FINAL ENGINEERING REPORT
on the
13C ELECTRONIC CALCULATOR
MAGNETOSTRICTIVE DELAY LINE

by

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FRIDEN, INC.

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130 ELECTRONIC CALCULATOR
MAGNETOSTRICTIVE DELAY LINE

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The following report is a summary of the delay line design existing at the time of its production release, and the reasons for that design. The design areas to be covered in this report will be the delay line wire, the line supports, the coil design, the magnetostrictive ribbons, the dampening pads, the biasing magnet system, and the mode converter junction. In addition, recommendations will be made in areas where it is felt either initial or additional investigation will be productive to further delay line improvement.

1. Delay Line Wire

a. Material. The decision to select Ni-Span C as the line material was based primarily on its relatively high mechanical Q factor or low hysteresis and low dampening characteristics. The Q factor is directly related to how much the stress impulses are attenuated as they travel down the line medium. The higher the Q, the greater is the bandwidth and output of the delay line. The mechanical Q of Ni-Span C is increased by heat treatment. Maximum strength and hardness, which is indicative of a high Q, is obtained by a precipitation-hardening or age-hardening heat treatment of the material received in a solution annealed and 50% cold-worked condition. The proper heat-treating temperature, which ranges from 1150°F to 1350°F, varies with each mill run and should be selected according to the report sent with each mill shipment. A heat-treating time of three hours is generally recommended by the manufacturer. However, I feel 25 to 30 minutes is adequate and will reduce heat-treating costs. This decision was based on tests that indicated no increase in hardness could be obtained by holding the material in the furnace for a longer period of time. The rate at which Ni-Span C is heated and cooled from the age-hardening temperature is not critical. Any convenient rate can thus be used which expedites the heat-treating operation.

It is suggested by the literature that for precision applications it is advisable to remove internal stresses resulting from cold working by suitable heat treatment prior to age hardening. Varying internal stresses can produce varying degrees of age hardening and thus lead to slight property differences after heat treatment. A stress relieve anneal of 750°F from one to four hours, is recommended to minimize this condition. This stress relieving was not specified in the final release because results were satisfactory without it and would add to the cost of the wire processing.

Music wire, another material considered as a line material, also possesses a relatively high mechanical Q factor. Some investigators found music wire to be superior to Ni-Span C in this respect, although the heat-treated condition of the Ni-Span C was not clearly defined when making this comparison. At no time in our investigations did we find music wire superior to a properly heat-treated Ni-Span C sample. However, I feel further studies are justified in view of the low cost of music wire and the economies that could be realized by eliminating the heat-treating process. Ni-Span C was selected over music wire for the following reasons:

(1) Corrosion resistance--- if heat treated in a properly controlled atmosphere, Ni-Span C, due to its nickel and chromium content will exhibit good corrosion resistance. Music wire, on the other hand, would require a protective coating, which may be detrimental to line performance.

(2) Length of line - sound travels faster in music wire and would require longer line lengths to achieve the same delay time. This would increase pulse attenuation and the scope of problems dealing with adjustment to correct dispersion.

(3) Ribbon-wire impedance match - to properly match the mechanical impedance of the wire to that of the nickel

transducer ribbons, music wire would require larger diameters which increases dispersion and degrades resolution.

(4) Coil diameter - control over the coil diameter is important because the size of the coil of wire directly affects the amount of pressure on the wire at the supports. Since music wire does not require further heat treatment, it would become necessary to control coil size at the mill, a less practical solution.

(5) Constant delay time with temperature change - unlike music wire Ni-Span C is a constant modulus material, which gives it the ability to maintain a fairly constant delay time over a considerable range of temperature. Although this property is not as important for our delay line application, it does yield us a certain margin of safety.

Other materials were also considered, including copper, sterling silver, aluminum and magnesium. Copper and sterling silver were considered primarily because of their relatively low sonic velocity properties---sterling silver has a sonic propagation velocity nearly one-half that of Ni-Span C. A five millisecond line composed of sterling silver requires a line length of only 25 feet compared with 47 feet for Ni-Span C. The advantages of a relatively shorter line length, to summarize again, are smaller packaging requirements, less pulse attenuation and less dispersion. However both copper and sterling silver evidenced such low mechanical Q and high dispersive characteristics that the shorter line lengths could not compensate for the resulting poor quality and level of signal output. The copper investigated was hard drawn. The sterling silver admittedly was in a softer condition. Attempts to work harden it were tried unsuccessfully because tooling marks on the material produced high level noise effects. In addition these materials are susceptible to tarnishing, which may be detrimental to line performance.

