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NASA TN D-4590

A PIEZOELECTRIC TRANSDUCER FOR MEASURING CARDIAC AND GROSS MOTOR ACTIVITY OF SMALL ORGANISMS

by Vernon L. Rogallo, Robert S. Jenkins, and Gordon J. Deboo

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1968

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SUMMARY

A sensitive-piezoelectric transducer has been developed for biological applications. The transducer system incorporates both mechanical and electrical noise rejection features. The mechanical feature is achieved by a dual arrangement, essentially two transducers, one of which senses the organism activity and noise while the second senses only the noise. Subtraction of the output of the individual transducers results in a cancellation of the environmental noise. The electrical noise rejection is achieved by low-noise preamplifiers with differential input to reject 60 Hz. A low-noise-RC-active filter is used to eliminate frequencies outside the bandwidth of interest.

It was found that the rejection features provided sufficient discrimination against environmental noise to allow the transducer to be used in a normal laboratory environment. The instrument is sufficiently sensitive to measure heart rates in insects, reptiles, mammals, and developing chick embryos as young as 3 days.

INTRODUCTION

The use of a piezoelectric transducer to measure heart rate of avian embryos has been described in reference 1. The useful sensitivity of that instrument was limited by noise from the environment. As a consequence, soundproof chambers and special mounting provisions were required in order to obtain data from young embryos. Also the heartbeat waveform was distorted by the highly resonant response of the transducer. In view of the potential of the transducer as a biological research tool, development to eliminate these limitations was continued and an instrument was produced which can obtain useful rate and waveform data from avian embryos as young as 4 to 5 days without requiring special control of the environmental noise. The instrument can be readily adapted for studies of activity of numerous types of organisms ranging from insects to small mammals.

Presented herein is a complete description of the transducer including the arrangement for the rejection of mechanical common-mode noise, calibration techniques, and the instrument performance characteristics. Typical test results utilizing avian embryos are presented to show the application of the transducer as a ballistocardiograph.

INSTRUMENT DESCRIPTION

The Basic Instrument

The avian-embryo heart-rate detector described in reference 1 has been redesigned specifically for use in a noise environment. Figure 1 is a photograph of the instrument as adapted for avian embryo studies, and figure 2 is a detailed isometric drawing. The piezoelectric elements act in the dual capacity of motion-sensing elements and of springs in the spring-mass system. The elements support the weight of the mass as columns, and are sensitive to motion in the horizontal direction. The piezoelectric columns used as springs and sensing elements are polycrystalline modified-lead-zirconate-titanate ceramic. Design information for the mechanical and piezoelectric elements of the instrument are given in reference 2.

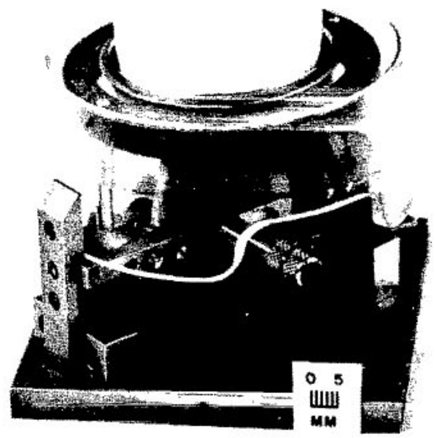

Figure 1.- The ballistocardiograph with egg in basket.

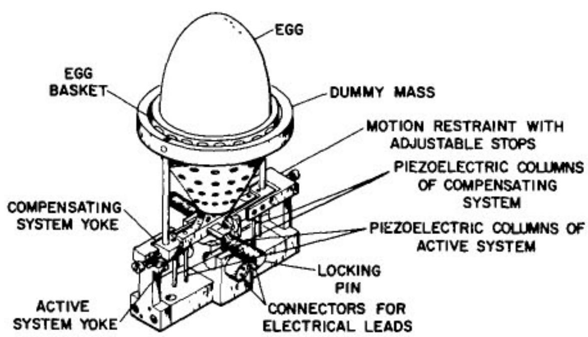

Figure 2.- Schematic diagram of avian ballistocardiograph.

