commanded by pulses of the oscillator and is opened during exactly one or more oscillation periods. This means that we determine:

$$\int_0^{mT} e_x\, d\, t \quad \text{and} \quad \int_0^{mT} e_y\, d\, t.$$

T being the period of the oscillator, m being 1, 2, 3 or 4.

The integration is again carried out by a chopper stabilised amplifier; the circuit is shown in figure 7. The transfer function of this circuit is:

$$- \frac{e_o}{e_i} = \frac{1}{R\,C\,p} \quad \text{or,}$$

$$- e_o = \frac{1}{RC} \int_o^t e_i \, d\,t.$$

The gating circuits are commanded by a bistable multivibrator. As soon as a pulse from the photocell of the oscillator reaches the multivibrator, this changes its state and the gates are opened.

A second pulse of the photocell, following exactly after m periods of the oscillator, changes the multivibrator to its original state and the gates are closed. At the same time the input to the multivibrator is blocked and the integrators are clamped in a "hold-position". A new measurement is possible only by pressing a reset button, deblocking the input to the multivibrator and resetting the integrators to zero.

Between the photocell and the input of the multivibrator a chain of two multivibrators is inserted. Herewith it is possible to open the gates at choice over 1, 2, 3 or 4 periods of the oscillator. In figure 8 the diagram of the gating circuit is shown.

ACKNOWLEDGEMENT

The design of these oscillators is the result of a close cooperation of the staffmembers of the Shipbuilding Laboratory of the Delft University. The design of the mechanical part was carried out by Mr E. Baas and Mr A. Roest.

APPENDIX

The time function of the signal from the dynamometer which is superimposed on the carrier frequency is:

$$E(t) = \sum_{k=1}^{\infty} A_k \sin (k\omega t + \phi_k) + B \sin (x\omega t + \phi_x)$$

where:

ω = angular frequency of the oscillator

$k\omega$ = any harmonic of ω (k=1, 2, 3, ...)

$x\omega$ = any other frequency, not harmonically related

ϕ_k = phase angle between the k^{th} harmonic of the force and the motion

ϕ_x = a time phase between the motion and a not harmonic part of the signal.

The modulated signal will be:

$$E(t)\ e_c \sin \omega_c\ t$$

ω_c being the angular frequency of the carrier frequency (see fig. 9).
This signal is fed to the rotor of a resolver. The outputs of this resolver are:

$$z_1(t) = E(t)\ .\ e_c \sin \omega_c\ t\ .\ \sin n\ \omega\ t$$

$$z_2(t) = E(t)\ .\ e_c \sin \omega_x\ t\ .\ \cos n\ \omega\ t \qquad \text{(See fig. 9).}$$

After phase-sensitive rectifying, we obtain:

$$e_x = E(t)\ .\ \sin n\ \omega\ t \qquad \text{and}$$

$$e_y = E(t)\ .\ \cos n\ \omega\ t \qquad \text{(See fig. 9),}$$

while:

$$E(t) = \sum_{k=1}^{\infty} A_k \sin (k\omega t + \phi_k) + B \sin (x\omega t + \phi_k)$$

$$e_x = \left[\sum_{k=1}^{\infty} A_k \sin (k\omega t + \phi_k) + B \sin (x\omega t + \phi_k) \right] \sin n\omega t$$

$$e_y = \left[\sum_{k=1}^{\infty} A_k \sin (k\omega t + \phi_k) + B \sin (x\omega t + \phi_x) \right] \cos n\omega t$$

Considering only the sine component, we find:

$$e_x = \sum_{k=1}^{n-1} A_k \sin (k\omega t + \phi_k) \sin n\omega t + A_n \sin (n\omega t + \phi_n) \cdot \sin n\omega t$$

$$+ \sum_{k=n+1}^{\infty} A_k \sin (k\omega t + \phi_k) \cdot \sin n\omega t + B \sin (x\omega t + \phi_x) \cdot \sin n\omega t$$

or:

$$e_x = \sum_{k=1}^{n-1} A_k \sin k\omega t \cdot \sin n\omega t \cdot \cos \phi_k + \sum_{k=1}^{n-1} A_k \cos k\omega t \cdot \sin n\omega t \cdot \sin \phi_k$$

$$+ A_n \sin^2 n\omega t \cdot \cos \phi_n + A_n \cos n\omega t \cdot \sin n\omega t \cdot \sin \phi_n$$

$$+ \sum_{k=n+1}^{\infty} A_k \sin k\omega t . \sin n\omega t . \cos \phi_k + \sum_{k=n+1}^{\infty} A_k \cos k\omega t \cdot \sin n\omega t \cdot \sin \phi_k$$

$$+ B \sin x\omega t \cdot \sin n\omega t \cdot \cos \phi_x + B \cos x\omega t \cdot \sin n\omega t \cdot \sin \phi_k$$

