INSTRUMENTATION AND CONTROL
OF THE M.I.T. ROWING TANK

by

JESSE BARUCH LIPCON

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ABSTRACT

This thesis concerns the development of systems for the new M.I.T. rowing tank which will simulate rowing on the tank and provide instrumentation to give the coach an objective means for choosing his varsity boat.

In attempting to simulate real rowing on the tank, it is found that the tank itself has a lagging time response, characterized by a time constant of 2.8 seconds. Thus, it is possible to use feedback to the pump to correctly simulate the average velocity, but it is impossible to simulate the quick variations around average velocity, so that the oarsman does not feel the boat "jump at the catch". In order to allow for this, a feedback system is postulated in which the men sit on a platform which moves as an actual boat would, and is prevented from leaving the tank by "drag bodies" in the water, which is pumped by at the correct average velocity. This system is analyzed and found to be satisfactory for simulating real rowing on the tank.

Under the category of instrumentation, circuits are designed which take information from strain gauges mounted on the oarlock pins to compute the integral of force over time (impulse) that each oarsman has contributed to the progress of the boat during a particular practice run, and to determine when a given man has begun his stroke early or late with respect to the stroke man. These circuits have been built and tested in the lab, and have worked in breadboard form. At the time of writing, a hardware system has been built to test the instrumentation in a two-man shell on the river, but it is not yet operational.

Acknowledgement

I would like to take this opportunity to thank my thesis advisor, Professor Truman S. Gray, for the aid he has given me. Always willing to lend an ear, he has provided much encouragement, as well as many helpful suggestions.

Additional invaluable aid has also been gotten from Wayne Haase on differential amplifiers and from Ray Petit, whose parallel work on computer simulation of rowing provided many useful insights.

Great thanks are also owed to Debbie Peretz for her selfless work in typing the thesis.

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Chapter 1 - Background and History

The problem of simulating rowing while off the water and of finding means to evaluate objectively the skills of an individual oarsman have been close to the hearts of crew coaches since the advent of boat racing.

A variety of "rowing machines" is now on the market, each claiming to represent the feel of real rowing more than all the others. While these may be better than nothing, several colleges in the United States have attempted to simulate rowing in a better manner by constructing tanks, equipped with pumps to move the water past a stable platform on which the oarsmen sit. These tanks suffer from two main difficulties.

The first of these is a lack of pump power, so that a maximum water speed of six to eight miles per hour has been attainable, while actual racing shells average over twelve mph over a long race, and can attain speeds of up to fifteen mph. This particular problem has already been solved for the M.I.T. tank, by equipping it with a 350-horsepower diesel engine.

A more serious difficulty of these tanks has been that the pumps may only be set for one particular velocity, thereby disregarding the real life situation in which the harder the oarsmen pull, the faster the water moves by. In order to simulate real rowing, it is necessary to have a feedback system which controls pumping, and hence water speed, as a function of how fast the eight men rowing on the tank would have a real boat moving on the river.

In a team sport like crew racing, it is often much more difficult for a coach to choose his eight best oarsmen than in an individual sport, or even a sport like basketball, in which individual efforts are clearly discernible. Thus in the past coaches have had to resort to a practice known as "musical chairs", in which many possible combinations are tried out against each other and against the clock. Since there are 32!/8!24! ways to choose a varsity boat out of a squad of thirty-two oarsmen, this procedure is impractical, and when used is quite time-consuming.

Efforts to apply objective methods for the measurement of oarsmen's abilities have been few and far between, however. The University of California experimented in the early 1950's with a system utilizing strain gauges mounted on the oarlocks of an actual shell to plot instantaneous force as a function of time, but the results were mainly qualitative in nature, and it appears that the system was never used to differentiate among the oarsmen.[1]

Jack Frailey, head coach of rowing at M.I.T., presently evaluates oarsmen on the basis of the static force they are able to exert in an isometric contraction, in one of several different rowing positions. However, this will not necessarily be the same as the force the same oarsman can exert dynamically, against the moving water, when a relatively weak man may outpull a stronger man by rowing more efficiently, or by using quickness to get his available power on earlier in the stroke. In addition, there is the question of stamina: a weak man may outlast a strong man over an extended period. Thus, M.I.T. crew members are given the "Harvard step test", which provides a measure of overall conditioning and stamina but ignores the problem of muscle fatigue.

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1 Baird, E.D., and W.W. Soroka: "Measurement of Force-Time Relations in

The University of Pennsylvania crew, under head coach Joe Burk, has developed an instrumentation system for use on their varsity shell. It uses strain gauges to control a set of lights for each oarsman. The number of lights turned on indicate how hard the particular oarsman has pulled on the previous stroke. This system created quite a stir when it was introduced at the 1965 intercollegiate championship regatta, and is being credited with the success of Pennsylvania's crew in its early 1966 races. While solving the problem of taking measurements under actual dynamic rowing conditions, its output is a function only of the previous stroke, however, so that a premium is put on strength over stamina.

It is apparent that a good method of evaluation must be based on measurements made during actual rowing, either on a tank or in a shell, over the course of a practice run lasting as long as the average race. The output for each oarsman should be the time integral of the force which he has applied, equivalent to the momentum he has imparted to the shell over the entire race.

This thesis concerns the development of an instrumentation system to provide the coach with the necessary information for the evaluation of oarsmen, based on measurements taken over an extended period of rowing on the tank, under race conditions.

Chapter 2 - Control of the Tank for Rowing Simulation

2.1 Description of the Tank

Operation of the M.I.T. rowing tank is shown schematically in figure 2.1. A flow of water I (ft^3/sec) is pumped into the head tank. This water can either flow out through the troughs or change the level of water in the head tank. Velocity of water leaving the head tank is proportional to the height of water in the head tank above its equilibrium level (h). Thus, operation is described by the following equations:

$$v = K h \tag{2.1}$$

$$\frac{d}{dt}(\text{Water Volume in Head Tank}) = A_2 \frac{dh}{dt} \tag{2.2}$$

$$I = A_2 \frac{dh}{dt} + A_1 v = A_2 \frac{dh}{dt} + A_1 k h \tag{2.3}$$

$$\tau = \frac{A_2}{A_1 K} \tag{2.4}$$

According to these equations, the water velocity will approach its steady state value ($dh/dt=0$) with time constant τ if the pump is suddenly set at some value of I. Using dimensions obtained from the tank's blueprints, $(A_1/2)=7.67\ ft^2$, $(A_2/2)=74.4\ ft^2$, and $k=v_{max}/h_{max}$ or $k=18\ ft/sec\ /\ 5.25\ ft = 3.4\ sec^{-1}$. Thus we get a time constant of approximately 2.8 seconds.

2.2 Feedback System Using Pump Control Only

We can now postulate the feedback system shown in figure 2.2, and calculate the response of water speed v_o to an input v_i

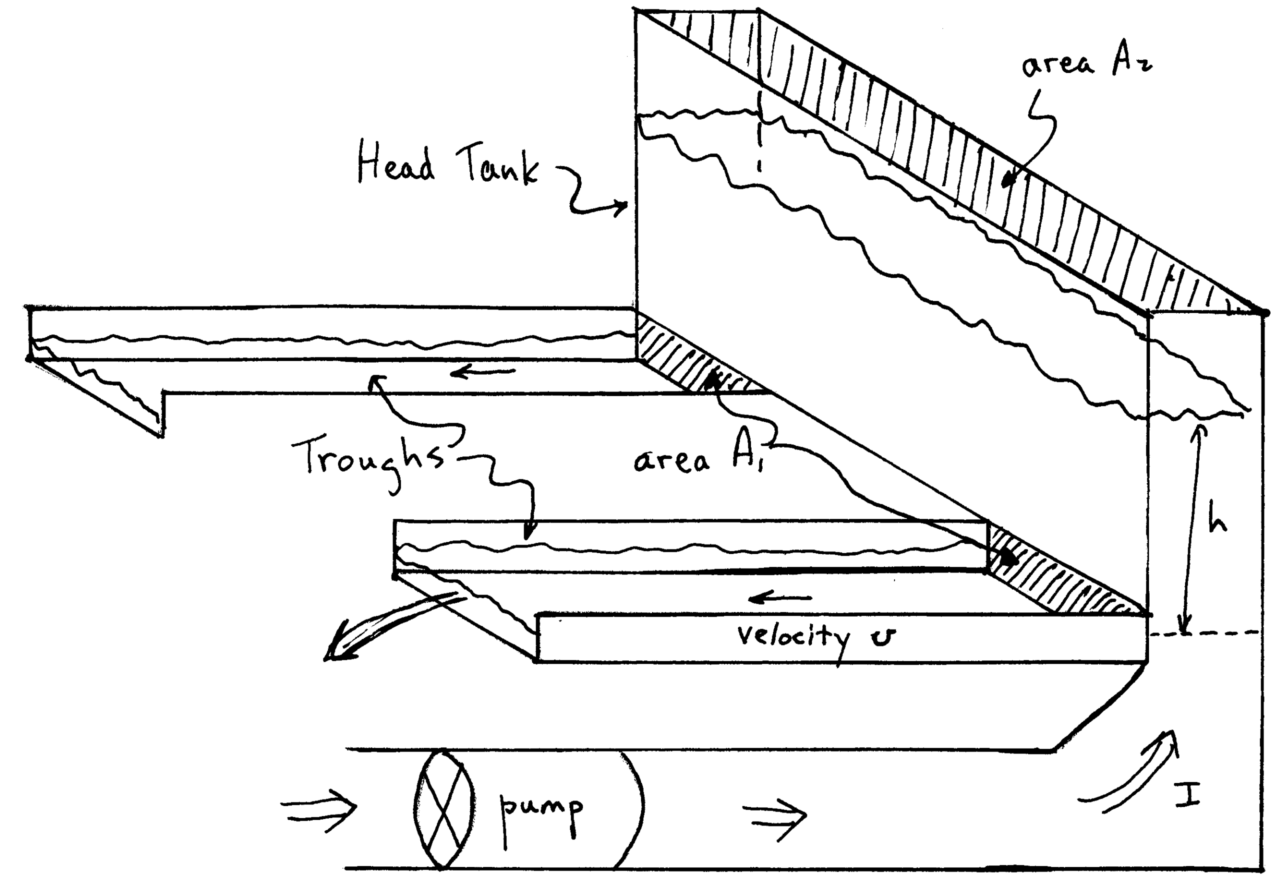

Figure 2.1 Rowing Tank Operation

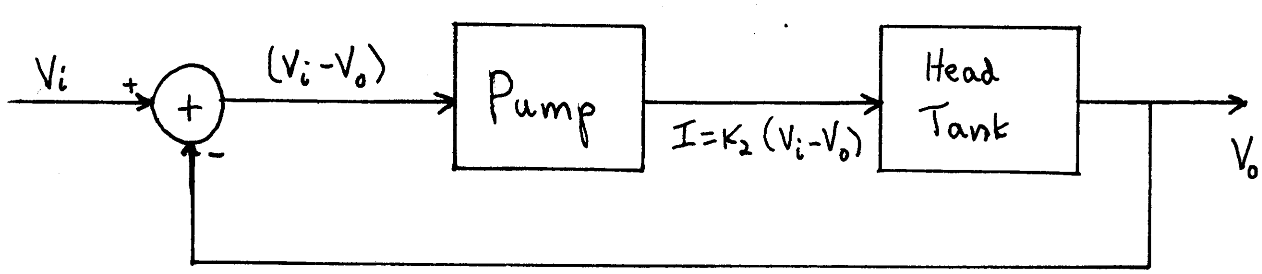

Figure 2.2 A Possible Control System

representing the velocity to be simulated, i.e. the velocity the same eight men would have if on the river.

$$I = A_2 \frac{dh}{dt} + A_1 v_0 = \frac{A_2}{K} \frac{dv_0}{dt} + A_1 v_0 = \left(\frac{A_2}{K} \frac{d}{dt} + A_1 \right) v_0 \qquad (2.5)$$

Taking a Laplace transform of this differential equation, we get:

$$\frac{V_0}{I} = \frac{1}{\frac{A_2}{K} s + A_1} = \frac{1/A_1}{s\tau + 1} \qquad (2.6)$$

$$I = K_2 (V_i - V_0) \qquad (2.7)$$

$$V_0 = \left[\frac{1/A_1}{s\tau + 1} \right] K_2 (V_i - V_0) \qquad (2.8)$$

We now solve for the system output response v_0 to an input velocity v_i:

$$V_0 \left[1 + \frac{K_2/A_1}{s\tau + 1} \right] = \frac{K_2/A_1}{s\tau + 1} V_i \qquad (2.9)$$

$$V_0 (s\tau + 1 + K_2/A_1) = (K_2/A_1) V_i \qquad (2.10)$$

$$\frac{V_0}{V_i} = \frac{K_2/A_1}{s\tau + 1 + K_2/A_1} \qquad (2.11)$$

Thus the output velovity v_0 can be thought of as approaching the input velocity v_i with time constant τ_2, defined by:

$$\tau_2 = \frac{\tau}{1 + K_2/A_1} < \tau = 2.8 \text{ sec} \qquad (2.12)$$

This would seem to imply that we can make the response arbitrarily fast just by increasing the constant k_2 relating the output I from the pump to its input $(v_i - v_o)$. However, if we refer to figure 2.3, we see that the above solution, using equation 2.7, is good only in the linear range of the pump, up to an I_{max} corresponding to a steady-state v_o of eighteen ft/sec.