A shortcoming of the previous detector was its sensitivity to externally produced acceleration. To avoid this problem, a dummy transducer and the specimen-supporting transducer are mounted on the same base and their outputs are electronically subtracted to eliminate acceleration caused by external sources. For good common-mode rejection it is important that the active and dummy transducers be as similar as possible, with their supported mass and their centers of mass and support points as nearly coincident as possible. This similarity was achieved by designing the dummy transducer concentrically around the specimen transducer, and by keeping the corresponding supporting columns attached to the base in very close proximity to each other. The specimen transducer, designed to support an egg, moves in response to forces induced on the egg shell by the embryo and in response to environmental accelerations coupled through the air and the instrument base. If the dummy and specimen transducers respond equally to environmental effects, only the motions induced by egg activity will remain when the electrical outputs are subtracted.

The instrument can be further isolated from environmental vibrations by the conventional procedure (i.e., by placing it on a platform supported by a soft spring suspension). A soft suspension having a natural frequency of the order of 1 Hz, both laterally and vertically, can be provided by four 0.25 meter lengths of latex rubber tubing connected to a 1.5 kilogram platform which supports the transducer. This simple suspension is very effective in reducing vibration transmissibility over the frequency range of interest pertinent to avian embryo research.

Transducer Design

An accurate mathematical description of the transducer performance would necessarily include the effects of mechanical coupling associated with support compliance, acoustical coupling, air-damping, etc. To avoid the spurious responses resulting from differences in phase and amplitude introduced by such effects when the transducer is used with biological specimens of different masses could require careful readjustment of the dummy mass and damping characteristics. By sacrificing sensitivity of the instrument, however, it is possible to design the piezoelectric beams so the first resonant frequency is sufficiently high that these spurious effects are negligible at the frequency regime of interest. To a first approximation, the response of the instrument in the regime well below resonance is given by the equation.

$$F = Kx$$

where

F the response resulting from the applied force

K the spring constant of the piezoelectric columns

x the displacement

Since F represents the applied force, the acceleration, a, of the mass free to move, M, is readily determined from

$$F = Kx = Ma$$

Because the output at low frequency of a column (both ends fixed) transducer is proportional to the relative displacement of its ends, this configuration should allow a simple method of measuring the acceleration of a test specimen.

It may be noted in figure 2 that each pair of piezoelectric columns is rigidly attached to a yoke and a base. Thus forces transmitted to the yoke or base cause a lateral movement of the yokes always parallel to the base, and the piezoelectric columns bend symmetrically about their midpoints (in "double cantilever bending"). (See ref. 2.) The equal and opposite curvature introduced by this bending induces opposite and canceling charges on the two longitudinal halves of the piezoelectric electrodes on each side of a column.

The electrodes on the columns are therefore interrupted at the column midpoint, and the electrode halves that pick up the same sign of potential are connected in parallel.

With this arrangement, the voltage output from the piezoelectric element is that of half a column, and the capacitance is twice that of half a column. For the column used, the output voltage E_o at low frequency is:

$$E_o = \frac{3}{8} \frac{LF}{Wt} g_{31}$$

where

F the total applied force

g_{31} the piezoelectric constant of the column material

L the length of the column

t the thickness of the column

W the width of the column

(Units are the MKS system)

The total force, F, is the result of specimen acceleration forces, F_s, and of forces introduced by the environment, F_e. Thus if the two transducers are of identical sensitivity, the difference in their outputs is given by the equation:

$$E_o = E_s - E_e = \frac{3}{8} \frac{L}{Wt} g_{31}[(F_s + F_e) - F_e]$$

$$\frac{E_o}{F_s} = \frac{3}{8} \frac{L}{Wt} g_{31}$$

$$E_o = \frac{3}{8} \frac{LM}{Wt} a g_{31}$$

The mass and acceleration of concern here are the totals for the specimen and its holding fixture. If the biologically active element being studied is a small portion of a complex structure (as in the case of an embryo chick heart in an egg), the interpretation of the output voltage waveform may require detailed knowledge of the coupling between the active element and the rest of the system. In many applications, however, the output voltage waveform can provide useful information without complex analysis.