Now the integration $\frac{1}{T} \int_o^T e_x \, dt$ is carried out, T being $\frac{2\pi}{\omega}$:

$$\frac{1}{T} \int_o^T e_x \, dt = \frac{1}{T} \int_o^T \sum_{k=1}^{n-1} A_k \sin k\omega t \cdot \sin n\omega t \cdot \cos \phi_k \, dt$$

$$+ \frac{1}{T} \int_o^T \sum_{k=1}^{n-1} A_k \cos k\omega t \cdot \sin n\omega t \cdot \sin \phi_k \, dt$$

$$+ \frac{1}{T} \int_o^T A_n \sin^2 n\omega t . \cos \phi_n \, dt + \frac{1}{T} \int_o^T A_n \cos n\omega t . \sin n\omega t . \sin \phi_n \, dt$$

$$+ \frac{1}{T} \int_o^T \sum_{k=n+1}^{\infty} A_k \sin k\omega t \cdot \sin n\omega t \cdot \cos \phi_k \, dt +$$

$$+ \frac{1}{T} \int_o^T \sum_{k=n+1}^{\infty} A_k \cos k\omega t \cdot \sin n\omega t \cdot \sin \phi_k \, dt$$

$$+ \frac{1}{T} \int_o^T B \sin x\omega t . \sin n\omega t . \cos \phi_x dt + \frac{1}{T} \int_o^T B \cos x\omega t . \sin n\omega t . \sin \phi_k \, dt$$

For $k \neq n$, $k \neq o$ and $n \neq o$, the following integrals are all equal to zero:

$$\int_o^T A_k \sin k\omega t \cdot \sin n\omega t \cdot \cos \phi_k \, dt = 0$$

$$\int_o^T A_k \cos k\omega t \cdot \sin n\omega t \cdot \sin \phi_k \, dt = 0$$

$$\int_o^T A_n \cos n\omega t \cdot \sin n\omega t \cdot \sin \phi_n \, dt = 0$$

$$\int_o^T B \sin x\omega t \cdot \sin n\omega t \cdot \cos \phi_x \, dt = 0$$

$$\int_o^T B \cos x\omega t \cdot \sin n\omega t \cdot \sin \phi_x \, dt = 0$$

The final result will be:

$$\frac{1}{T} \int_o^T e_x \, dt = \frac{1}{T} \int_o^T A_n \sin^2 n\omega t \cdot \cos \phi_n \, dt,$$

or:

$$\frac{1}{T} \int_o^T e_x \, dt = \frac{1}{2} A_n \cos \phi_n$$

In the same way it is shown that:

$$\frac{1}{T} \int_o^T e_y \, dt = \frac{1}{2} A_n \sin \phi_n$$

These terms are proportional to the in-phase and quadrature components of the n^{th} harmonic of the force.

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(W&S 5137)