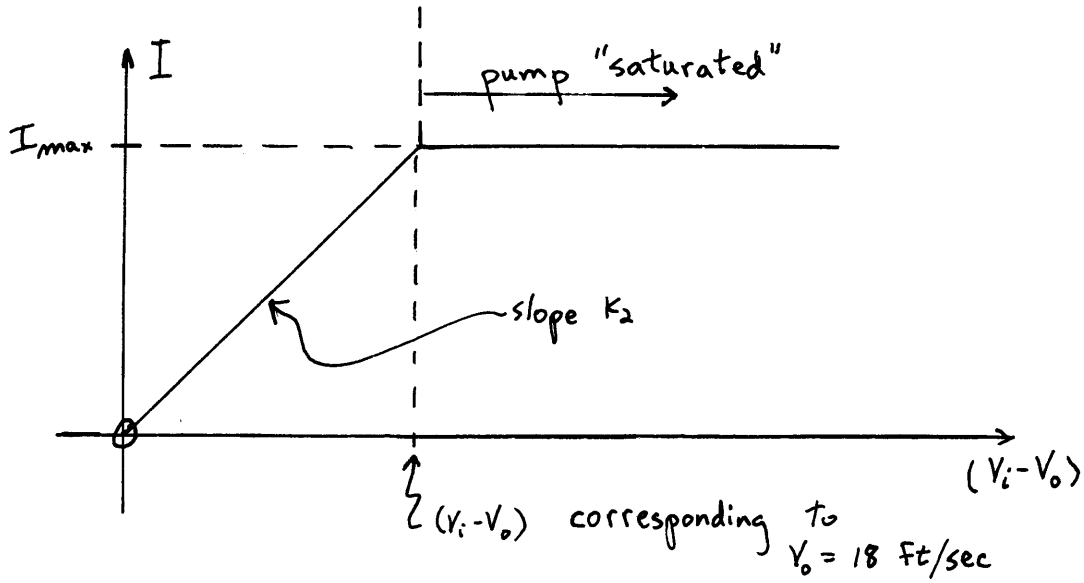

Figure 2.3 Pump Input-Output Relation

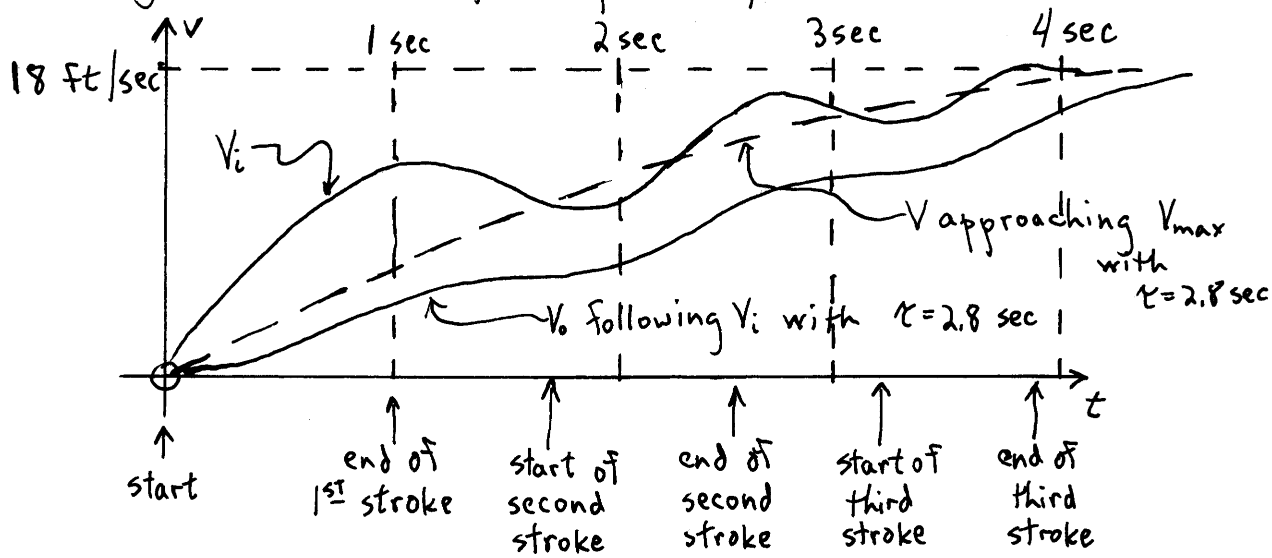

Figure 2.4 Racing Start Simulation

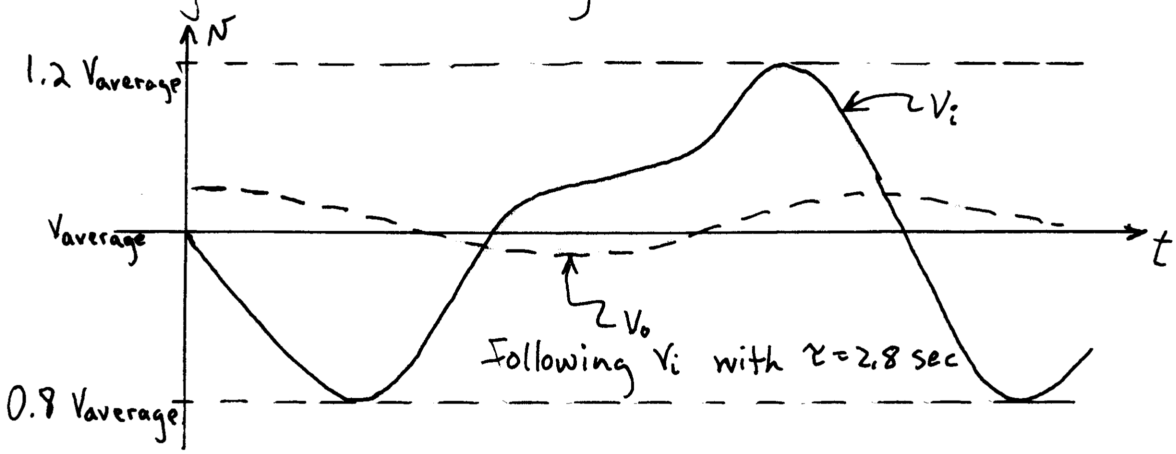

Figure 2.5 "Steady State" Rowing Simulation

The problem is that for a sudden variation in v_i, with large k_2, (v_i-v_o) will go out of the range of validity of equation 2.7, the pump will be in its "saturated" state, and instead of approaching v_i with time constant τ_2(short), v_o will approach v_{max}=18 ft/sec with time constant τ=2.8 sec.

As an example, consider the case where k_2/A_1=9, so that τ_2 is only .28 sec. We also see, from equations 2.8, that in this case the maximum v_o of 18 ft/sec corresponds to (v_i-v_o)=2 ft/sec. On a typical racing start, v_i actually "jumps" by far more than two ft/sec so that it is the long time constant of 2.8 sec which will predominate.

Figure 2.4 illustrates the fact that this particular feedback system does not do a good job in simulating a racing start. The curve labeled v_i is an approximation to the actual velocity vs. time curve for a racing start, based on rowing experience (a good crew should be up to full speed by the end of the third stroke).

Figure 2.5 shows the equivalent curve for "steady-state" racing at thirty strokes per minute. In this figure, v_i is a measured velocity vs. time curve gotten from the world champion Ratzeburg crew of Germany

From these diagrams, it is evident that this system can do a correct job in simulating the average velocity, but falls down when trying to simulate the variations around that average, or changes of average velocity like a racing start or the beginning of a sprint. Thus, the oarsmen would not get the feel of the boat "jumping at the catch" as it does on the river.

2.3 Pump Control plus Mechanical System

From section 2.2, it is apparent that in addition to the pump feedback loop providing the correct average water speed, there must be some sort of mechanical system, with the men sitting on a movable platform, to provide the velocity variations around the average.

At first, an attempt was made to design a mechanical system of springs, weights and dampers which would allow the platform to move forward by just the right amount when the oarsmen were pulling, and then return the platform to its original position in time for the next stroke. However, before a suitable design could be found, this plan was scrapped in favor of an idea proposed by Bill Weber, an ex-M.I.T. oarsman now serving as varsity lightweight crew coach at Harvard.

2.4 The Simulated Boat

Under this plan, the moving platform has attached to it two bodies which sit in the water and approximate the drag of an actual shell. The men are then in an actual "boat", rowing in the tank, and the pumps must only provide the right average velocity to keep the platform from "rowing itself out of the boathouse".

If we make an analog computation of the velocity the boat should be going, by means of strain gauges on the riggers and electrical circuits, then the water velocity v_o approaches this calculated v_i with a time constant of 2.8 sec. Thus, the distance the platform travels on a racing start before settling down in steady state is just the area between the two curves v_i and v_o in figure 2.4. An approximate graphical estimate of this area is fifteen feet. Since each oarsman in a shell uses 4'4" of length, the moving platform must be approximately 35' long. Since the length of the tank is exactly 50', it can be seen that we are operating pretty close to the limit: Using this method to control the pump, a crew could well take a good fast racing start and find themselves literally climbing the wall!

The solution to this problem is to use the position of the platform as an input to the electrical feedback system. This position can then be differentiated with respect to time, so that the feedback system has available not only the platform's position, but also its velocity and acceleration (and thus the instantaneous force). In fact, by differentiating an arbitrary number of times, and using adjustable gain amplifiers, the Laplace transform of the system's differential equation can be given an arbitrary desired polynomial in s for its right hand side.

This method of feedback can be thought of as analogous to a man running on a treadmill, which is turned by a motor. This motor is then controlled by some sort of feedback system which watches the man's position and adjusts the motor speed such that the man never gets to the end of the treadmill. If the man is blindfolded, he never knows that he is not running a set distance.

The feedback system input position is given by:

$$x = x_0 + \int_0^t (V_i - V_o)\,dt \qquad x_0 = x(t=0) = 0 \qquad (2.13)$$

$$x = \int_0^t (V_i - V_o)\,dt \qquad (2.14)$$

where x is position of the boat with respect to the fixed boathouse frame of reference, v_i is velocity of the boat with respect to the water, v_o is water velocity with respect to the boathouse, and $(v_i - v_o)$ is velocity of the boat with respect to the boathouse.

Thus, the kinematic part of the overall feedback system can be represented as in figure 2.6a, and the overall system is shown in

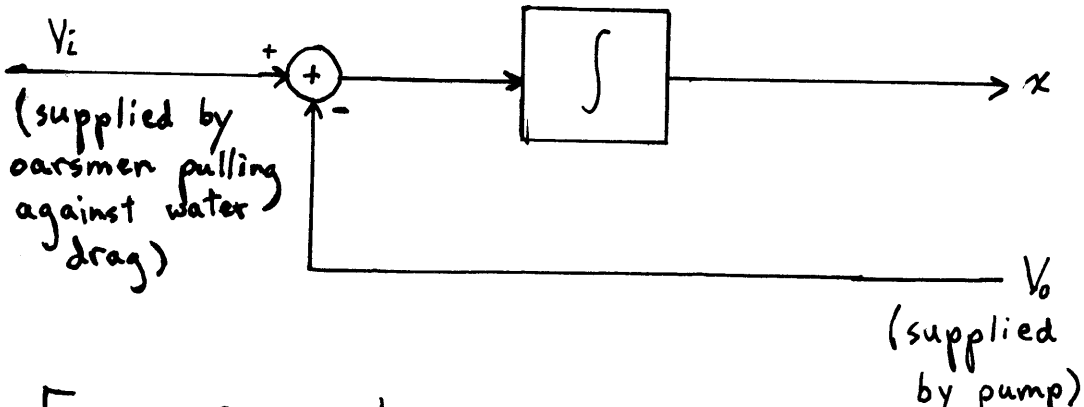

Figure 2.6a Kinematics of the Simulated Boat

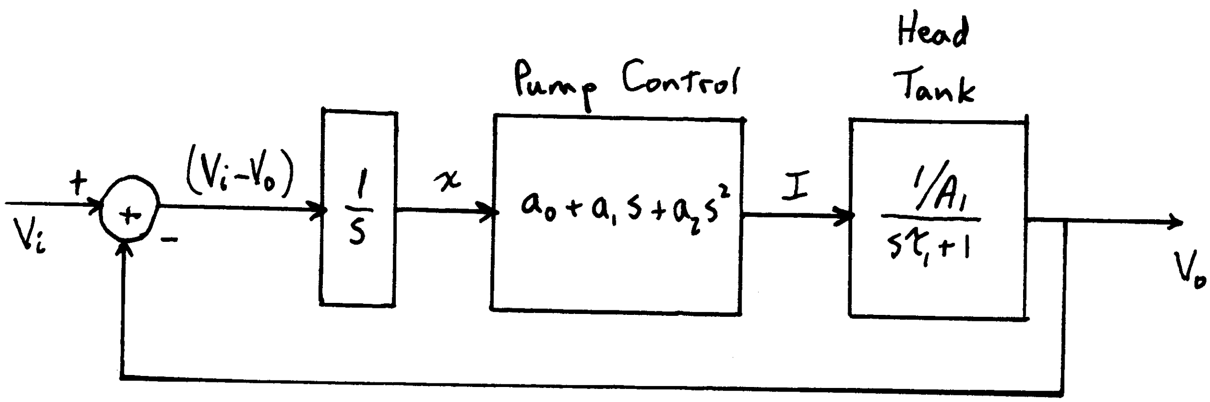

Figure 2.6b Overall Control System

figure 2.6b, where the pump output I (input to the head tank) is given by:

$$I = a_0 x + a_1 \frac{dx}{dt} + a_2 \frac{d^2x}{dt^2} \qquad (2.15)$$

It should be noted that this diagram is only valid in the range for which the pump is "unsaturated", and if the a_i's, x, dx/dt, and d^2x/dt^2 are too high, we revert to a system with v_o approaching 18ft/sec with time constant 2.8 sec.