Although it is desired to realize the maximum possible sensitivity (i.e., max E_o) the criterion of the design dictates that the resonant frequency of the transducer must be sufficiently high so that the frequency range of interest is within the flat response of the transducer. In addition, the structural integrity of the transducer must also be considered for the supported specimen mass and anticipated applied forces. Therefore the design necessitates a compromise. For the subject transducer, the piezoelectric design mechanical and electrical parameters (i.e., compliance, natural frequency, and voltage constant) were obtained from reference 2. The transducer design resulted in an instrument having a natural frequency of 125 Hz for a specimen mass of 57 grams (average mass for chick embryo research) and a sensitivity of 0.3 mV/dyne.

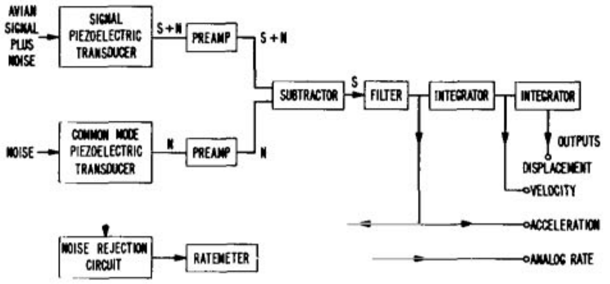

Figure 3.- Block diagram of the electronics system.

The electronics system is shown in block form in figure 3. The output from each transducer is amplified by a low-noise preamplifier having a gain of 10 with differential input to reject 60 Hz. The two resulting signals are then processed by a differential amplifier so that only the difference in magnitude is obtained. To compensate for differences in sensitivity of the two systems and differences in specimen masses, provision has been made to adjust the dummy signal intensity for optimum noise rejection. Since the signal level varies, and since the amplification of weak signals is desired before they are processed, the balancing and summing unit incorporates selective gains of 1, 10, or 100.

Past experience has indicated that most of the energy spectrum of the avian embryo heart beat lies below the tenth harmonic. Therefore, the platform and its surgical-cord suspension are designed to provide a limiting lower frequency response of 1 Hz, and the piezoelectric transducer is designed to provide a first resonance of approximately 125 Hz. Flat response within these limits is provided by the RC active band-pass filter with 3 dB pass-band points of 3.5 and 68 Hz. The overall effect of the mechanical response of the instrument and the electrical response of the filter will be discussed subsequently.

Provisions for integrating the signal are included for indicating specimen velocity and displacement.

MEASUREMENTS AND TEST RESULTS

Calibration

A convenient means for applying precisely controlled calibration forces is available in the piezoelectric columns. Reference 2 gives a procedure whereby charge is applied to one of the columns which is subsequently discharged, resulting in a repeatable pulse force to the system. The response obtained by this technique is a pulse almost indistinguishable from that obtainable by an impact on the basket. A typical calibration curve is shown in figure 4. The linearity and repeatability obtained by the induced-deflection technique were excellent until the signal became indiscernible from

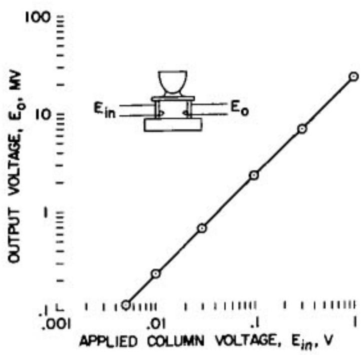

Figure 4.- Instrument response obtained by induced-displacement technique.

the noise. These data were obtained with the instrument installed in an incubator as it would be in avian embryo ballistocardiography.

After it was established from the foregoing calibration that the system was essentially linear, the sensitivity of the instrument was determined by testing its response to a known force. To accomplish this, a technique was devised for producing low-level quasi-static accelerations. A simple parallel-platform pendulum with four relatively long parallel strings was utilized. The pendulum is, by virtue of its suspension, constrained to keep the platform always horizontal. The instrument was placed in the center of the platform with its sensitive axis alined parallel with the lateral displacement to be impressed by the platform. The platform was displaced a measured amount, then released, so that the pendulum would swing freely. The lateral acceleration is given by the expression:

$$a = g\theta_0 \cos \omega t$$

where g is the acceleration of gravity, θ_0 is the initial angle of deflection, and ω is the angular frequency. The sensitivity of the instrument was found to be 0.30 mV/dyne. This value was in excellent agreement with values obtained by other calibration techniques and with values computed from manufacturers' parameters on the piezoelectric columns.

