DESIGN OF MULTIPLE CHANNEL HOT WIRE ANEMOMETERS

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ABSTRACT

An anemometer design is presented which provides 138 channels of hot wire anemometry for simultaneous sampling of low frequency turbulent events. Each anemometer is fitted with a sample and hold circuit and an 8th order, low pass Bessel filter. There are 16 anemometers placed on a circuit board. A multiplexer is mounted on each board to select one of the anemometers for data output to an analog to digital (A/D) computer. Each board is therefore connected to only one channel of the A/D. With 16 channels of A/D and 16 anemometers on a board it is possible to measure at 256 different locations simultaneously. The cost of the individual anemometers was kept low (about $50 each) so that many anemometers could be utilized.

The experiment to which this anemometer design will be applied is the simultaneous sampling of the velocity field in the mixing layer of an isothermal, axisymmetric jet. Proper care is taken to resolve the entire flow field, thereby limiting the amount of spatial aliasing of the azimuthal modes. The use of long hot wires aids in the reduction of spatial aliasing.

INTRODUCTION

In order to study the dynamics of large scale turbulent structures in the axisymmetric jet mixing layer, it is necessary to sample the velocity field at many positions simultaneously. The entire velocity field must be known at a single instant because this is a requirement of the Galerkin projection of the orthogonal functions, obtained via the Proper Orthogonal Decomposition (Lumley, 1967), onto the velocity field. Performing the projection allows the determination of the orthogonal function coefficients which govern the coherent structure dynamics.

The minimum number of measuring positions required to resolve the essential modes in the streamwise velocity field of the axisymmetric jet mixing layer was determined to be 138, and so 138 anemometers and single-wire hot wire anemometers are required. The cost of commercial systems precluded their use so a new multichannel anemometer design was needed. A simple anemometer design was utilized and new features were added to measure the numerous positions simultaneously.

The positions at which velocity measurements will be made in order to recover the instantaneous velocity field in the mixing layer of the jet were determined using the data of Glauser *et al* (1987). Each measurement position requires a separate hot wire anemometer probe and a supporting scaffold will hold each probe in place. The purpose of the probes is to measure the streamwise velocity field at enough points so that the large scale structures, which have been obtained by application of the Proper Orthogonal Decomposition, may be projected back onto the instantaneous velocity field. The actual probe positioning is discussed in Citriniti and George (1994). The probes and scaffold outlined there combined with the anemometer design presented here will be used to determine information pertinent to understanding the dynamics of the large scale structures in the axisymmetric jet mixing layer.

The overall requirements for the anemometers are not extreme. The dominant structures in this flow are found in the 500-800 Hz range and since the Nyquist criterion must be met, the sampling rate must be at least 1000-1600 Hz. This is easily handled by the anemometer design to be presented. Also, the study aims to educe the large scale, energy containing eddies in the flow which contain a majority of the kinetic energy. Accordingly, since only the most energetic scales are of interest, the smaller scale motion and noise are undesirable features, especially if they are aliased into the lowest frequencies and contaminate the large scales. However, since the turbulent velocity field will be dominated by the large scale structures, small scale perturbations will be minimal.

ANEMOMETERS

The design of the individual anemometers for the proposed experiment follows that of Perry (1982). A sketch of Perry's anemometer design is presented in figure 1. Perry's design was chosen for this experiment because it is simple and well documented. It requires only two operational amplifiers and a Wheatstone bridge. The design, described in detail below, lends itself readily to the numerous anemometers required here and the dynamical characteristics of this design are more than sufficient for the low frequency measurements to be made.

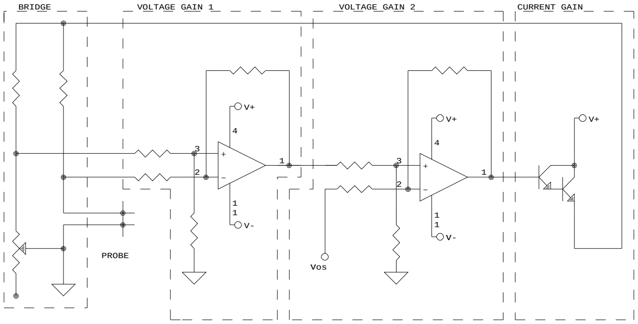

FIGURE 1. ANEMOMETER DESIGN FROM PERRY (1982) WITH CURRENT GAIN STAGE.