System response is given by:

$$V_o = (V_i - V_o)\ \frac{\frac{1}{A_1}\left(a_0 + a_1 s + a_2 s^2\right)\frac{1}{\tau_1}}{s\left(s + \frac{1}{\tau_1}\right)} = (V_i - V_o)\ A(s) \qquad (2.16)$$

Solving this for system response to input velocity v_i, we get:

$$\frac{V_o}{V_i} = \frac{A(s)}{1 + A(s)} = \frac{\frac{K}{A_2}\left(a_0 + a_1 s + a_2 s^2\right) / s\left(s + \frac{1}{\tau_1}\right)}{1 + \frac{K}{A_2}\left(a_0 + a_1 s + a_2 s^2\right) / s\left(s + \frac{1}{\tau_1}\right)} \qquad (2.17)$$

$$\frac{V_o}{V_i} = \frac{\frac{K}{A_2}\left(a_0 + a_1 s + a_2 s^2\right)}{s^2 + \frac{1}{\tau_1} s + \frac{K}{A_2}\left(a_0 + a_1 s + a_2 s^2\right)} \qquad (2.18)$$

$$\frac{V_o}{V_i} = \frac{\left(\frac{a_2 K}{A_2}\right) s^2 + \left(\frac{a_1 K}{A_2}\right) s + \left(\frac{a_0 K}{A_2}\right)}{\left(1 + \frac{a_2 K}{A_2}\right) s^2 + \left(\frac{1}{\tau_1} + \frac{a_1 K}{A_2}\right) s + \left(\frac{a_0 K}{A_2}\right)} \qquad (2.19)$$

We see that making a_1 and a_2 arbitrarily large, we can make $v_o = v_i$ however this fails to take into account the pump saturation problem, and in addition, since this is a second-order system, we have to worry about stability. The stability criterion is that the denominator polynomial have real roots. The condition for this is:

$$\left(\frac{1}{\tau_1} + \frac{a_1 K}{A_2}\right)^2 > 4\left(1 + \frac{a_2 K}{A_2}\right)\frac{a_0 K}{A_2} \qquad (2.20)$$

The constant a_o relates position of the shell to the amount of water flowing into the head tank in the steady state condition, when the position of the shell with respect to the boathouse is constant. If we choose to have three feet to spare for variations around this position at maximum velocity, then a_o is determined by:

$$a_o = \frac{I_{max}}{12\ ft} = \frac{A_1 v_{max}}{12\ ft} = 1.5\ A_1/sec \qquad (2.21)$$

$$a_o = 23.8\ \ ft^2/sec \qquad (2.22)$$

Using this value of a_o and the previous values of A_1, A_2, k and τ_1, the stability criterion reduces to:

$$2.3\ a_1^2 + 1.6\ a_1 > 205.3 + 5 a_2 \qquad (2.23)$$

For the ideal case of $v_i = v_o$, we would like to have:

$$\frac{a_1 K}{A_2} \gg \frac{1}{\tau_1} \qquad \frac{a_2 K}{A_2} \gg 1 \qquad (2.24)$$

which comes out to:

$$a_1 \gg A_1 = 15.33\ ft^2 \qquad a_2 \gg \frac{A_2}{K} = 43.8\ ft^2 sec \qquad (2.25)$$

For a racing start, the best response we can get is if the pump is saturated, so that v_o approaches v_i with time constant 2.8 sec. We see in figure 2.4 that if the pump is saturated through most of the racing start, the distance travelled by the moving platform is just the area between v_i and $18(1-e^{-t/2.8})$, which is enough less than the area between v_i and v_o (15 ft) that we can be assured that the platform does not row itself out of the boathouse.

Thus a_1 and a_2 must be chosen large enough to saturate the pump on racing starts, the beginning of sprints, and going from a "paddle" to full power, but not for the ordinary variations around the average. That is, in the steady state, the term $a_o x$ must be the predominant one. This is particularly important when we consider that it is not good for the diesel engine to be constantly revved up and down.

From the racing start plot in figure 2.4, it appears that a typical value of dx/dt during the start is five ft/sec (dx/dt is just $v_i - v_o$). Typical d^2x/dt^2=d/dt (distance between curves) is also five ft/sec.

In order to have $a_o x$ predominate in the steady state, we have to choose a_1 and a_2 as small as possible, consistent with saturation for a racing start.

$$I_{max} = (12\ ft)\, a_o = 286\ ft^3/sec \qquad (2.26)$$

$$\left(a_1 \frac{dx}{dt} + a_2 \frac{d^2x}{dt^2}\right)_{\text{racing start}} = 5a_1 + 5a_2 > 286 \qquad (2.27)$$

This inequality is satisfied if we choose a_1=20 ft^2 and a_2=40ft^2 -sec, where the ratio between a_1 and a_2 is chosen with equations 2.25 in mind. When used with equation 2.23, these values of a_1 and a_2 do indeed give us a stable system. In order to check whether the zero order term ($a_o x$) does predominate in the steady state, it is necessary to estimate dx/dt and d^2x/dt^2. Since the boat's velocity goes from $.8v_{av}$ to $1.2v_{av}$ (see figure 2.5), a good estimate of dx/dt in the steady state is $.2v_{av}$=3.6 ft/sec. It is known that at full speed, each man is only able to exert about one-fourth as much force as he can on the first stroke of a racing start. Thus a good estimate of d^2x/dt^2 in the steady state is $\frac{1}{4}d^2x/dt^2$ for a racing start, or about $1\frac{1}{4}$ft/sec^2. Using these values, the zero order term is about three times the sum of the first and second order terms, and does indeed predominate.

2.5 Computer Models

In the absence of the completed tank, it became apparent that the design for the feedback system described in section 2.4 would have to be tested with a computer simulation. At first it was thought that an analog simulation would be ideal, as it would then be quite simple to try out different values of the gain parameters a_0, a_1 and a_2 to find the optimum combination which would save wear and tear on the diesel engine (minimum variation of I in the steady state) while assuring that the platform would never find itself up against the wall at the end of the tank on a racing start.

It was soon realized, however, that little was known about the actual functional form of the velocity vs. time for different conditions. Consequently, Raymond Petit, who was originally responsible for design of the control system, branched out to undertake a full-scale digital computer simulation of what was actually going on in a racing shell.

This was done in two stages. The first was a program which would predict the functional form of output variables such as velocity and bootstretcher force given the functional form of force applied by the oarsmen. The model was refined until the computer output curves matched exactly with curves of velocity and bootstretcher force actually measured by German and Japanese crews. As more and more factors were added to the computer model, it was interesting to note the "wiggles" they added to the output curves, and several previously unexplained dips and rises in the measured curves could be identified with particular motions of the oarsmen.

A major weakness of the first model was its use of half-sine waves for the input force of the oarsmen, thereby ignoring the physiological factors which enable oarsmen to pull harder when the boat is going slowly (as on a start), than when the boat is up to full speed.

The second stage of computer simulation of rowing involved the development of a program taking physiological factors into account, thereby making it possible to predict the exact velocity vs. time curve for a racing start. This program is now complete down to the last detail, simulating such typical situations as coxswains calling for "big tens", a rate of rowing somewhere near but not exactly on the value called for by the coach, and oarsmen "catching crabs".

Although this program was originally started with simulation of the control system in mind, as a by-product, the coach now has available a potentially valuable tool for experimenting with rowing style by varying input parameters to the simulation. As an example, the computer has already suggested that the oarsmen are not properly "impedance-matched" to the oars, and may be able to row more efficiently with longer oars at a lower rate of stroking.

The reader is referred to Mr. Petit's thesis for further details.[2]

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2 Petit, Raymond C.: "Computer Simulation of the Racing Eight"; M.I.T. Electrical Engineering Bachelor's Thesis, May, 1966

Chapter 3 - Instrumentation of the Tank

3.1 Requirements

There are two types of information which the coach may wish to have concerning a practice run in progress on the tank: information on each man's performance, and information of a general nature.

Under the general category, the following should be measured:

1) rate of rowing, in strokes per minute.

2) ratio, the amount of time spent on the recovery divided by the amount of time spent on the drive, a measure of how well the "boat" is going at a particular rate of rowing.

3) velocity of the boat with respect to the water.

4) distance travelled (the time integral of #3), with a switch enabling it to be read out in either meters or yards.

5) time elapsed since the beginning of the run.

In addition, there should be a turn-off mechanism for the counters providing a readout of #4 and #5, so that the clock may be set to stop after a set distance, like 500 meters (automatic stopwatch), or the distance readout may be set to stop and tell the coach how far the boat has gotten in a set time.

Under the category of performance of individual oarsmen, of primary importance is a system using strain gauges to measure the net force each man puts into moving the boat, integrated over the whole run. This system has to have a digital readout in order to get sufficient resolution to differentiate among the oarsmen.

In addition, there should be circuits to detect when an oarsman starts his stroke early or late relative to the stroke man. The output of these timing circuits should be two sets of lights, one visible to the oarsman and one to the coach, as well as counters to keep a running total of how many times each man has caused his "early" and "late" lights go on.

It would also be desirable to have circuits to tell when an oarsman puts a "check" (negative force) in the boat, and to count up the occurrences of a "check" for each oarsman.

The experimental work of this thesis concerns the development of actual hardware to measure and integrate an oarsman's propulsive force, and to detect and count the occurrences of early and late strokes. It was found that inclusion of "check" detecting circuitry introduced considerable complications. The marginal advantage of having the "check" indicators was deemed not sufficient to justify the added circuit complexity. This will be explained further in the section concerning placement of the strain gauges.

Circuitry to implement measurement of the quantities under the general category is conveniently broken down into small portions which would be suitable for projects in the undergraduate electrical engineering laboratories.

The "distance travelled" and "time-elapsed" circuits involve adapting the integrator-counters used for force to a different input: velocity in the case of "distance travelled" and pulses from a .1 second multivibrator in the case of "time elapsed". The clock-distance turn-off mechanism involves an ordinary combination-all logic circuit.

3.2 Placement of Strain Gauges

In determining the optimum placement for the strain gauges it is essential to bear in mind that we are trying to measure just the force which the oarsman contributes to forward motion of the boat. Thus it is necessary to analyze the force diagram of figure 3.1 in order to choose strain gauge locations whose output will be the desired one.

The forces F_{water}, F_{pin} and $F_{oarsman}$ are defined as the forces exerted by the water, pin and oarsman on the oar. The force which we wish to measure, that is the forward propulsive force on the entire system (boat plus men), is just F_{water}. If we make a quasistatic approximation and ignore the acceleration of the center of mass of the oarsman, then $F_{oarsman}=F_{bootstretcher}$ (the oarsman is able to exert a particular force on the oar handle by pushing sternward with his feet against the bootstretchers).

If we consider the oar as a lever arm, we have the following two relationships:

$$F_{water} + F_{oarsman} = F_{pin} \qquad (3.1)$$

$$F_{oarsman} = 3\,F_{water} \qquad (3.2)$$

Both of these are based on quasi-static approximations. Equation 3.1 assumes that the pin is not accelerating, and 3.2 assumes that the angular acceleration of the oar is zero. Using these relationships, we find:

$$F_{water} = F_{pin} - F_{bootstretcher} = \frac{1}{3}\,F_{oarsman} \qquad (3.3)$$