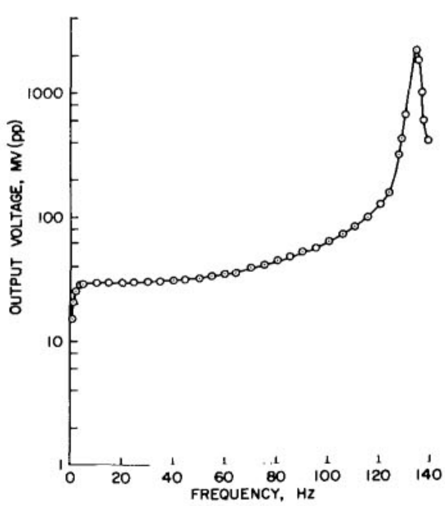

Figure 5.- The instrument response with preamplifiers; constant applied sinusoidal voltage to piezoelectric column of basket transducer.

Frequency Response

The combined frequency response of the mechanical sensor and the preamplifier is shown in figure 5. For these data one of the columns of the specimen transducer was driven with a sinusoidal voltage of constant amplitude and varying frequency while it was mounted on a rigid, massive support. Adding a band-pass filter with response as shown in figure 6 modifies the overall response (fig. 7) so that it is generally insensitive to the undesirable effects of mechanical resonance. The combination results in a relatively flat response from 3 to 60 Hz. It can be seen that the resonances of the platform suspension and instrument are essentially eliminated.

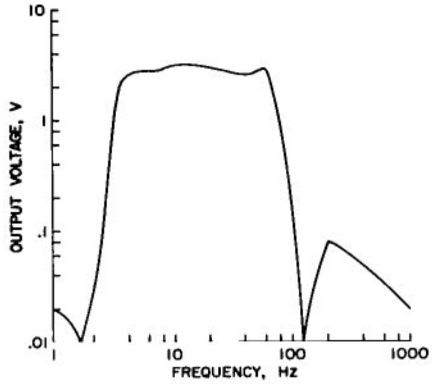

Figure 6.- Band-pass filter response.

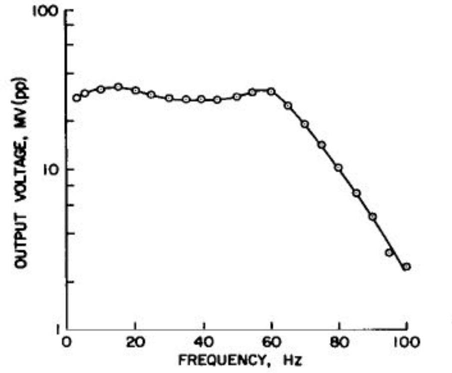

Figure 7.- The ballistocardiograph response for avian embryo research, complete system, constant applied sinusoidal voltage to column of basket transducer.

Effectiveness of Common-Mode-Noise Rejection

Two techniques were used to evaluate the effectiveness of the common-mode noise rejection feature.

Measuring the effectiveness of mechanical common-mode-noise rejection as a function of frequency requires an excitation device that can produce precisely controlled displacement at any given frequency over the operating range. No such device was available for handling the combination of high sensitivity and low load capacity of the instrument. A device was improvised which employed a folded-pendulum platform suspension. The platform on which the instrument was mounted was driven sinusoidally by a small electronically controlled shaker. The instrument output was recorded with and without the common-mode-noise rejection, that is, with electronic subtraction of dummy signal from the basket, and with the basket signal only. Rejection ratios varying from 25 to 60 dB, depending on frequency, were obtained. The variation in rejection was attributed to the excitation of cross-axis modes in the platform suspension.

The second technique involved looking at the background noise of the instrument system set up as it would be in actual use, but with an inert mass substituted for the egg. The noise level with and without common-mode-noise rejection was recorded (not simultaneously). As seen in figure 8, the common-mode-rejection feature lowered the overall noise level by about one order of magnitude.