Aluminum and magnesium were considered because of their known high Q characteristics and light weight. The sonic propagation velocities of these materials are about equal to that of music wire. The mechanical Q values were found to be satisfactory although there was little evidence to prove they were superior to Ni-Span C. In addition both would require wire diameters twice the size of Ni-Span C to gain an impedance match at the weld with the nickel ribbon. Also, both are difficult to weld and would create additional problems at the mode converter junction.

b. Wire Diameter. The diameter of the Ni-Span C wire was selected by considerations of the mechanical impedance match between the wire and the transducer ribbons at the mode converter weld. A formula for matching the impedances of the wire and ribbon were derived in Scarrott and Naylor's paper on "Wire-type Acoustic Delay Lines for Digital Storage" in the 1956 Proceedings of the Institution of Electrical Engineers. The formula is shown below.

$$A = \frac{\pi r^2}{2n} \sqrt{\frac{\rho_w G_w}{\rho_r E_r}}$$

where A = cross-sectional area of one ribbon
n = number of ribbons used
r = radius of the wire
ρw = density of the wire material
ρr = density of the ribbon material
Gw = shear modulus of the wire
Er = Young's Modulus of the ribbon

There was correlation between this formula and our experimental results, and a wire size was specified primarily on the basis of this formula. However, it is difficult to know whether the best choice of wire diameter could or should be based on a theoretical impedance match since there are many other factors involved. True, a perfect impedance match between the line and the ribbon will transfer energy from the one medium to the other without reflections and resulting energy losses. Yet, the formula above does not take into account the method of connecting the media, which imposes an additional impedance that in all probability will not match the impedance of the other two. (i.e. the weld puddle and the possible change of Young's Modulus in the materials during the weld cycle, or the addition of an adhesive layer in bonding techniques.) In addition, as the wire diameter is increased, the supports will impose larger perpendicular forces on the wire as the coil of wire is prevented by the supports from assuming its free diameter. The supports are dampening in nature and tend to increase signal attenuation and degrade bandwidth as the support forces increase. However, conversely to this, delay line investigators have stated that larger wire diameters produce higher outputs, (independent of support systems, of course), although at a sacrifice of increased dispersion and loss of resolution. In conclusion, further investigation in this area may improve performance if care is taken to isolate each parameter from the rest and study only its effects on performance.

c. Coil Diameter. Selection of a wire coil diameter involved two main parameters, R_n, the natural or "free" radius of the wire coil, and R_f, the confined or "forced" radius dictated by the support system. First of all, let it be understood that without additional considerations and limitations, R_n and R_f should both be as large as practical in theory. This is based on Scarrott and Naylor's derivation

$$V_t \cong c_t \left[1 + \frac{K\lambda}{R_n R_f} \right]$$

where v_t = phase velocity of torsional stress waves
c_t = torsional phase velocity of sound in a straight wire
K = a constant, whose value is immaterial in this discussion
λ = wavelength of a particular frequency component
R_n = and R_f as defined above

If $v_t = c_t$, then theoretically all frequency components of a sonic pulse traveling down a line should arrive at the end in exactly the same time phase relationship as when it started and no phase distortion, or dispersion, should result. To accomplish this feat either R_n or R_f should be infinitely large, but in any event, both should be as large as practical. As a result of this work, a patent was granted Ferranti Electric on the use of naturally straight lines ($R_n = \infty$). Friden did not choose to lease patent rights from Ferranti nor expend money on the development of a straight wire process, so the R_n of our wire coil was restricted to seven and one-half inches. Packaging restrictions limited the mean R_f of the wire coil to a maximum of four and three-quarters inches. A R_n of four and three-quarters inches would minimize the effects of the forces exerted on the wire by the supports. However, a maximum R_n of seven and one-half inches would minimize dispersive effects. The problem became one of compromise. A coil R_n of four and three-quarters inches was selected because it was determined that the support forces would be more detrimental to signal amplitude than dispersion effects in the R_n

range of four to seven inches. Additionally, the slight increase of dispersive effects could be adjusted out by the positioning of the receiver transducer biasing magnet.

d. Heat Treatment. The reasons for the heat treatment of the Ni-Span C line material and the time and temperature involved have been discussed earlier in this report. However, no mention was made of the importance of maintaining a good protective atmosphere during heat treatment. Earlier experimental delay lines composed of Ni-Span C wire were heat treated in a normal non-carburizing electric furnace atmosphere. This heat treatment yielded wire with a dark blue oxide film. These lines performed adequately, but it was felt that a clean bright material surface free of oxides would improve performance as well as appearance. Thus the wire was heat treated in a hydrogen and nitrogen atmosphere - an atmosphere selected because it was already being provided at Friden. The result was successful and no further investigation into some of the other atmospheres, such as vacuum, dissociated ammonia, or helium atmospheres was planned. Although a fairly oxide-free surface can be accomplished in the hydrogen and nitrogen atmosphere, the importance of careful wire handling and cleanliness of the wire before, during and after heat-treat can not be over stressed.