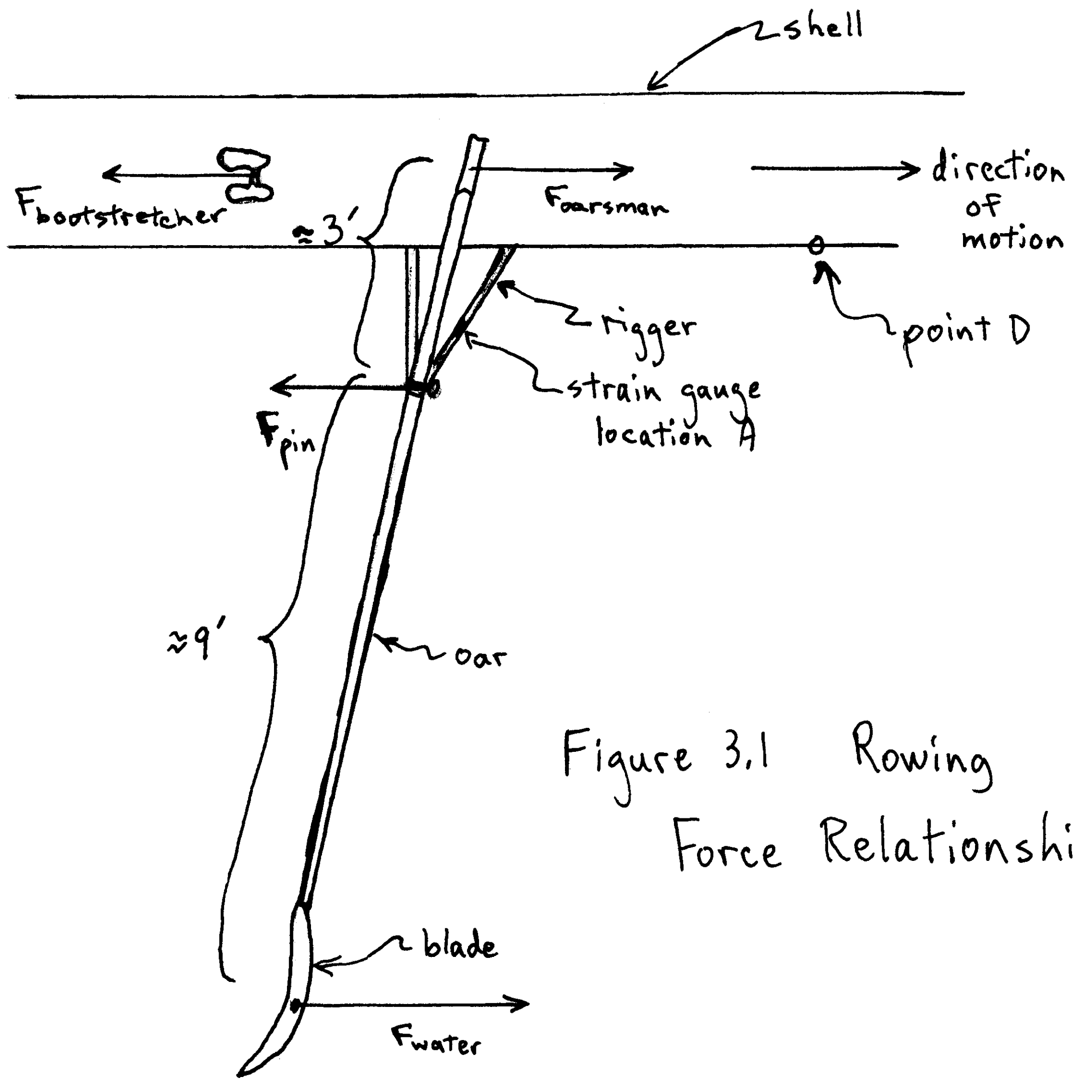

Figure 3.1 Rowing Force Relationships

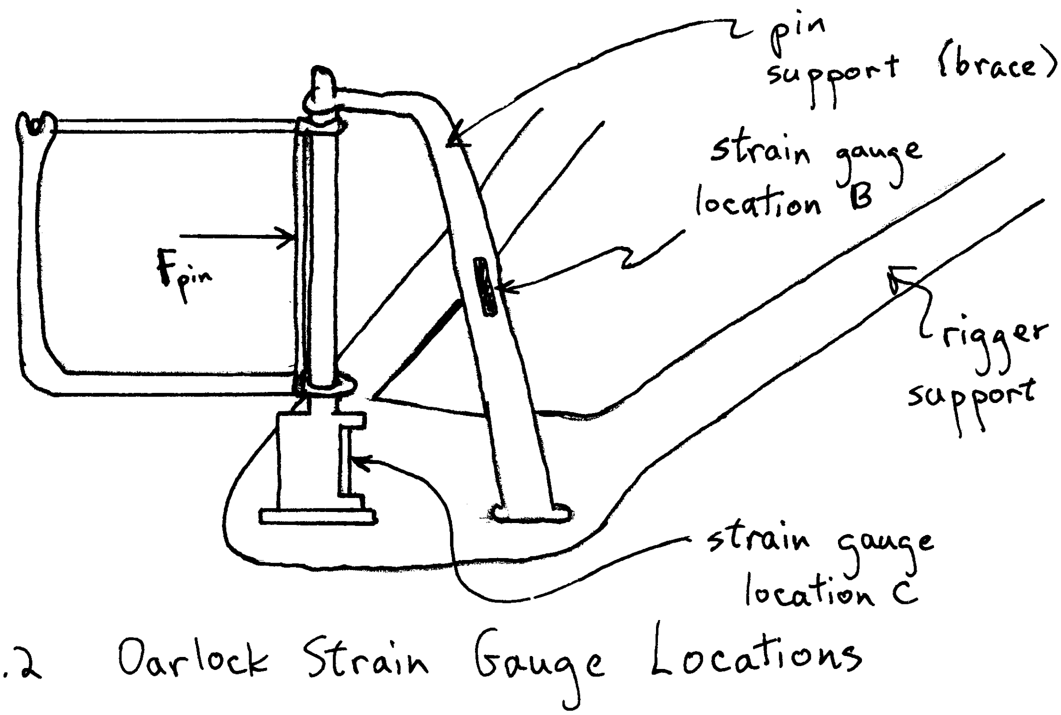

Figure 3.2 Oarlock Strain Gauge Locations

We see that to get the actual propulsive force on the boat, we need strain gauges on the pin and bootstretcher as inputs to a differential amplifier. However, our analysis tells us that when the oar is in the water, these forces are always proportional, so that we only need one as an input.

Here is where the ability to detect a "check" or negative force comes in. A "check" occurs when the oarsman fails to anchor his blade at the beginning of the stroke, so that $F_{bootstretcher}$ appears before F_{pin}, and the measured F_{water} goes negative. Thus when the force output goes negative (in the case where we have strain gauges on both the pin and bootstretcher), we know that a "check" has occurred.

In order to see the difficulties introduced with this method, it is necessary to consider the operation of the strain gauges. Strain gauges are simply 120-ohm resistors which are mounted on a surface to which a force is being exerted. As the surface is lengthened or compressed as a result of the force, the resistor undergoes a percent resistance change given by:

$$\frac{\Delta R}{R} = 2\,\frac{\Delta \ell}{\ell} \qquad (3.4)$$

In mounting the strain gauges on the pin, we have a choice of three locations: location A, shown in figure 3.1, measures F_{pin} by measuring the related compression on the rigger support; location B, in figure 3.2, measures F_{pin} by measuring the related compression on the pin support; and location C, in figure 3.3, measures F_{pin} by measuring compression at C due to bending of the pin.

The mounting of a bootstretcher strain gauge, however, can only be done in such a way as to measure compression of the metal at the bootstretcher base. Since we are subtracting the pin and bootstretcher forces in order to detect a "check", it is necessary to have strain gauge outputs of the same magnitude. This eliminates location C (it will be shown later that this location gives a much higher strain gauge output, than any of the other locations, either for pin or bootstretcher force).

In the project at University of California[3], location A was ruled out because it gave an output which was sensitive to lateral forces. In particular it was found that by squeezing the gunwale at point D of figure 3.1, it was possible to produce a spurious F_{pin} output. Since there was no desire to measure a "check", location C was chosen.

For the purposes of this thesis, however, location B was tentatively chosen, in order to have an F_{pin} output comparable to that of $F_{bootstretcher}$. For compression, the percentage change in length is given by:

$$\frac{\Delta l}{l} = \frac{\text{Force}}{(\text{cross-sectional area})(\text{Young's modulus})} = \frac{F}{AE} \qquad (3.5)$$

For the tubular steel brace in question:

$$A = 2\pi r\,(\text{thickness}) = 2\pi\left(\tfrac{1}{2}\right)\left(\tfrac{1}{8}\right)\ in^2 = .4\ in^2 \qquad (3.6)$$

$$E = 3\times10^{7}\ lbs/in^2 \qquad (3.7)$$

Assuming forces of the order of 150 lbs. (a high estimate), we come out with a percent resistance change:

$$\frac{\Delta R}{R} = 3\times10^{-5} \qquad (3.8)$$

---

3 Baird, op. cit.

Even if we go to specially-made aluminum pin supports, with $E=10^{-7}$psi, the best we can get is:

$$\frac{\Delta R}{R} = 10^{-4} \qquad (3.9)$$

This value corresponds to measuring the effect of placing a 1Meg resistor in parallel with the 120-ohm strain gauge, and at the recommended strain gauge current level of 10ma, gives us an amplifier input voltage of only .1mV.

For reasons to be explained in section 3.3, this low level of amplifier input voltage change was deemed unsatisfactory. Thus it became necessary to consider sacrificing the "check" detecting capability and mounting the strain gauge to measure bending of the pin, as was done at University of California.

The configuration is that of figure 3.3. Bending of the pin is given by[4]:

$$\delta = \frac{F(lbs)}{6E\,I_{yy}}\left(3x^2a - x^3\right) \qquad (3.10)$$

where the parameters are defined by figure 3.4.

$$I_{yy} = \int_A y^2\,dA \quad \text{(over cross-section of pin)} \qquad (3.11)$$

$$I_{yy} = 4\int_0^r y^2\sqrt{r^2-y^2}\,dy = \pi r^4/4 \qquad (3.12)$$

If we use an aluminum pin ($E=10^{-7}$psi), with r=3/16 in, a=3in, and x=1in, a force of 200 lbs produces a deflection of 1/40 in.

4 Crandall, Stephen H., and Norman C. Dahl, "An Introduction to the Mechanics of Solids" McGraw-Hill, 1959, p.378

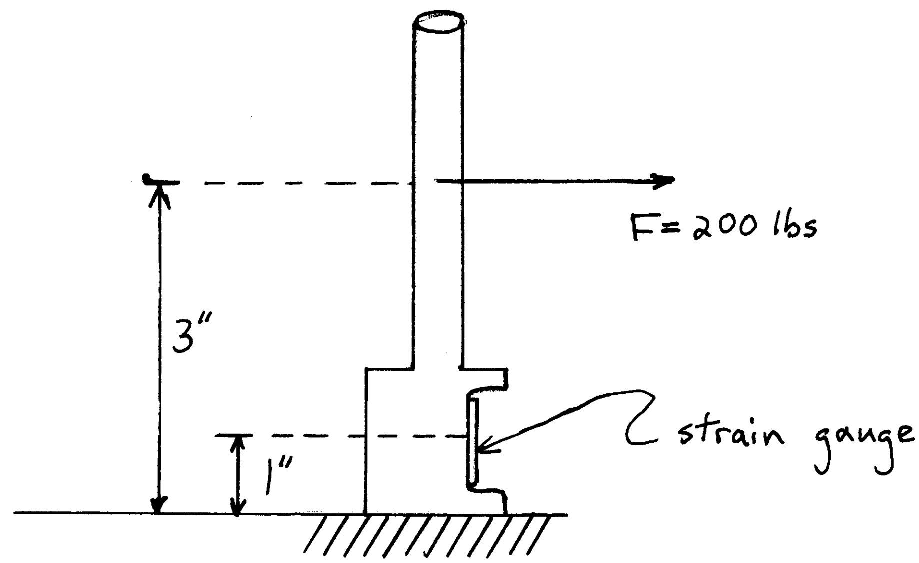

Figure 3.3 Oarlock Pin

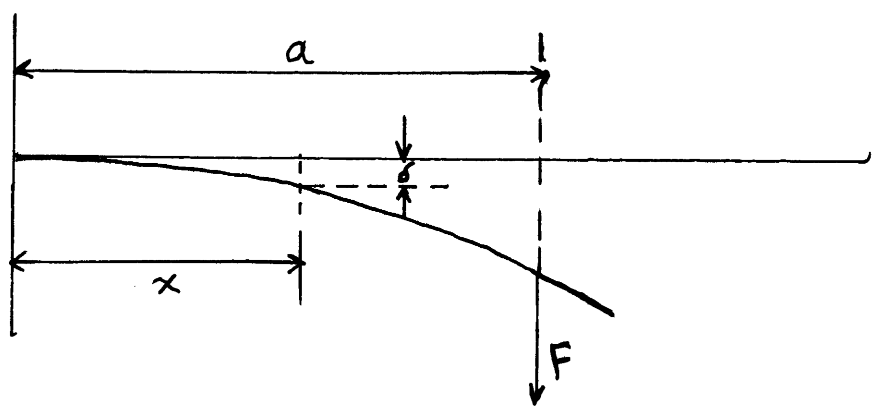

Figure 3.4 Bending of the Pin

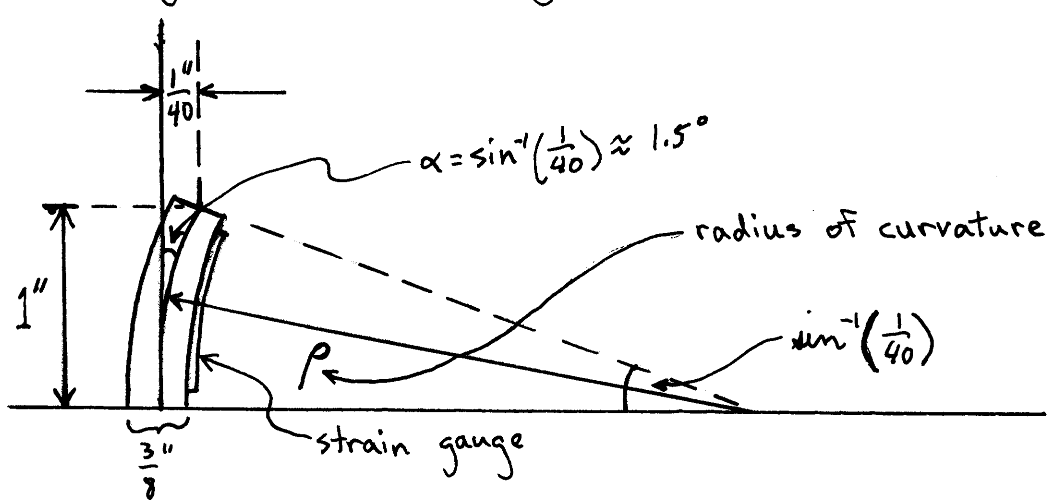

Figure 3.5 Geometry for Calculation of $\left(\frac{\Delta l}{l}\right)$

In order to calculate the percent resistance change in the strain gauge due to a deflection of 1/40 in at a height of 1in up the pin, we refer to figure 3.5.

$$\ell_0 = 1 \text{ in} = \rho \sin^{-1}(1/40) \qquad (3.13)$$

$$\rho = 40 \text{ in} \qquad (3.14)$$

$$\ell_0 - \Delta\ell = (40 \text{ in} - 3/16 \text{ in}) \sin^{-1}\left(\frac{1}{40}\right) \qquad (3.15)$$

$$\Delta\ell = \frac{3}{16 \times 40} \text{ in} = 5 \times 10^{-3} \text{ in} \qquad (3.16)$$

$$\frac{\Delta R}{R} = 2 \frac{\Delta\ell}{\ell} = 10^{-2} \qquad (3.17)$$

Thus, by relocating the strain gauge at location C, we have increased the gauge output by two orders of magnitude, so that we are now working with inputs to our differential amplifier of the order of 10mV. As will be seen in section 3.3, this greatly simplifies the amplifier design. Consequently, it was decided not to include the "check" indicators, which would force us to work with signal levels one hundred times less than otherwise necessary.