The most effective measure of the improvement introduced by the common-mode rejection feature was directly measured avian embryo heart rates. In one particular noisy location for instance, the instrument of reference 1 could obtain no heartbeat information from chick embryos younger than 12 days. In the same location, the new ballistocardiograph gave good waveform, as well as heart rate, for 6-day-old chick embryos. Similar results have been obtained in other areas having random noise levels. A typical example of the efficiency of the common-mode-noise rejection is shown in figure 9 for a 6-day-old

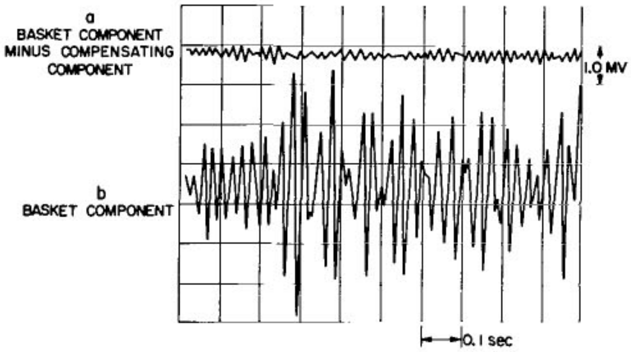

Figure 8.- Common-mode-noise rejection effectiveness; inert mass.

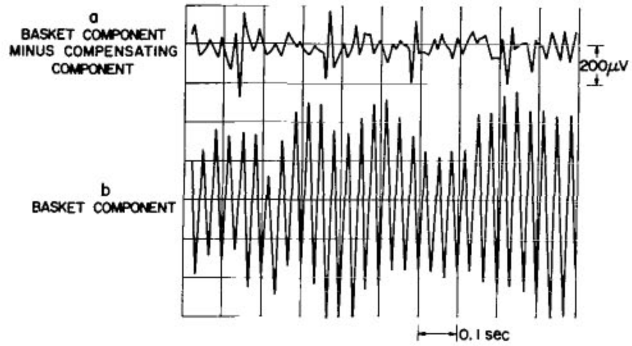

Figure 9.- Common-mode-noise rejection effectiveness; 6-day quail embryo.

quail embryo. The two traces shown here were obtained simultaneously by use of two identical electronic systems except that the dummy-signal subtraction was omitted in the lower trace. A clearly discernible heartbeat is seen in the upper trace; in contrast, none can be seen in the lower trace.

Discussion

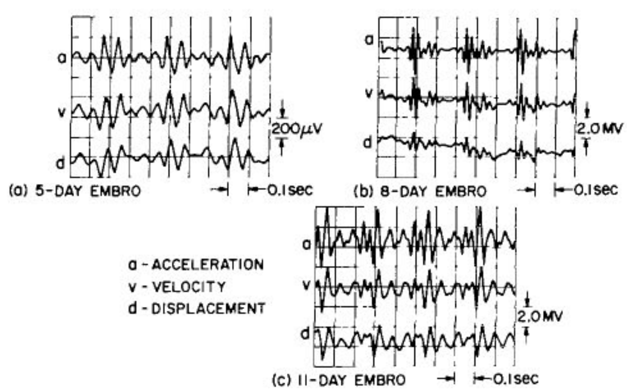

Figure 10.- Acceleration, velocity, and displacement responses of embryos of various ages.

It was of interest to compare the ballistocardiographs of chick embryos of various ages. Through the use of signal-conditioning equipment previously described, acceleration, velocity, and displacement waveforms have been obtained simultaneously. Typical results are shown in figure 10. The responses for any given embryo change within short intervals of time and are greatly different for embryos of different ages. A group of embryos of the same age exhibit similar responses and will repeat a given pattern many times within relatively short periods of time. Some of the variability undoubtedly results from the fact that the embryo is free to reorient itself continuously with respect to the sensitive axis of the instrument.