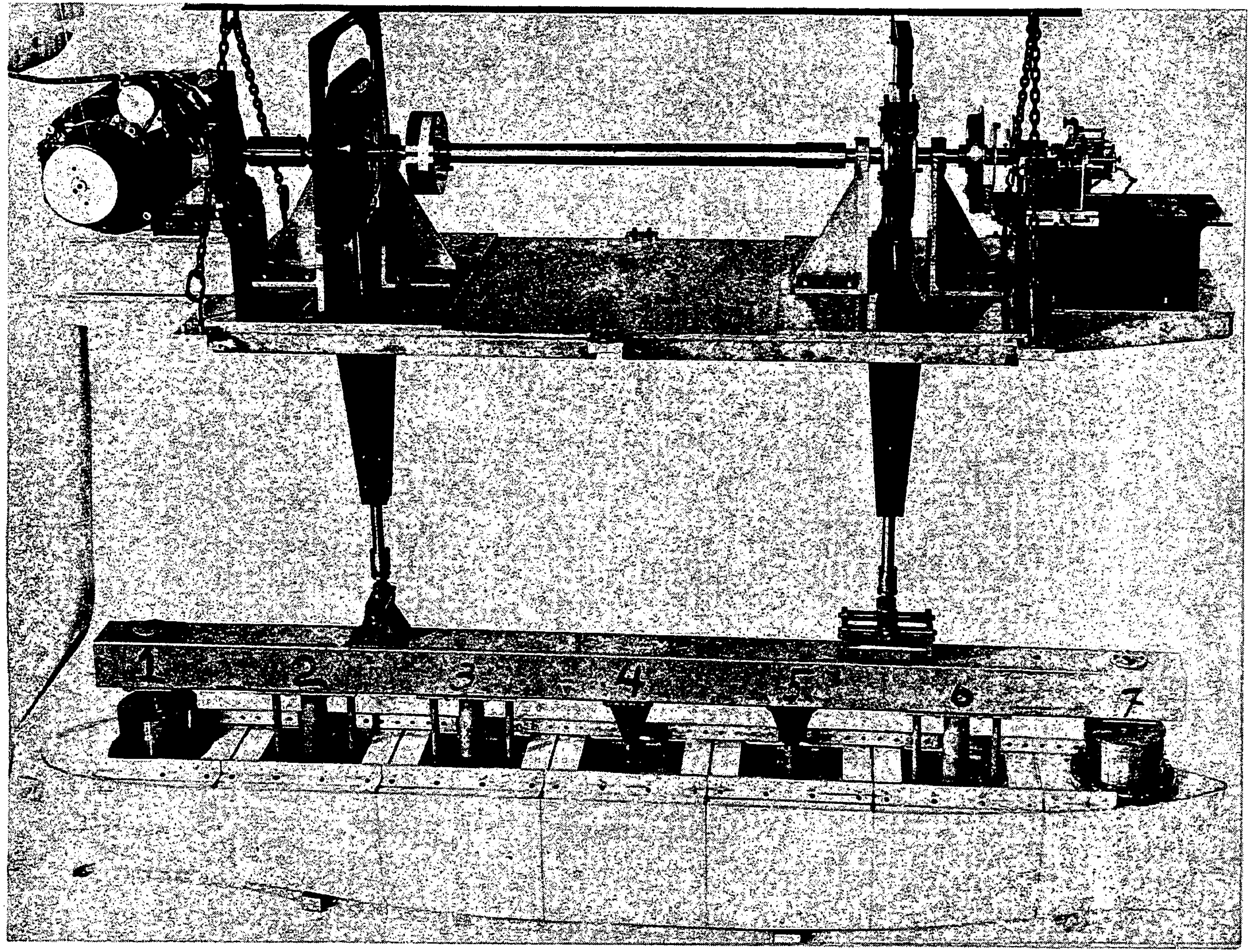


FIG. 1