3.3 Design of Force Amplifier and Integrator

The system for measuring and integrating the oarsmen's force is shown in block diagram form in figure 3.6. It is basically a d-c amplifier, receiving its input from strain gauges and providing an output current proportional to force being exerted at any particular instant. This current is fed into the capacitor, giving an output voltage V_1 proportional to the time integral of force.

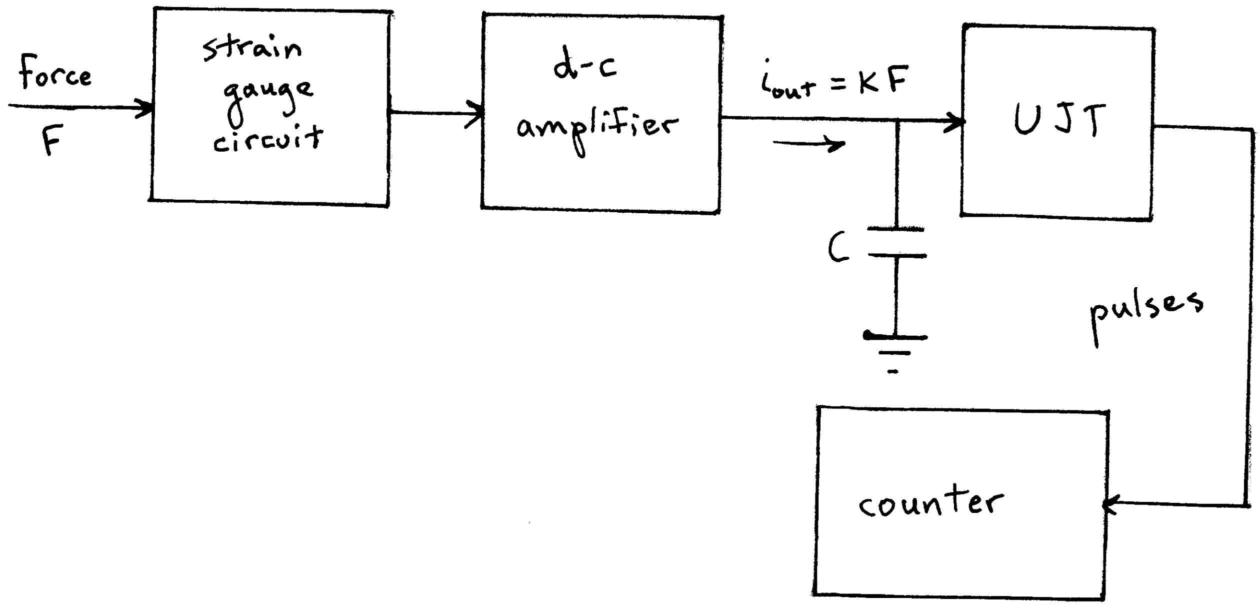

Figure 3.6 Basic Instrumentation System

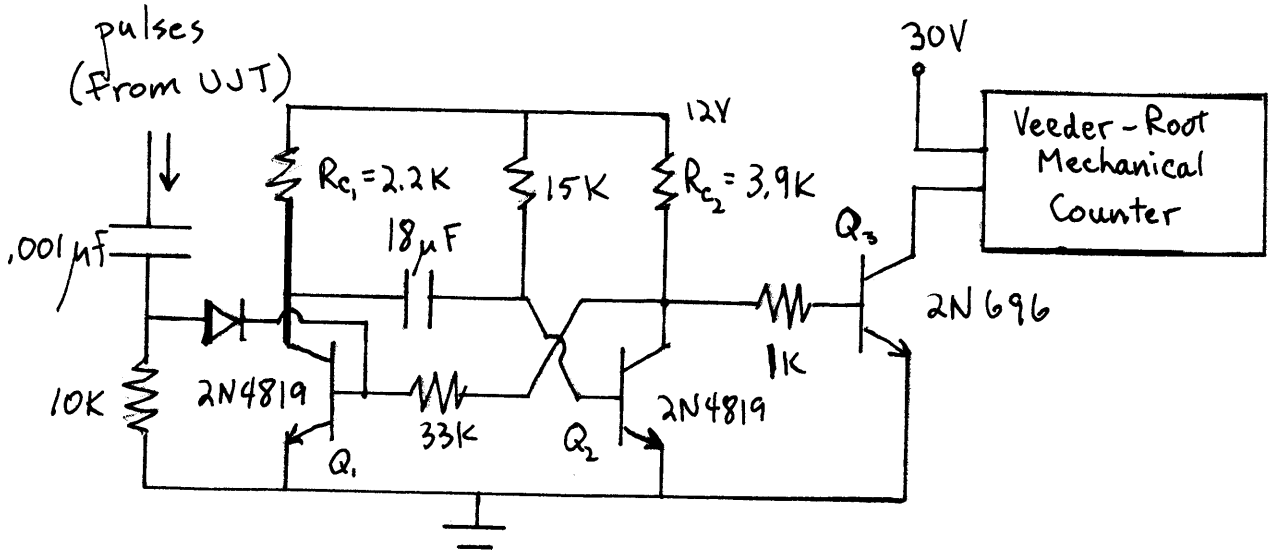

Figure 3.7 Counter Circuit

When this voltage reaches a threshold value, the unijunction transistor "fires", simultaneously resetting V_1 and producing an output pulse, which is then counted. Thus the counter provides a digital indication of each oarsman's force integrated over time.

3.3.1 Counter Design

At first it was planned to use a series of flip-flops in a simple counter arrangement, however this ran into two problems which, while not insoluble, would have led to great expense, in terms of the number of circuit components needed.

The first of these problems is connected with our reason for using a digital output in the first place: In order to be able to differentiate among the oarsmen, the output must have sufficient resolution, i.e. it must be able to count in the range of thousands of pulses. Since the number of bits equals the log to the base two of the maximum output the counter is capable of reaching, we are faced with the necessity of having at least ten counter flip-flops per oarsman, or over 160 transistors for the counter circuits alone.

An even more serious problem comes from the need to convert the counter output to some form which can be quickly read out by the coach. Electronic indicators are available, however these are quite expensive, and in addition it is necessary to decode the outputs of the counter flip-flops in order to drive them. A simpler and less expensive solution is to have one light indicating the state of each counter flip-flop, so that the row of lights is just a binary display representing integrated force. The difficulty here is that most crew coaches are born with ten fingers rather than two, and consequently are not used to reading binary numbers.

All these problems led to the decision to use mechanical counters which would accept electrical pulse inputs and provide their own decimal readout. This type of counter has a speed limitation which precludes its use in most applications, but this limitation need not affect us, as it is possible to achieve sufficient resolution among oarsmen over a run lasting several minutes with an average pulse frequency of as little as three per stroke.

A large factor in favor of the selection of mechanical counters was the availability of thirty used Veeder-Root electro-mechanical counters from the M.I.T. Nuclear Reactor building.

These counters were designed to trigger on pulses of 110 volts a-c, however it was found that they could be made to trigger on 30V d-c pulses of duration of at least 100 msec. This led to the configuration shown in figure 3.7, in which a monostable multi-vibrator provides a pulse with width of approximately 200 msec.

Transistor Q_2 is normally on. A positive pulse from the unijunction transistor turns on Q_1, and the circuit stays in this state for a time $T=(18\mu f)(15K)\ln 2 = 200$ msec.

Originally R_{C_2} was equal to 2.2K, but its value was increased to 3.9K in order to further saturate Q_2. This served to decrease the frequency of spurious firings of the multi-vibrator due to noise pulses from the unijunction transistor. In this manner, it was possible to reduce the average frequency of these random firings to about one every two or three minutes, a rate sufficiently smaller than the frequency of signal pulses.

A 2N696 was chosen for Q_3, the mechanical counter driver transistor, because its breakdown voltage V_{cbo} is greater than 30V. The 2N4819's are germanium transistors chosen chiefly for their availability.

3.3.2 Unijunction Transistor Circuit

The unijunction transistor is a semiconductor device whose symbol and circuit model are shown in figure 3.8. Its operation can be thought of as follows: With $I_e=0$, the voltage at point A is just determined by the voltage divider relation:

$$V_a = V_{B_1} + \frac{R_1}{R_1 + R_2} V_{BB} = V_{B_1} + \eta V_{BB} \qquad (3.18)$$

If V_e is less than V_a, the diode is back-biased, and we do have $I_e=0$. However, if V_e increases to V_a, the diode becomes forward biased, I_e is non-zero, and R_1 begins to decrease due to the presence of the carriers of I_e present in the semiconductor material. It can be seen that I_e will therefore increase and V_a will decrease in a regenerative process, until some small limiting value of R_1 is reached, with V_a slightly larger than V_{B_1}. As this regenerative process is occurring, a pulse of current appears at B_1.

Let us now consider the circuit of figure 3.9, which is used to integrate an input current proportional to instantaneous force, and to provide an output pulse whenever the time integral of this current reaches a certain threshold value.

If the emitter diode is open, I_s goes into the capacitor, so that V_e is proportional to the time integral of force. When this voltage reaches V_a, the unijunction transistor fires, sending a pulse to the counter circuit and at the same time discharging the