The hot wires to be used with these anemometers are made of unplated, 12.7µ Tungsten wire (Sigmund-Cohn, Mt. Vernon, NY). The wires are welded to in-house probe holders manufactured using Ciba-Geigy Araldite epoxy. Two 0.05 cm steel music wires are embedded in the epoxy which act as leads and the Tungsten wire is welded between them such that the $l/d \sim 1,000$. The time constant of these wires is approximately $1x10^{-4}$ sec and each hot wire draws approximately 50 mA. These parameters are all considered in the design of the individual anemometers.

CIRCUIT DESIGN

The basic circuit is a Wheatstone bridge with a bridge resistance ratio of 10:1. Two operational amplifiers (National LF347 Quad JFET) are used to amplify the bridge unbalance voltage (see figure 2). The second of the two has an offset voltage which starts the feedback operation and controls the frequency response of the electrical circuit. The two operational amplifiers have low noise, high gain and wide band width characteristics. The open loop voltage gain for both op-amps is 10^5. Following the second operational amplifier is a Darlington transistor which is used to control the current in the feedback loop. The overheat ratio on the Wheatstone bridge is adjusted with a Clarostat 200 Ω potentiometer which provides sufficient range for this experiment.

There is no compensation on the bridge for inductance and capacitance effects due to cable lengths because they were found minimal during initial testing. The numerous channels of anemometry would require individual tuning of the compensating devices and phase matching all of the anemometers would therefore be difficult. In particular, the improvement of frequency response by adjusting the bridge inductance was slight and determined unnecessary for this experiment. Preliminary measurements show the frequency response of the circuit is about 10 kHz. This is orders of magnitude higher than the signals of interest in this flow (200-500 Hz) without compensating inductance. The frequency response can be improved however by adjusting the offset voltage on the second operational amplifier.

The noise in the circuit has been kept to a minimum. The circuit board design provides a good connection for all components and the ground plane reduces unwanted externally induced noise. The voltage fluctuation about the mean induced by the circuit noise (noise from the power supplies, circuit components and connection cables) was less than 1mV in steady laminar flow. When the sensitivity of a hot wire with an $l/d \sim 200$ was factored in this corresponded to a turbulence intensity of 0.02%. This value represents the turbulence intensity artificially created by the noise in the circuit and provides a measure of the accuracy that the anemometer-probe circuit can provide. Testing continues on the anemometers to determine the exact frequency response, noise properties and overall phase characteristics.

ANTI-ALIASING FILTERS

There are a number of unique features which were developed for this anemometer design. Firstly, to avoid temporal aliasing of the velocity signals due to the low overall sampling rate of the circuit, anti-aliasing filters were added to each anemometer. These 8th order, low pass Bessel filters have a 48dB per octave roll-off. The corner frequencies can be set from 0.1 to 25 kHz and are clock tunable using a standard function generator. The 8 pin DIP design provides a low noise, fast settling time device.

Bessel filters were chosen because they provide a fast roll-off and a linear phase shift. The linear phase shift is vital since the velocity measurements in this experiment must be made simultaneously. Other filters (*e.g.* Butterworth filters) have non-linear phase shift properties making it impossible to recover the phase characteristics of the instantaneous velocity using them. With a linear phase shift filter the effect on the measured instantaneous velocity is simply a constant time lag which can be accounted for in the post processing of the data.