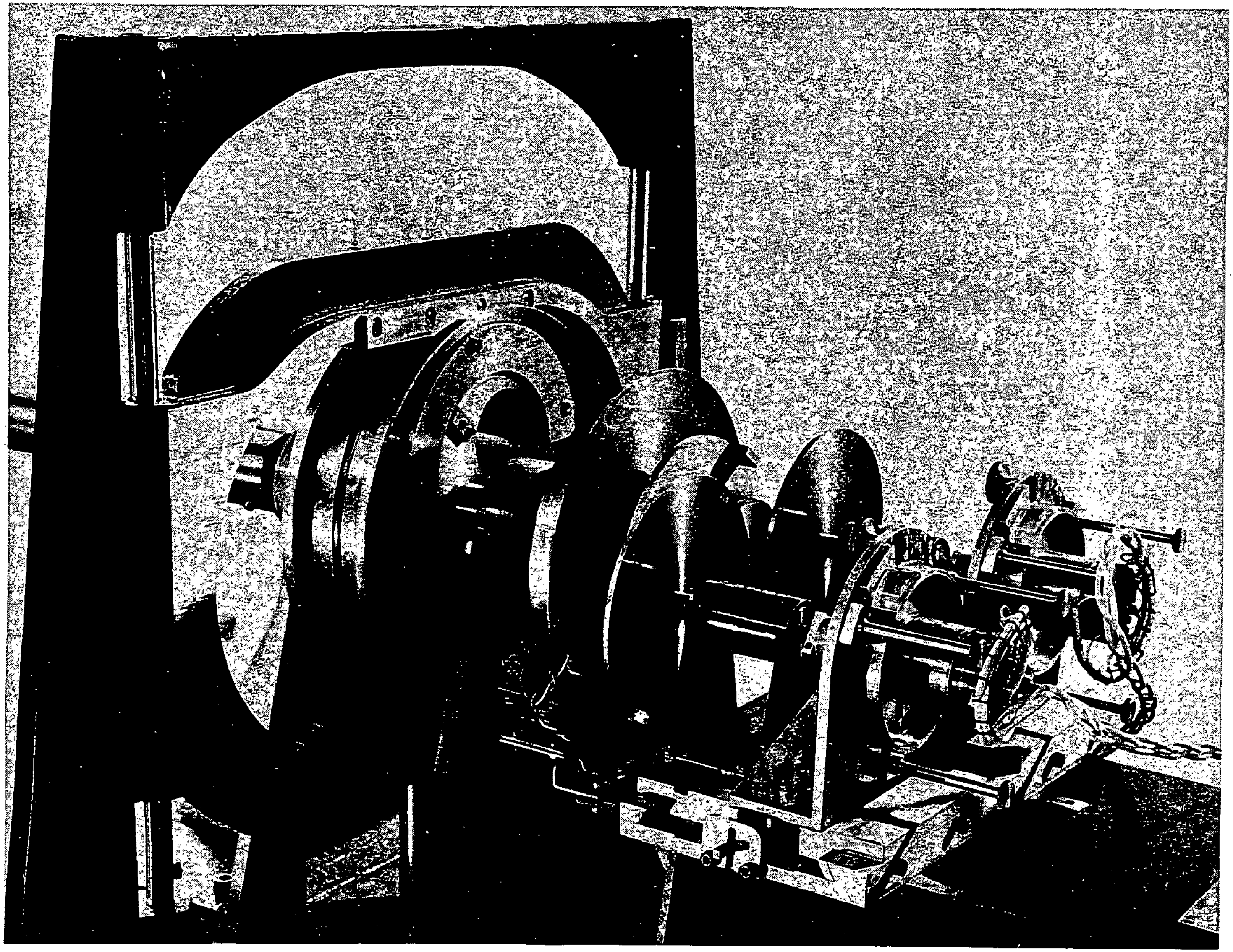


FIG. 2