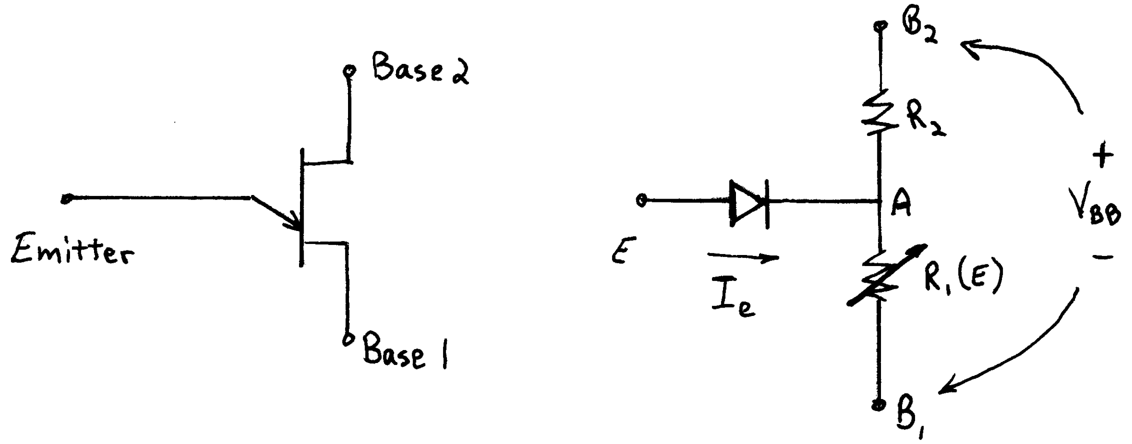

Figure 3.8 Unijunction Transistor and Model

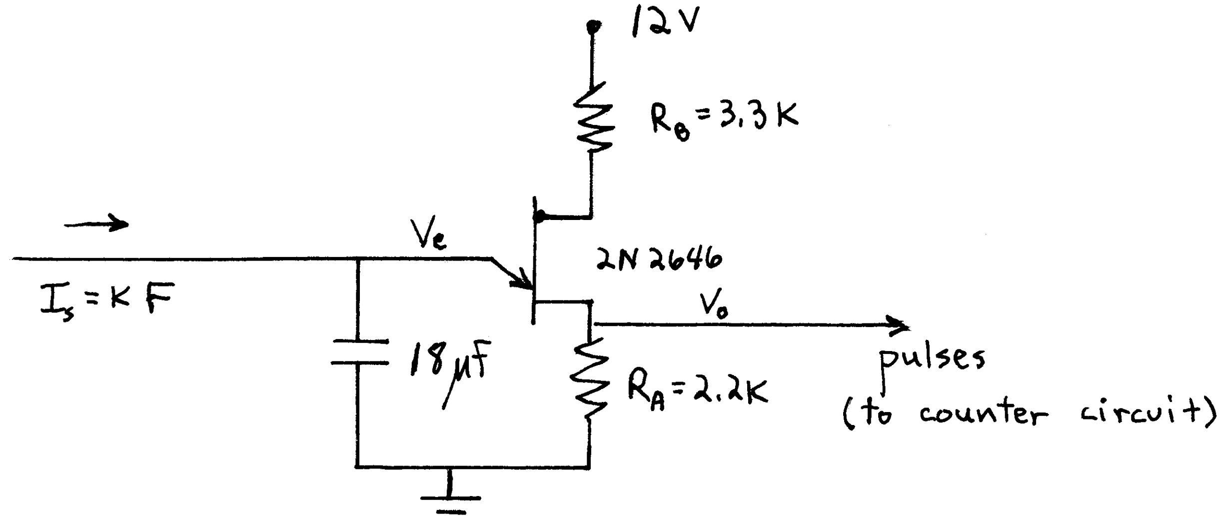

Figure 3.9 Unijunction Transistor Integrator Circuit

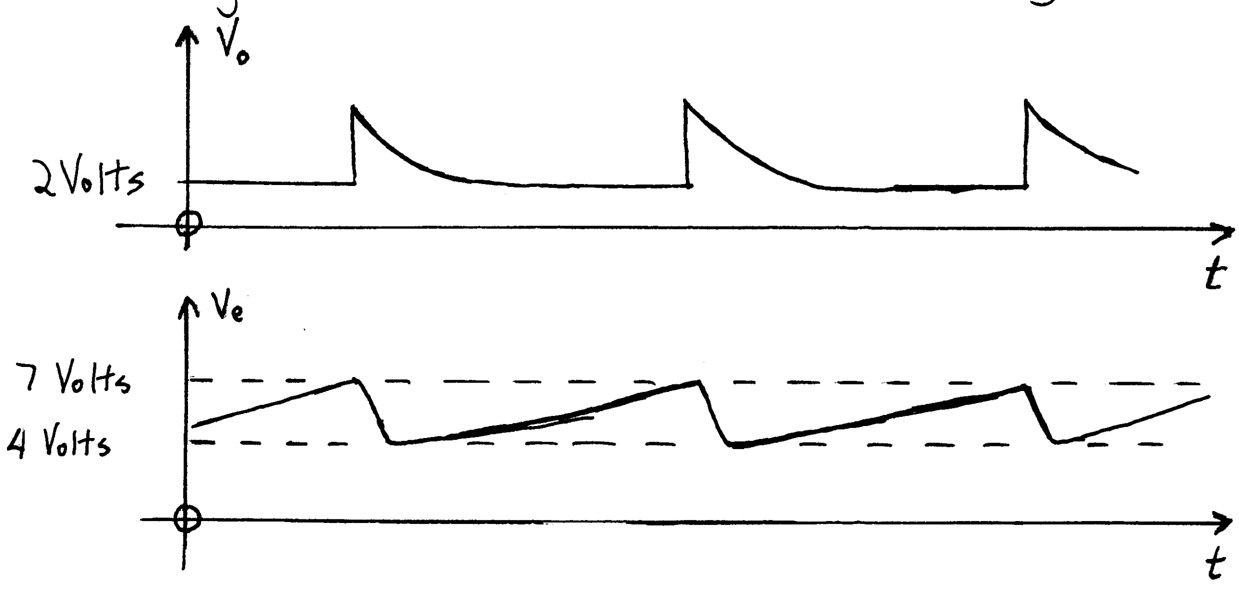

Figure 3.10 Unijunction Circuit Waveforms (for constant force)

capacitor. At the end of the pulse, V_e is one diode voltage drop above the final value of V_a, and if the emitter current is small enough the diode closes and the cycle repeats itself.

The associated waveforms are those shown in figure 3.10. It was decided to limit V_e to a three-volt swing due to practical problems at the output of the amplifier. In order to have the amplifier output appear as a current source, the voltage it sees should vary as little as possible. As we shall see in section 3.3.3, if we are to insist on a minimum V_{ce} of one volt for the amplifier output transistors, then V_e is constrained to be between 3V and 8V. Thus it was decided to let V_e swing over a range of 4V to 7V.

This was accomplished by means of resistors in series with the two bases of the unijunction transistor. The transistor used had an interbase resistance R_1+R_2 of 6K to 7K and an η of approximately .7. Thus the maximum value of V_e is given by:

$$(V_e)_{max} = \left(\frac{R_A + R_1}{R_A + R_B + R_1 + R_2}\right) 12\,V \qquad (3.19)$$

$$\frac{R_1}{6.5K} = .7 \longrightarrow R_1 = 4.5K \qquad (3.20)$$

$$R_2 = 2K \qquad (3.21)$$

If we choose R_A=2.2K and R_B=3.3K, we get:

$$(V_e)_{max} = \left(\frac{2.2 + 4.5}{2.2 + 3.3 + 6.5}\right) 12V = 6.7V \qquad (3.22)$$

It was found experimentally that V_e drops to slightly less than 2V more than the d-c value of V_o.

$$(V_o)_{d.c.} = \left(\frac{2.2}{2.2 + 3.3 + 6.5}\right) 12V = 2.2\,V \qquad (3.23)$$

Thus the minimum value of V_e should be about 4V. It was found that using these values of R_A and R_B, V_e did actually move over the calculated 4V to 7V range.

The value of capacitance is chosen to fit expected input current and the amount of time desired between output pulses. Since we are using a 200 msec multi-vibrator in the counter circuit, the minimum time allowable between output pulses is 200 msec.

It was found that with this particular unijunction transistor, any value of I_s greater than .5ma was large enough to prevent the emitter diode from turning off when the capacitor is discharged, thereby preventing further operation of the circuit. Therefore it is necessary to work with input currents of the order of .25ma.

This restricts us to a range of capacitance values in which 18μf is the only capacitor readily available. Using this value, and a V_e swing of 3V, we find that with I_s=.25ma, the time between pulses is:

$$T = \frac{cV}{i} = \frac{(18 \times 10^{-6})3}{.25 \times 10^{-3}} = 216 \text{ msec} \qquad (3.24)$$

Since this is near the minimum time of 200 msec, it is necessary to design the amplifier with output current no greater than .25 ma.

3.3.3 Amplifier Circuit

Design of the d-c force amplifier proved to be the major stumbling block in the way of a simple device which would not only measure force but also detect a "check", or instantaneous negative force. We recall from section 3.2 that in order to meet this specification, it is necessary to use two strain gauges, supplying signals of the order of a few tenths of a millivolt in magnitude, as inputs to a differential amplifier.

The major problem was not one of increasing amplifier gain in order to get an acceptable output signal level, but of decreasing the drift. The amplifier configuration is that shown in figure 3.11. At first a single transistor was used in place of the differential second stage (Q_3 and Q_4).

The voltage at point A represents the output of the amplifier circuit. Transistor Q_5 can be thought of as a current source whose output is some d-c value of current plus signal current. Q_6 is just a current source which is adjusted in such a way as to balance the d-c level of the current from Q_5, so that output current is zero for zero signal.

When an input force of the correct magnitude was simulated by placing a 1Meg resistor across the 120-ohm resistor representing the pin support strain gauge, an output current swing of the order of 100μa was observed, however it was necessary to continually readjust the Q_6 emitter resistance in order to have a d-c output current of zero. Due to drift in the d-c amplifier if the emitter resistance was left at one setting, the output current would vary over a range as big as the peak signal swing of 100μa.

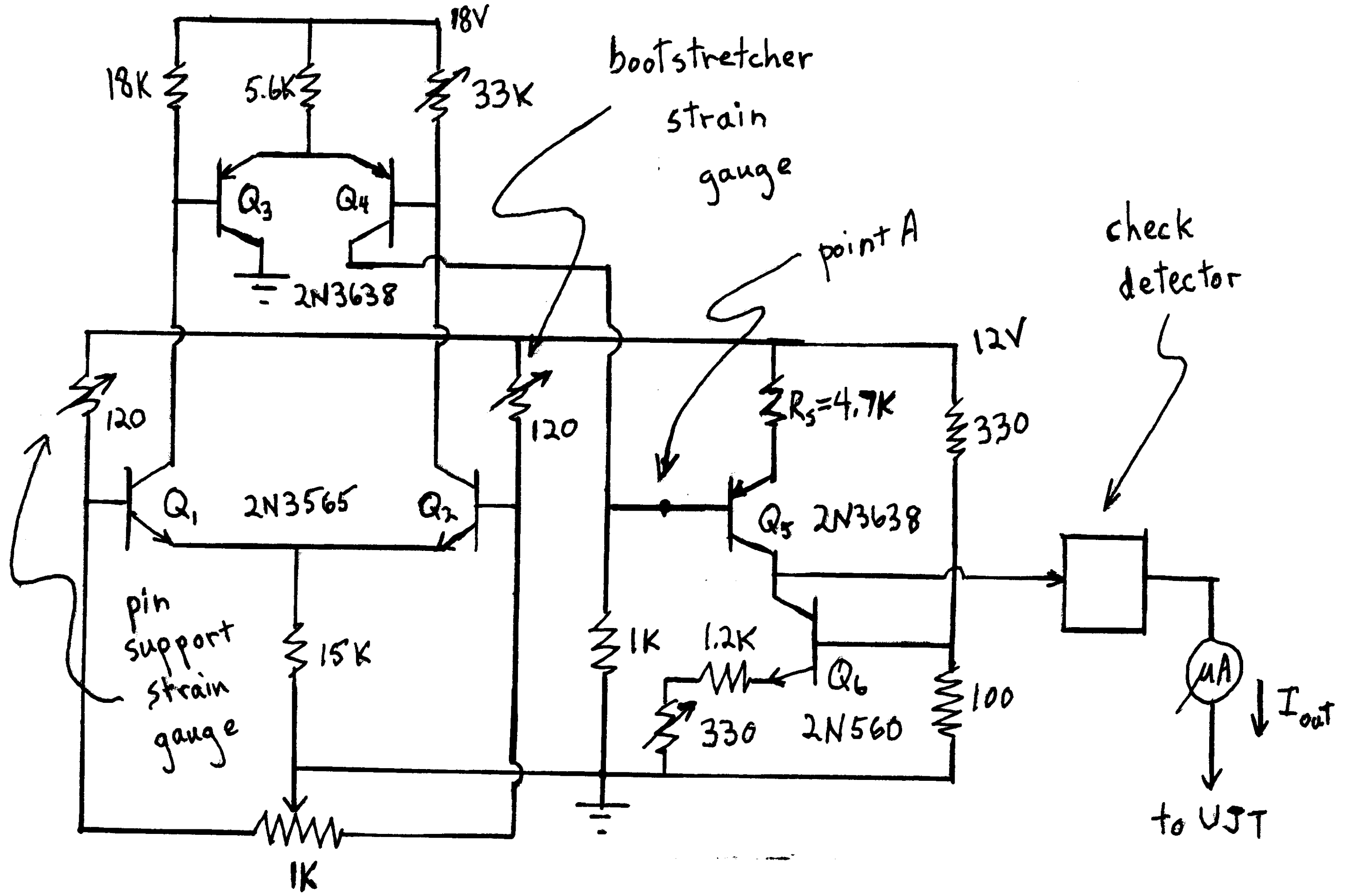

Figure 3.11 Basic Amplifier Circuit - Without Feedback

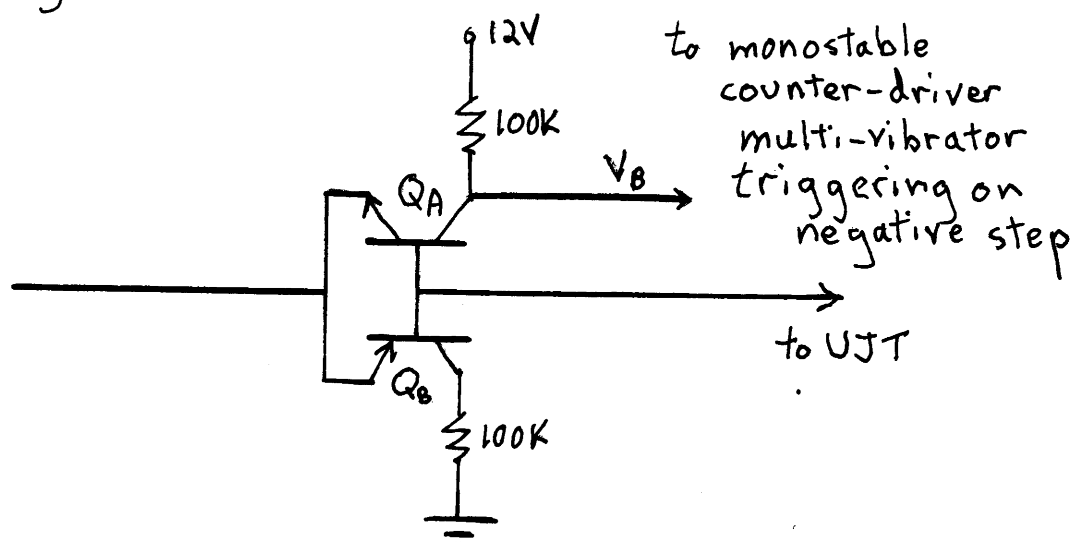

Figure 3.12 "Check" Detector

Thus it became apparent that it would be necessary to reduce the drift, The first step was to include the differential second stage as shown in figure 3.11. In order to minimize the drift, the input transistors Q_1 and Q_2 were chosen with equal V_{BE}'s.[5] Only silicon transistors were used in order to minimize drift due to variations of V_{BE} due to temperature.

These changes did serve to reduce the drift appreciably, but not to an acceptable point. This is due to the fact that even with silicon transistors, V_{BE} changes by a millivolt every 10°C. Thus our signals are equivalent in magnitude to drift signals which would be introduced by a relative change of only one or two degrees in temperature between the emitter junctions of the two input transistors. We see that if we wish to use a d-c amplifier of this type, the problem is one of input level vs. drift as seen at the input. In this case, it is impossible to stabilize the amplifier by means of feedback because the feedback does nothing but reduce the effective gain. If input drift and input signal are of the same magnitude, it is impossible to separate them at the output.