To see the phase lag look at the phase shift introduced by the filter,

$$\hat{\underset{\sim}{u}}(f) \rightarrow \boxed{\text{FILTER}} \rightarrow e^{i\phi(f)}\hat{\underset{\sim}{u}}(f) \tag{1}$$

where $\hat{\underset{\sim}{u}}(f)$ is the Fourier transformed velocity vector and $\phi(f)$ is the phase shift introduced by the filter. Let $\hat{\underset{\sim}{u}}_f(f) = e^{i\phi}\hat{\underset{\sim}{u}}(f)$ be the velocity vector in Fourier space after passing through the filter and using the definition of the Fourier transform,

$$\underset{\sim}{u}_f(t) = \int_{-\infty}^{\infty} e^{-i2\pi ft}\hat{\underset{\sim}{u}}_f(f)df \tag{2}$$

substituting in for the post filter velocity,

$$\underset{\sim}{u}_f(t) = \int_{-\infty}^{\infty} e^{-i2\pi ft}e^{i\phi(f)}\hat{\underset{\sim}{u}}(f)df \tag{3}$$

The linear phase shift of the Bessel filter implies that the phase shift is linear with frequency so,

$$\phi = 2\pi qf \tag{4}$$

where q is the slope of the phase angle versus frequency curve for the filter. Combining (3) and (4) yields,

$$\underset{\sim}{u}_f(t) = \int_{-\infty}^{\infty} e^{-i2\pi f(t-q)}\hat{\underset{\sim}{u}}(f)df \tag{5}$$

or in real space,

$$\underset{\sim}{u}_f(t) = \underset{\sim}{u}(t-q) \tag{6}$$

This result shows that the linear phase shift of the Bessel filter merely adds a constant time lag to the instantaneous velocity. The time lag can be removed after the properties of the filter are known. If all filters are phase matched, the net effect of the Bessel filters is to delay all signals by the same time constant.

CONSTRUCTION AND ASSEMBLY

The experiment proposed requires the simultaneous measurement of the velocity field with 138 anemometers. The anemometer design presented in the previous section needs to be replicated for all 138 measurement positions. To accomplish this, circuit boards were manufactured which contain 16 anemometers each. A picture of one board of 16 anemometers is presented in figure 3.

The 16 individual anemometers on the board are arranged in rows of 5 starting at the top of the board with one extra on the lower left (see figure 3). The multiplexer, input power and connections to a digital control board are at the bottom of the board. The circuit photo-plot artwork for the boards was performed by Circuit Design Service in Buffalo, NY and the board manufacturing was done by Buffalo Circuits, Buffalo, NY. The boards are 22.86 cm (9 in.) wide and 27.94 cm (11 in) wide. There are two adjustable resistors per anemometer, one for overheat setting and one for output control. The board with all circuitry weighs about two pounds.

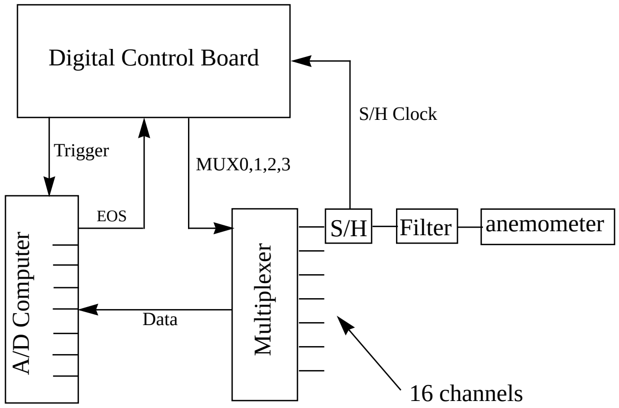

FIGURE 5. CONTROL PROCESS FOR DATA ACQUISITION.

SAMPLE AND HOLD

To ensure that all of the 138 velocity measurements are acquired simultaneously, each anemometer is fitted with a sample and hold. Each sample and hold is placed on the circuit board following the Bessel filter (see figure 2). This Burr Brown 12 bit DIP design chip has less than 10 µs acquisition time, a low droop rate (1mV/ms) and an aperture time of 200 ns. A digital control board (figure 4) maintains the timing of the collection circuit so that all sample and holds latch their measurement at the same instant. The digital control board is triggered by the A/D to ensure synchronized timing.