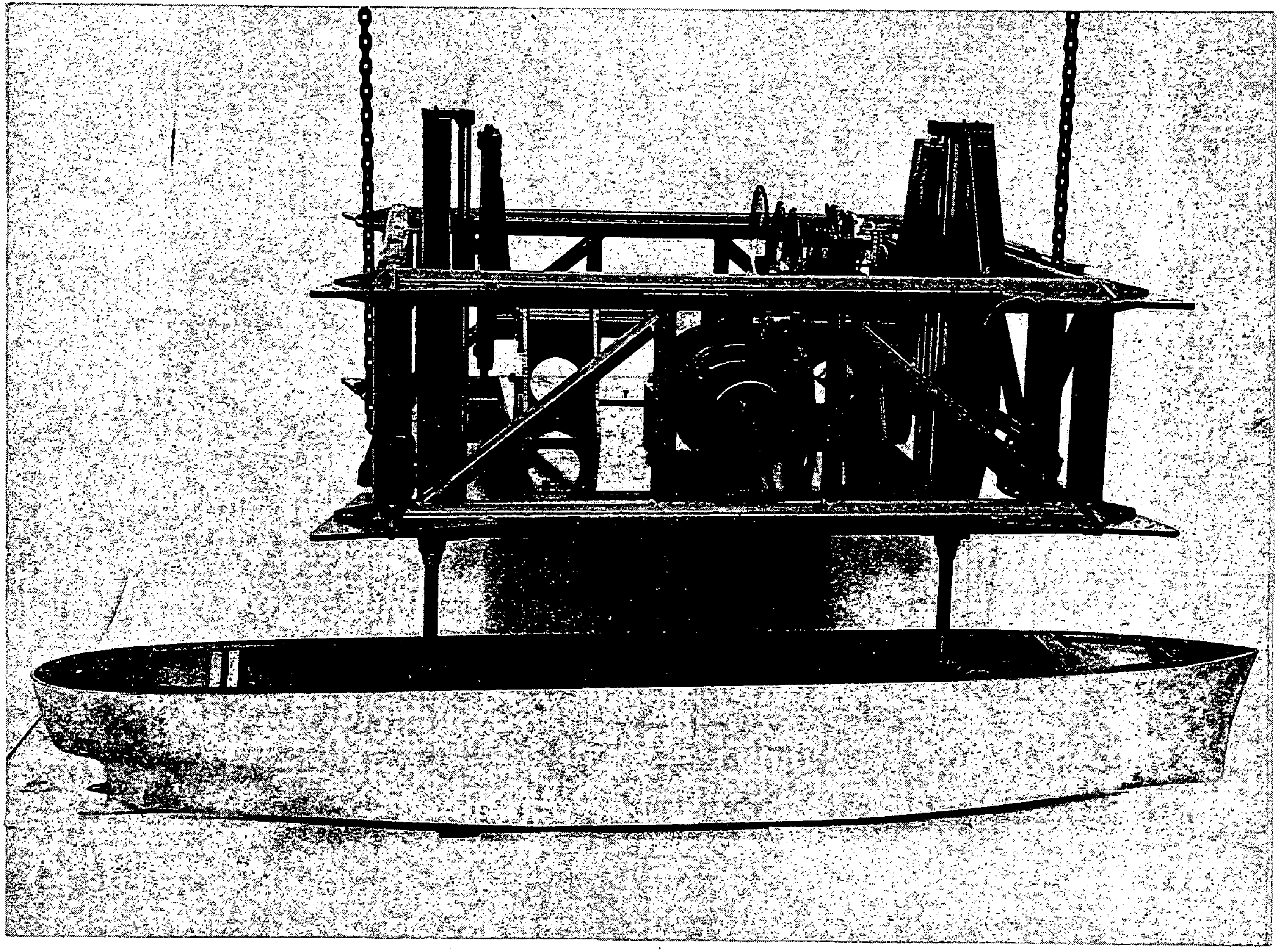


FIG. 3

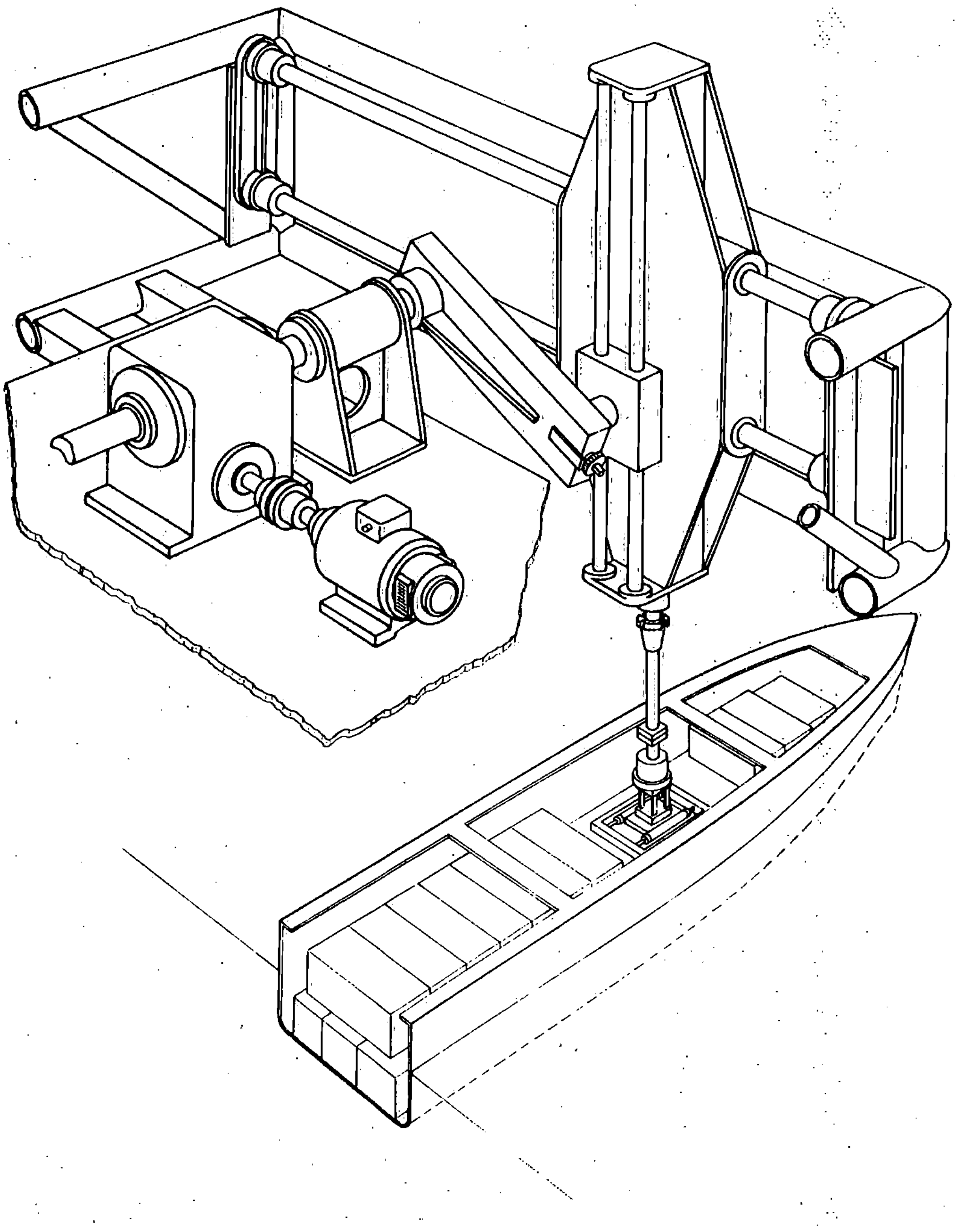