At this point we are faced with two alternatives. The first of these is to go to a chopper-stabilized d-c amplifier, so that we are effectively working with a-c signals. If we synchronously demodulate the output, it is still possible to have an output current which can go negative, indicating a "check". This negative current is then detected by the circuit of figure 3.12, in which Q_A quickly saturates as I_{out} goes negative, causing V_B to jump downward by several volts, thereby triggering a monostable multi-vibrator which drives a mechanical counter.

5 Hoffait and Thornton: "Limitations of Transistor D-C Amplifiers", Proceedings of the IEEE; February, 1964

The second alternative, which was chosen mainly for reasons of circuit simplicity, is to sacrifice the "check"-measuring ability, and to work with the much larger input level from a single strain gauge mounted so as to measure bending of the oarlock pin.

With this input, we are working with signals of sufficient magnitude relative to the drift present. Therefore, it is possible to increase the gain of the basic amplifier and then use feedback to stabilize both the output level for zero signal and the gain. The final amplifier configuration is shown in figure 3.13.

The resistor R_c=22K and emitter follower Q_7 were added in order to increase the open-loop gain by increasing the load resistance seen by the second stage of the amplifier, while leaving the impedance seen by Q_5 unchanged.

The resulting high gain operational amplifier is then stabilized by placing feedback resistor R_f between V_o and the input. We then have negative feedback, since the effect of an increase in input voltage (due to a compression force decreasing the strain gauge resistance) is to lower V_o, thereby drawing current away from the input through R_f.

When the appropriate force level is simulated by placing a 15K resistor across the 120-ohm strain gauge, the output current can be observed by means of a milliammeter .2ma, it was necessary to make R_f=1.5K.

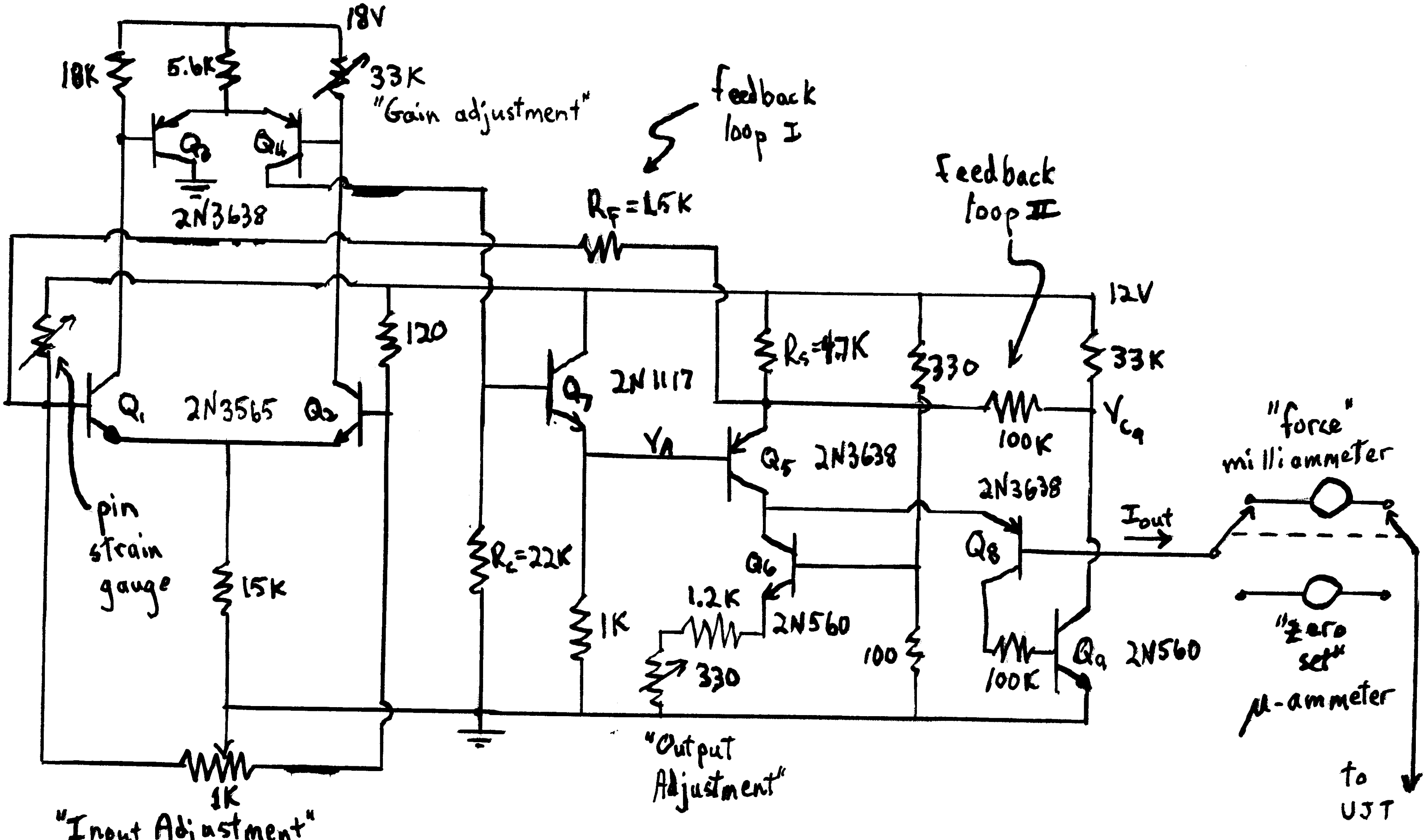

Figure 3.13 Amplifier Circuit-With Feedback

In addition to R_f, the feedback loop around the operational amplifier, a second feedback loop was introduced to further stabilize the d-c output current at zero by compensating for drift due to transistor Q_6. This can be thought of as a "saturating feedback loop", as it is only effective for very small values of I_{out}. Assuming that I_{out} is small enough for Q_8 to be in the linear region, then a slight increase in I_{out} due to drift in Q_6 causes β_8 times that increase in the base of Q_9 and $\beta_8\beta_9$ times that increase in the 3.3K collector resistor of Q_9. This causes a relatively large drop in V_{C_9} so that current is drawn through the 100K feedback resistor away from the emitter of Q_5, and I_{out} is decreased. If I_{out} is greater than a few microamps, however, Q_8 saturates, and the feedback loop ceases to affect I_{out}. Thus, feedback loop II is especially effective in that it decreases the gain for drift current but not for signal current. It was found that the combination of two feedback loops was quite effective in stabilizing the output current with no force present.

For proper operation of feedback loop II, it is best to set the output adjustment (330-ohm pot at emitter of Q_6) such that I_{out} with no force present is $1\mu a$, rather than zero. This does not lead to inaccuracies because the reverse-biased diode in the emitter of the unijunction transistor does have some finite leakage current of the order of a microamp. The input adjustment should be set so that the level of current through Q_5 is in the range which can be balanced by an adjustment of the 330-ohm pot at the emitter of Q_6. This will correspond to a level of V_o between 9V and 10V.

The variable resistor marked "gain adjustment" on figure 3.13 should be set so that all the signal current at the collector of Q_2 goes into the base of Q_4. Evidence of a correct setting of this pot is a high frequency oscillation (approximately 6Mcps) appearing superimposed on the d-c voltage at V_o. This oscillation, due to very high loop gain, has no effect on the output current, but is useful in determining whether or not the circuit is operating properly.

In practice, it is necessary to make several successive adjustments in turn to the "input adjustment" and "gain adjustment" pots, in order to get V_o at the proper d-c level and at the same time have gain high enough for oscillation. Once these pots are adjusted, I_{out} is set to 1μa using the "output adjustment" pot and "zero set" microammeter. The output current is then switched to the "force" milliammeter, and the circuit is ready for use.

3.4 Timing Circuitry

The logic circuitry for detecting whether a given oarsman starts his stroke early or late with respect to the stroke man is shown in figure 3.14.

When triggered, the monostable multi-vibrators stay on for an amount of time T, called the "timing threshold". From rowing experience, it was decided to set the threshold at about 80msec, so that only a timing error of greater than 80 msec appears at the output. In practice, it may appear that this threshold value is too great (obvious timing errors not being counted) or too little, however, the threshold time can be easily adjusted by varying the value of the coupling capacitor in the monostable multi-vibrator.

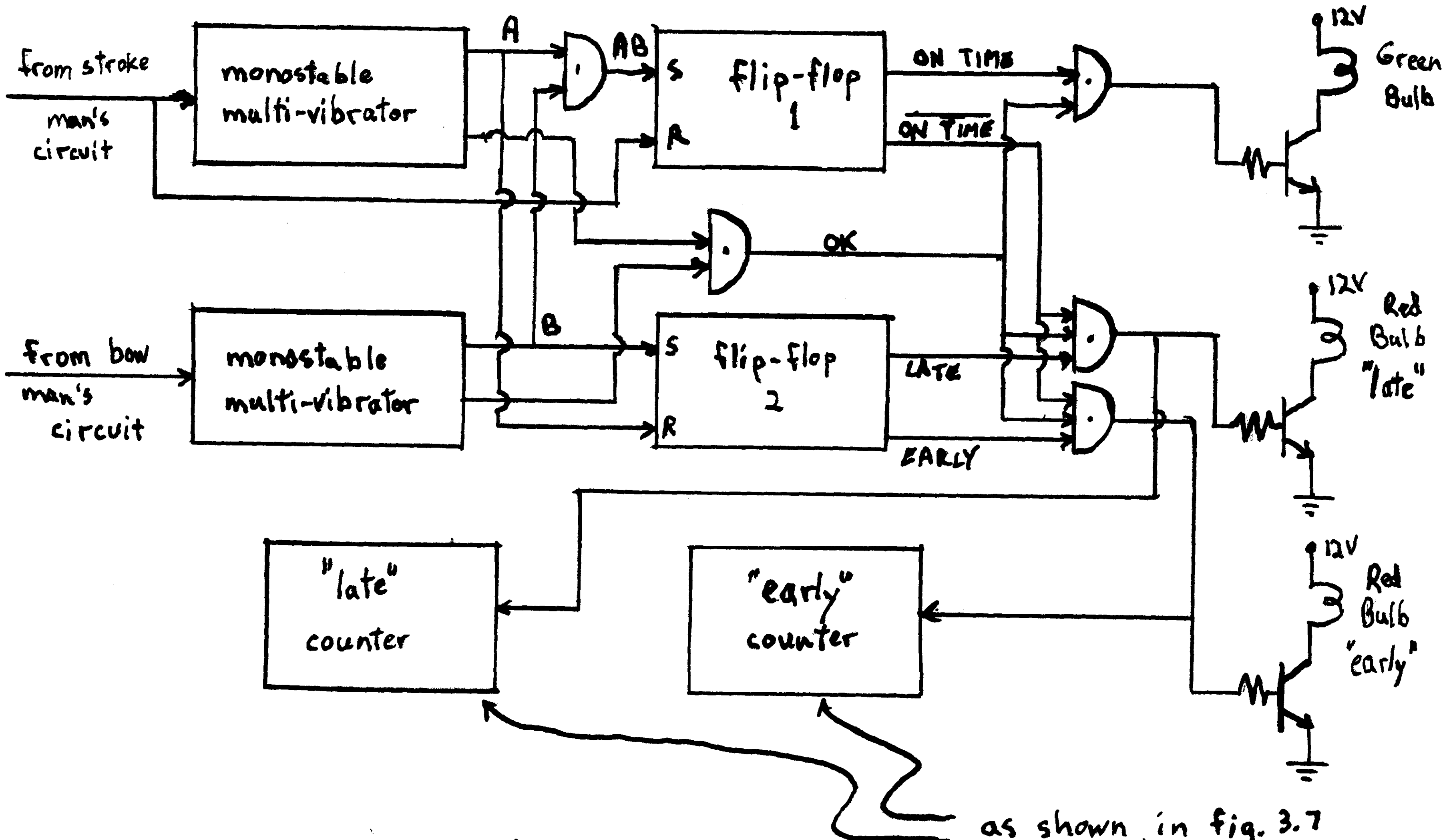

Figure 3.14 "Timing" Detection Scheme

Indeed, the coach may choose to utilize this capability to decrease the timing threshold as the season wears on and the oarsmen's timing sharpens up.

With this design, the bow man is judged to be "on time" if the beginning of his stroke comes within 80 msec of the beginning of the stroke man's stroke. Each monostable multi-vibrator is triggered by a signal from the respective man's force circuit. If the two strokes start within 80 msec of each other, then logical variables A and B are logical 1 simultaneously for some small instant of time (up to 80 msec). Thus the logical variable AB makes a zero-to-one transition and sets flip-flop 1, so that the logical variable ON TIME goes to 1.

We see that at the beginning of each stroke, it is necessary to reset flip-flop 1. At first it was thought that this could be done by means of the positive transition in logical variable A, however this leads to the following condition, known as a "race": If the bow man's stroke has begun before the stoke man's, but not 80 msec before, when the stroke man starts his stroke, we want to set flip-flop 1, indicating that the two strokes were within 80 msec of each other. However, if there is no delay in the AND gate, the positive transition in A occurs at the same time as the positive transition in AB, so that we are trying to set and reset flip-flop 1 at the same time. The remedy for this is to put a slight delay in the line between the AND gate and the set terminal of flip-flop 1, or alternately, to reset flip-flop 1 on the stroke man's triggering signal itself. This eliminates the race effectively, since there is a slight delay involved in the switching of the monostable multi-vibrator. This second alternative was chosen because it avoided the use of an added delay element.