DATA ACQUISITION AND ON BOARD MULTIPLEXING

Because of the relatively low upper frequency for the proposed experiment, the actual sampling rate required by the Nyquist criteria is substantially below the capabilities of the A/D in the lab at SUNY at Buffalo (maximum sampling rate 325 kHz). Therefore it is possible to sample many channels of anemometry through a single A/D channel by multiplexing the anemometers. Since there are 16 anemometers on a board, a 16 channel analog multiplexer was installed on each board. The duty of the multiplexer is to select a single anemometer, on a board of 16, whose signal is to be sent to the A/D.

The multiplexer is triggered by the digital control board which directs the multiplexer to select each anemometer on the circuit board in succession until all 16 anemometers are read by the A/D. The process is as follows: a GO pulse resets the entire system such that the multiplexer (MUX) is set to anemometer one on each board. The sample and hold on each and every anemometer goes high to record a data point and holds this data point. The digital control board (DCB) sends a trigger pulse to the A/D to begin recording data. The A/D records the data point in all 16 channels (note that each channel of A/D is connected to a separate MUX and each MUX has 16 anemometers connected to it). The A/D then sends an end of signal (EOS) pulse to the DCB. This prompts the DCB to increment all MUX's to the second anemometer and the process repeats. This continues until all 16 anemometers on all of the boards are read. Note that all sample and holds record a data point simultaneously so the time required to transfer the data points to the computer only affects the overall sampling rate and not the simultaneous sampling.

Sampling rate requirements for this experiment are easily met. The purpose of this study is to understand the dynamics of the large scale structures in the axisymmetric jet mixing layer and the structures of interest are dominant in the low frequencies. The A/D used for this study has a maximum sampling rate of 325 kHz which, when divided by the total number of channels sampled, provides the maximum sampling rate of any of the channels. With 138 channels this limits the sampling rate to over 2 kHz per anemometer. The A/D is the limiting factor in determining the sampling rate as the MUX and associated circuitry operates faster than the A/D.

CONCLUSIONS

The anemometer design presented in this paper is a relatively inexpensive (about $50 per anemometer), stable and reliable device. Multiple anemometers are thus easily obtainable and affordable by putting many anemometers on a circuit board. This allows for multiple velocity measurements for the cost of a single commercial unit. Each anemometers has its own Bessel low-pass filter to protect against temporal aliasing and sample and hold to collect many velocity measurements simultaneously. Multiplexing is provided for each board of anemometry to reduce the number of channels of Analog to Digital conversion required. In the future A/D modules may also be placed on each anemometer so that each would have its own complete data acquisition system. The design presented here opens new possibilities for multi-point measurements.

The instantaneous measurement of the streamwise velocity, azimuthal mode number spectra can be accomplished by the anemometers outlined in this paper. Proper attention to sampling rates and filter properties has been provided to ensure there is no spectral aliasing or loss of phase information. The characteristics of the anemometers presented here provide ample speed and sensitivity to accurately measure the velocity field at many locations instantaneously. The Galerkin projection of the POD orthogonal functions onto the velocity field at a single position downstream of the axisymmetric, isothermal jet can be accomplished.

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REFERENCES

Citriniti, J. H. and George, W.K., 1994, “Experimental Investigation into the Dynamics of the Axisymmetric Jet Mixing Layer,” *Inter. Symp. Turbulence, Heat and Mass Transfer,* Lisbon, Portugal, August 9-12.

Glauser, M. N., Leib, S. J. and George, W. K., 1987, “Coherent Structures in the Axisymmetric Jet Mixing Layer,” *Turbulent Shear Flows 5*, (Eds. F. Durst *et al.*), Springer-Verlag, 134.

Lumley, J. L., “The Structure of Inhomogeneous Turbulent Flows,” *Atmospheric Turbulence and Radio Wave Propagation*, (eds. A. M. Yaglom and V. I. Tatarski), Moscow: Nauka, 166-178.

Perry, A. E., 1982, Hot-Wire Anemometry , Oxford Uni versity Press, Oxford.