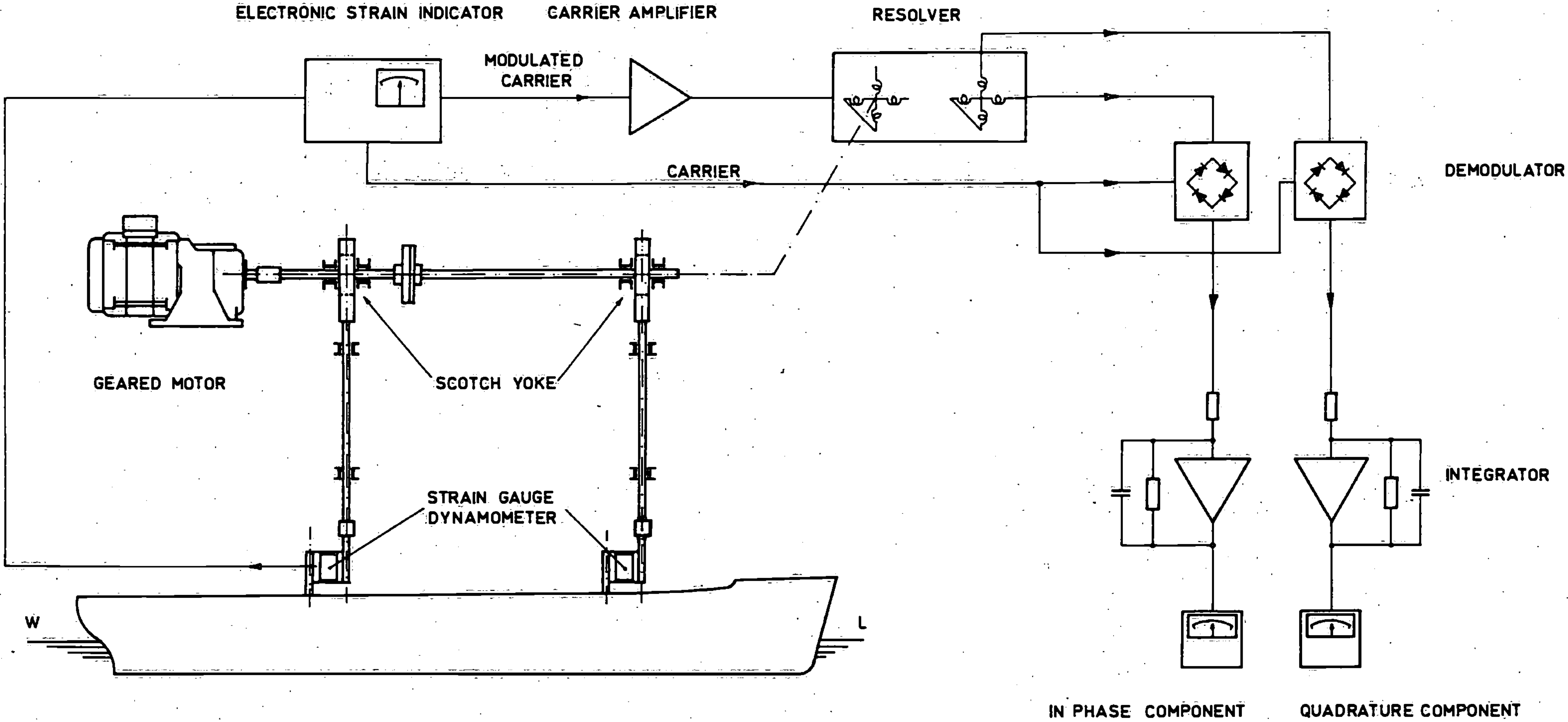