Although the significance of the waveforms is currently unknown because no attempt has been made by biological researchers to correlate the responses with embryo development, significant differences were often noted between normal embryos and ones with abnormal cardiac activity to predict the probability of mortality. A typical example is shown in figure 11. Figure 11(a) represents the typical acceleration pattern for an 11-day embryo that survived and hatched as an apparently normal chick. Figure 11(b) shows the response of a second embryo of the same age that is quite abnormal. It may be noted that one expected beat is actually missing, and that the beat amplitude and rate

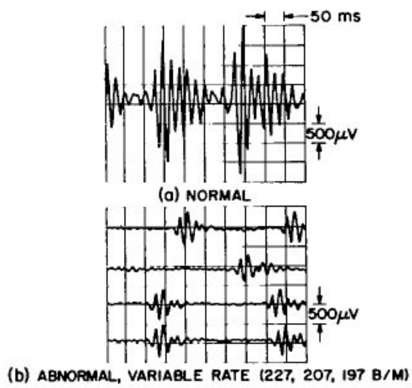

Figure 11.- Comparison of the response of a normal and abnormal 11-day embryo.

for the abnormal embryo are considerably lower and vary from beat to beat. This embryo died an hour after these records were taken.

Narrow band filtering can often be used when the heart rate is of prime importance and when the normal full-frequency-range background noise precludes the ability to discern it. A tunable filter of 20 Hz bandwidth was found to be quite satisfactory for measuring the heart rate of 3- and 4-day embryos in the presence of background noise with predominant frequencies from 27 to 31 Hz.

It is emphasized that using this instrument to measure activity of an organism such as an avian embryo does not harm the organism in any way. In research on embryo chicks, therefore, measurements can be made under controlled environmental conditions, either intermittently or continuously through the incubation period from an age of 3 days until they hatch.

The importance of minimizing physical injury to the embryo is evident from a comparison of embryonic heart rate obtained by the conventional probe technique and by ballistocardiography shown in figure 12. These data were obtained by Mr. J. R. Cain and Dr. Ursula K. Abbott of the Department of Poultry Husbandry, University of California (ref. 3).

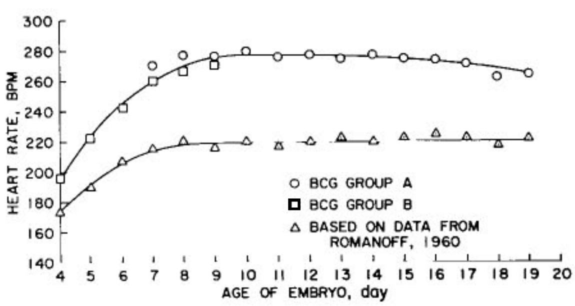

Figure 12.- Chick embryo heart rates during development.

Figure 13 illustrates the usefulness of continuous heart rate recording. From these data, a correlation of the chick embryo heart rate and the periodic environmental temperature change is evident.

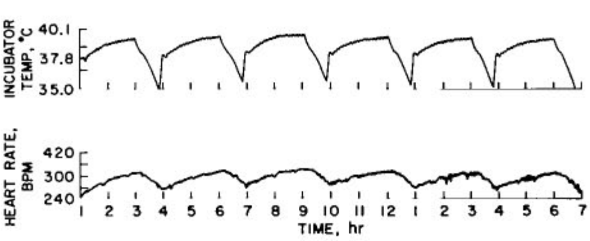

Figure 13.- Correlation of chick embryo heart rate with periodic environmental temperature changes obtained by automation.

Although the instrument has been demonstrated as an avian embryo ballistocardiograph, it can easily be simply adapted for studies of other organisms. Currently, at the Ames Research Center, for example, the biorhythms and heart rates of the lizard are being monitored continuously for periods as long as 3 weeks. The instrument has also been used to measure the heart rates of the cockroach, butterfly, snail, newt, baby chick, and young rat.

CONCLUDING REMARKS

Tests of the piezoelectric transducer used as a ballistocardiograph indicate the following:

The output of the transducer is directly proportional to the applied force and hence acceleration can be readily computed.

The frequency response can be made adequately flat over a given band width by the use of filters.

The mechanical feature for rejecting common-mode noise rejection was demonstrated to be sufficiently effective to allow the transducer to be used in a normal laboratory environment.

Since an organism is not restrained or harmed in any way, measurements can be made either intermittently or continuously over relatively long periods of time.

Slight modifications of the transducer allow measurement of cardiovascular and gross motor activity of a variety of species of biological organisms.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, February 28, 1968
125-24-02-07-00-21

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