FIGURE 3. PICTURE OF 16 ANEMOMETER CIRCUIT BOARD.

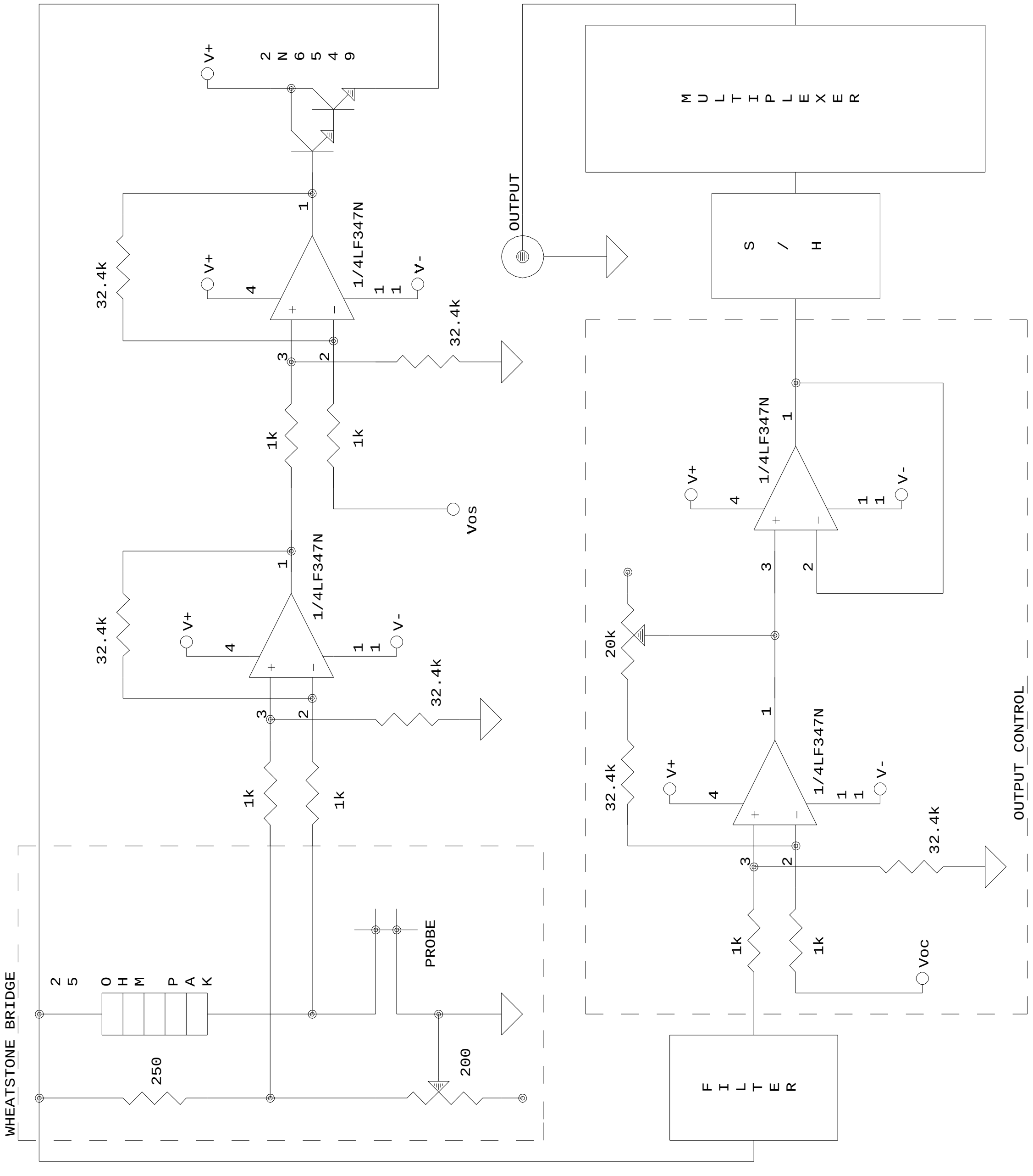

FIGURE 2. ANEMOMETER CIRCUIT DESIGN.