FIG. 4



PRINCIPLE OF EXPERIMENTAL SET_UP

FIG. 6

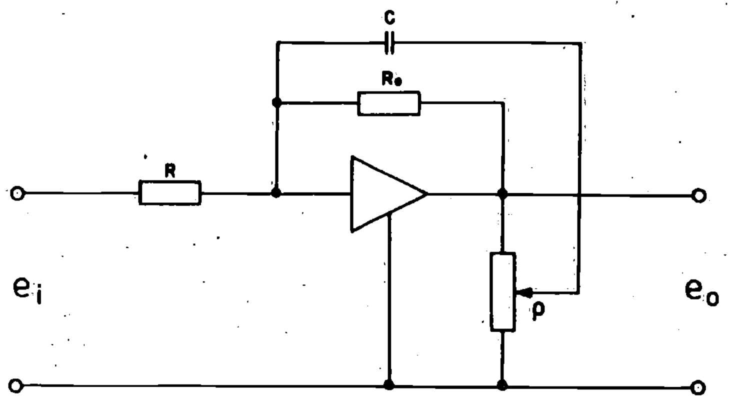


FIG. 5

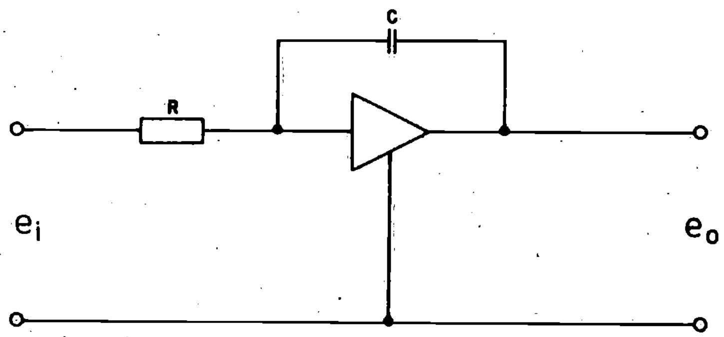


FIG. 7

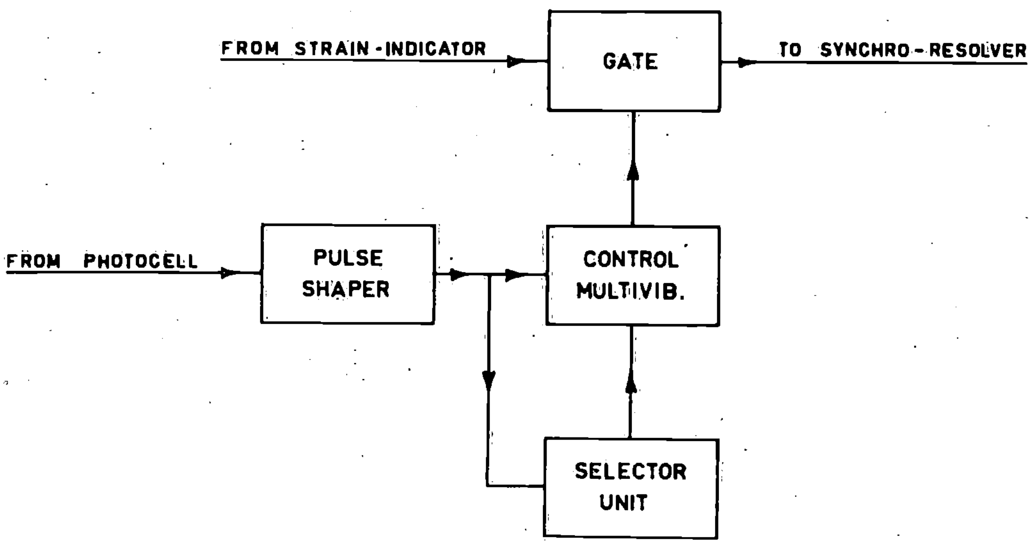


FIG. 8

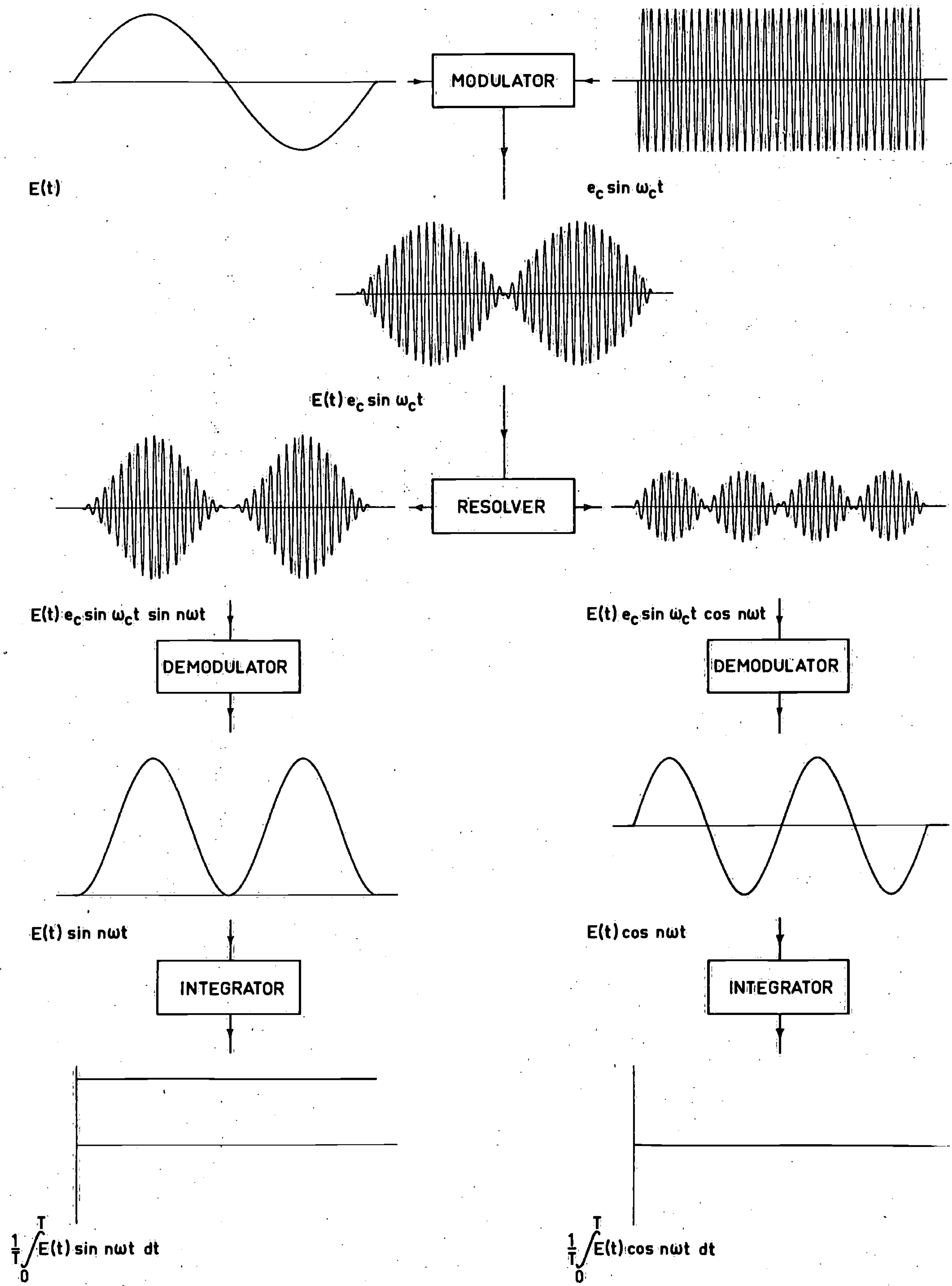

MODULATOR
E(t)
$e_c \sin \omega_c t$
$E(t)\, e_c \sin \omega_c t$
RESOLVER
$E(t)\, e_c \sin \omega_c t \ \sin n\omega t$
$E(t)\, e_c \sin \omega_c t \ \cos n\omega t$
DEMODULATOR
DEMODULATOR
$E(t) \sin n\omega t$
$E(t) \cos n\omega t$
INTEGRATOR
INTEGRATOR
$\frac{1}{T}\int_0^T E(t) \sin n\omega t \ dt$
$\frac{1}{T}\int_0^T E(t) \cos n\omega t \ dt$

FIGURE 9