Now let us see what happens when the two strokes do not start within 80 msec of each other. If the bow man goes in early, logical variable B goes to 1 before logical variable A, so that flip-flop 2 receives a "set" pulse first and then a "reset" pulse, and ends up in the state in which logical variable EARLY is 1.

If the bow man starts his stroke later than the stroke man, the transition of B occurs later, flip-flop 2 receives a "set" pulse after a "reset" pulse, and logical variable LATE is 1. In either case, ON TIME is 1 if the strokes began within 80 msec of each other, and $\overline{\text{ON TIME}}$ is 1 otherwise.

The logical variable OK, which is one when both monostable multi-vibrators are in their normal, or off, state, signifies that it is okay to display the output. Thus the timing indicator lights are off in the instant of time surrounding the beginning of the stroke, when all the variables are changing and the lights would be meaningless.

When OK goes to 1, the circuit will be in one of three states, ON TIME, ($\overline{\text{ON TIME}}$)LATE or ($\overline{\text{ON TIME}}$)EARLY, and the appropriate light will go on. At the same time, the associated "early" or "late" counter is incremented by one if necessary.

Let us now consider the source of the triggering signals. If we refer to figure 3.13, we note that, for very small values of I_{out}, with Q_8 unsaturated, the voltage on the collector of Q_9 is:

$$V_{C_9} = 12 - (3.3K)\beta_8\beta_9 I_{out} \qquad (3.25)$$

If we choose transistors such that $\beta_8\beta_9$=1000, and set the output adjustment so that I_{out}=1μa, then we get a value of V_{C_9} near 9V for the no signal condition. As the stroke begins, I_{out} immediately increases by several orders of magnitude, so that Q_8 saturates instantaneously. This causes V_{C_9} to jump sharply downward at the beginning of the stroke.

Thus, we must design the monostable multi-vibrators, as well as the reset terminal of flip-flop 1, to trigger on negative steps. Since we are using a positive power supply and npn transistors, this involves using the negative step to turn off the "on" transistor.

Flip-flop 2, and the set terminal of flip-flop 1, are triggered on positive transitions. This involves turning on the transistor which is off. Circuit diagrams for the multi-vibrators, flip-flops, and AND gates used are shown in figure 3.15.

The calculated value of R_b to give T=80 msec is approximately 40K. The reason it is necessary to use a value of R_b of 150K in order to get the required T is that the 2N4819 transistor has an emitter-base breakdown voltage of only a few volts. Thus, instead of charging from -12V through R_b, the coupling capacitance sees the small resistance of the avalanched emitter diode until the base voltage has increased to about -4V. The base voltage reaches -4V in very short time, and only has to go from -4V to 0 with time constant R_bC instead of from -12V to 0. A solution would be to use transistors with base-emitter breakdown voltage V_{EBO} greater than

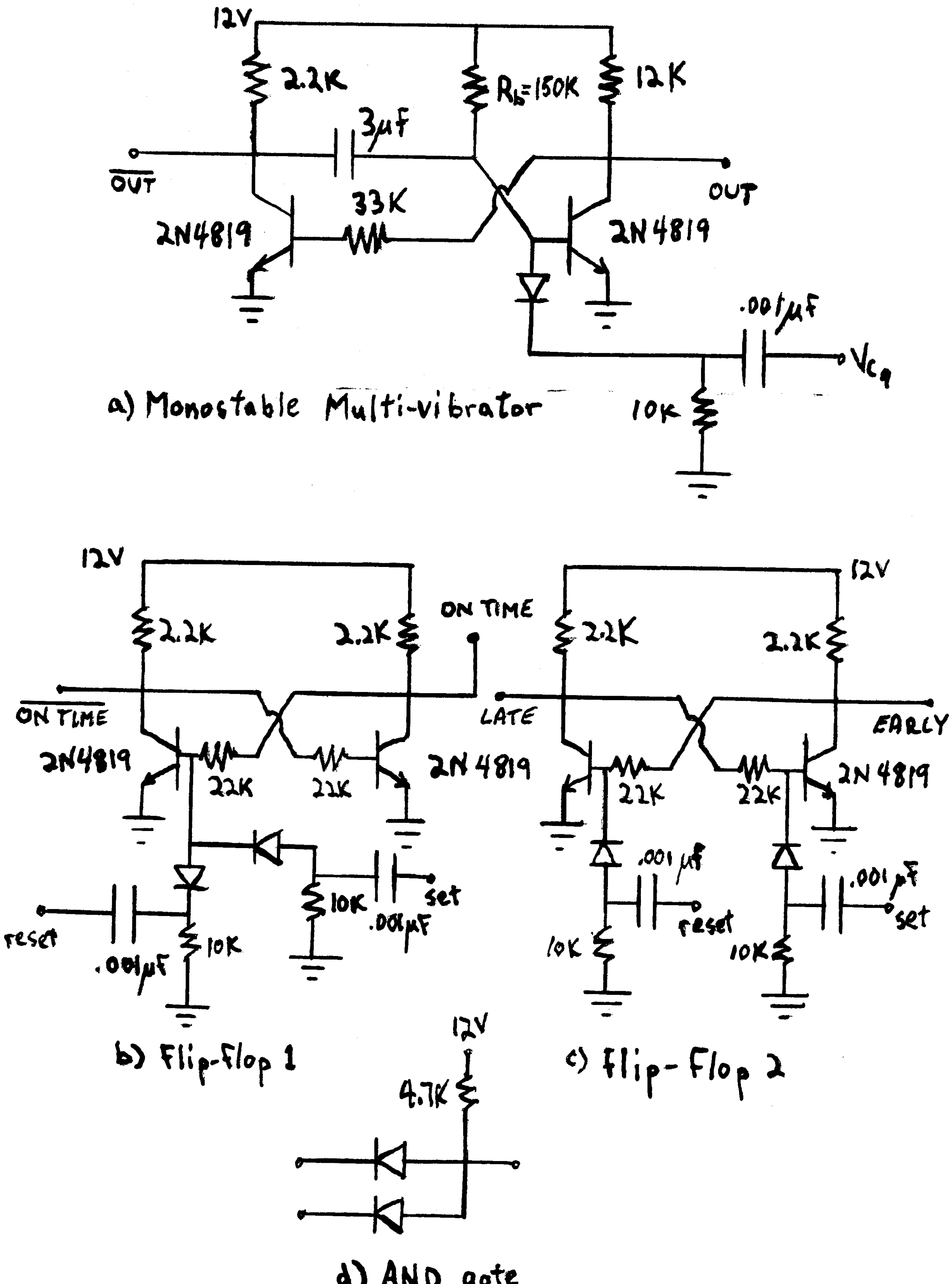

Figure 3.15 Logic Circuits Used to Detect Timing

12V, but it was decided to increase R_b instead, due to the availability of the 2N4819's.

When the timing detection system was built in the lab, it was found that the monostable multi-vibrators were triggering at the end of each stroke as well as the beginning. The reason for this was that in the lab, force was being simulated by placing a 15K resistor across the terminals of the strain gauge. Sometimes in removing this 15K resistor, inadvertent recontact was made, so that, as far as the multi-vibrators were concerned, a new stroke had been initiated. Within this constraint, the timing detection system worked well in the lab.

Chapter 4 - Results and Conclusions

Due to delays in the completion of the new M.I.T. boathouse and rowing tank it was decided to construct a force measuring and integrating system for use on a two-man shell, actually rowing on the river.

Amplifier-integrator circuits were built for each oarsman, on individual circuit cards. The circuits were placed in a small cabinet, whose front panel contained an input receptacle, mechanical counter face (readout of integral of force over time) for each oarsman, input, gain and output adjustment pots, and meters to read out instantaneous force for each oarsman and to set the output to zero for zero force. Photographs of this equipment are shown in figure 4.1.

The amplifier-integrator cabinet, as well as 12V, 18V and 30V power supplies are located in the head coach's launch during use. This launch is equipped with a 115V alternator. The strain gauges and amplifiers are connected by means of a three-conductor Belden waterproof cable, 50 feet in length, running between the launch and shell. The cable is equipped with plug units at both ends so that the shell is not constrained to be near the launch while tests are not in progress, and yet can be hooked up for the tests in a matter of seconds.

Two special oarlock pins, like the one of figure 3.3, were machined out of brass. SR-4 type A-3 wire strain gauges were mounted on these pins with Duco cement.

After the strain gauges were connected to lengths of lamp wire which were to run from the riggers to a point near the coxswain's

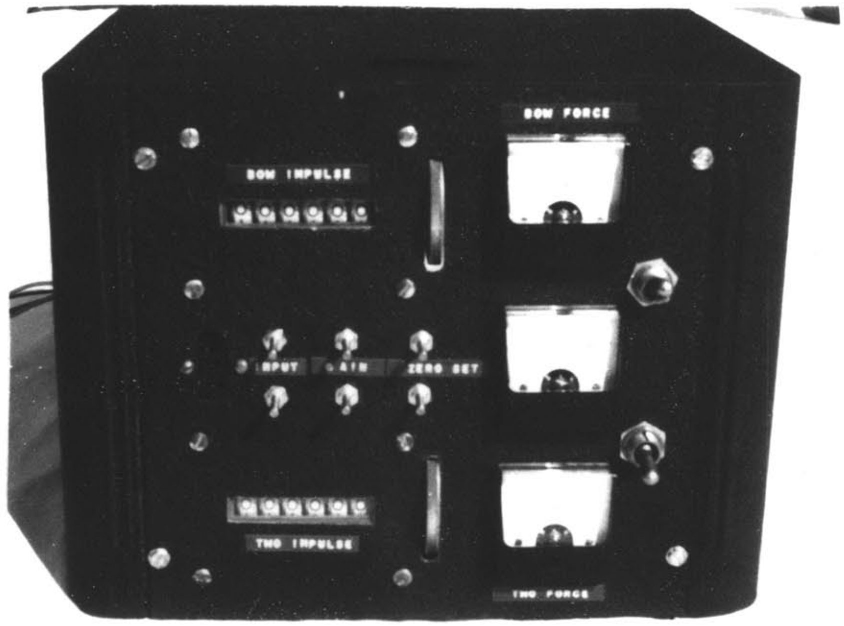

Figure 4.1 a Amplifier-Integrator Panel

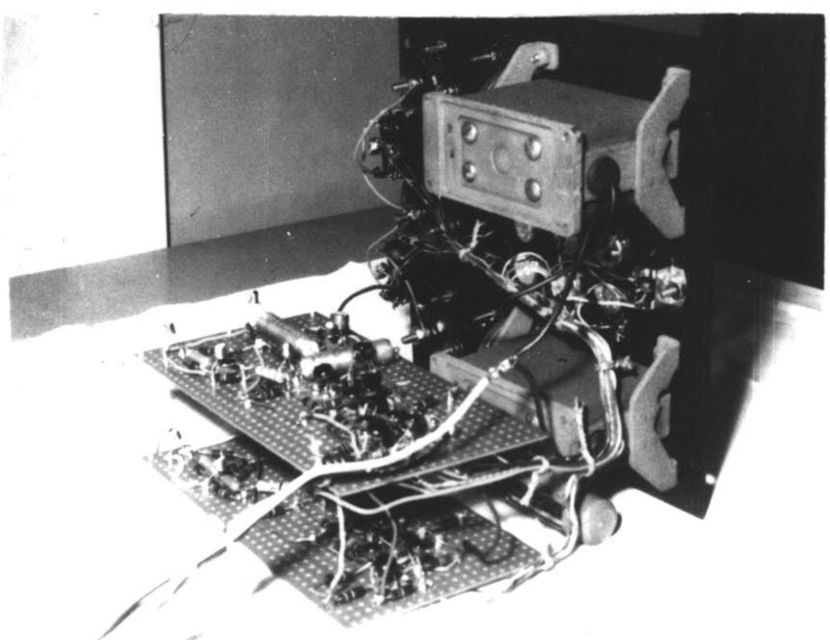

Figure 4.1 b Circuits and Back of Panel

seat, it was found that the stroke man's strain gauge had become an open circuit. Close inspection revealed that the break was at the point where the lead was attached to the thin loop of wire forming the actual gauge. This illustrates the point that extreme care must be exercised in handling the gauges during mounting.

At this point, it was decided to test the remaining circuit on the water. The circuit was adjusted properly in the lab, to facilitate adjustment at the boathouse, where an oscilloscope was not available. However, during transit, the setting apparently changed, and the 1K "input adjustment" pot became burned out as soon as power was applied to the circuit.

Thus due to last-minute malfunctions in the stroke man's strain gauge and bow man's circuit, it has been impossible to obtain data on the operation of the system in actual use on the river. It is anticipated that the system will be in operation within a week of this writing.

The 1K input will be replaced by a 330-ohm pot in series with two 330-ohm resistors, one on each leg of the input bridge. This will serve to prevent burnout of the pot and in addition will make the input adjustment less sensitive.

Before the system is installed in the boathouse, it will pay to try redesigning it to use an a-c input to the bridge, a-c amplifier, and simple envelope detector to demodulate the output.

The envelope detection scheme was not suitable for use with signals that can go both positive and negative, and therefore was not considered at first. When it was decided to sacrifice the "check" detecting ability and work with signals of only one polarity, it was easier to work with the same amplifier rather than go to an entirely new scheme. However, the a-c scheme rates consideration, as it would eliminate the fine adjustments that are necessary for the d-c scheme to work properly.

This question notwithstanding, the work done thus far has definitely proven the feasibility of a system to measure the force each oarsman puts into the forward progress of the boat and to integrate this force over time to get the impulse, or amount of momentum each oarsman contributes to the boat over a given practice run.