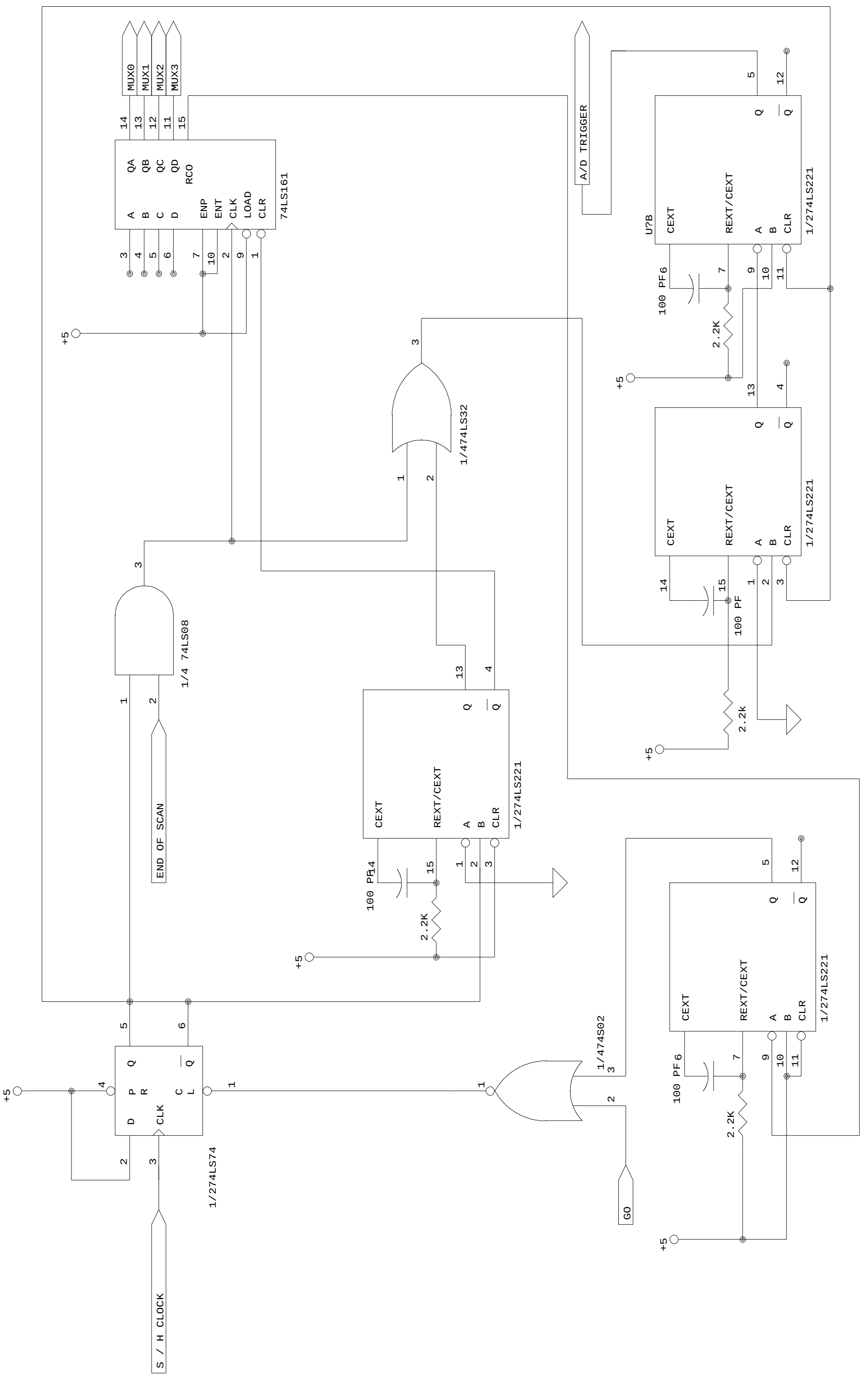

FIGURE 4. DIGITAL CONTROL BOARD CIRCUIT.