e. Line Configuration. A two layer, flat spiral line configuration was decided on for the following reasons. First a one layer, flat spiral line would allow a reduction in package height and reduce assembly time, but had many disadvantages. A one-spiral configuration would place one transducer assembly inside the spiral near the center of the delay line can. That is unless a special bridge could be devised to bring the wire over or under the spiral to the outside. This did not appear to be too practicable. With a transducer in the center, little air passage through the delay line package was possible and longer leads would be required from the transducer to the amplifier card.

With a single spiral more diviation from a mean natural coil radius would be necessary increasing line support loading and the attendant signal attenuation. Consideration of three or more layers of spiral line was not considered practical since it increased package height above the maximum design limit, and required more support brackets which would increase the time to assemble the line into the delay line package.

2. Line Supports

a. Material. An elastomer was selected as the line support material, because rubber was one of the few materials found which did not introduce mechanical discontinuities into the line. These discontinuities cause reflections that degrade the signal-to-noise ratio and produce distortion in the output pulses. Unfortunately, rubber is also a good sound absorber. Silicone rubber was chosen over the other elastomers for the support material because of its excellent electrical properties, its temperature stability, and because of its ability to allow passage of the mechanical pulses down the line with the least absorption. Under test it performed better in this respect than other "solid" elastomers, such as neoprene or gum rubber. However, loads must remain light for this to be true. Under heavy pressures silicone rubber can be an efficient dampener. That is why it was selected as the ribbon termination material. This will be discussed further under the section on dampening pads.

b. Support design. A system employing six separate supports for containing each layer of line was specified. This number of supports was selected when it became obvious that four separate supports were not adequate for the job. The four-support system allowed individual loops of the two layers to touch, thus producing "cross-talk" which seriously degraded the signal to noise ratio. A five-support system was not investigated, and may well prove adequate and result in a cost reduction. Such a system would, of course, have to be proven acceptable under the specified shock and vibration requirements.

The decision to use a combined metal stamping and molded rubber support instead of the more conventional metal bracket-tubular rubber support system was based on high-volume production considerations. Labor costs to assemble the wire into the present support system could be reduced considerably and more than outweighed the increased part cost.

3. <u>Transducer Coils</u>.

Two identical coils are used in the transmitter transducer and two different but identical coils are used in the receiver transducer. The two-coil system is an important part of the push-pull transducer concept. With this system larger output signals can be obtained than by a one-coil and ribbon concept. The push-pull effect is obtained by a biasing magnet and by wiring the same ends of the two coils together, the other ends being wired to the input leads in the case of the transmitter coils and to the output leads in the case of the receiver coils.

The design of the transmitter and receiver transducer coils is of great importance in achieving the optimum response of the system for a given input pulse, and is dictated by that input pulse and by the electrical requirements of the system.

a. Coil length. The physical coil length of both the transmitter and receiver coils, which in this case was one-tenth of an inch, was determined as follows. To produce an output pulse with optimum amplitude and resolution, that is a pulse which is properly coalesced, the effective length of the coils must be arrived at by use of the formula

$$l_e = \Upsilon v$$

where l_e = effective length of the coil.
Υ = time for the mechanical impulse to travel the length of the coil.
v = velocity of acoustical propagation in the magnetostrictive mat'l.

Since there is a certain amount of flux fringing at the ends where the ribbon leaves the coil, the physical length of the coil must be made smaller than the effective length to compensate for the fringing effects. Fringing can be reduced by fitting ferrite cups around the coils to more sharply define the edges of the field. However, it was not necessary to resort to ferrite cups in our application since an adequate physical length could be maintained to suit the electrical needs of the system.

Theoretical formulas are available for determining what the physical coil length should be for a given coil design. Rather than rely entirely on theoretical data, various lengths of coils were made up and tested for resolution by inserting them in a delay line system and varying the input pulse width. When the output pulse reached coalescence with the input pulse adjusted to the width requirement of the delay line design, we knew that our coil length was correct.

b. Coil diameter. The requirements for the coil diameter are basically simple. The mean diameter of the coil should be made as small as possible by winding the turns as close as possible to the magnetostrictive material. The reason for this is to avoid as much flux fringing as possible and closely couple the coil to the ribbon. The object of the transmitter transducer is to convert the induced magnetic energy into mechanical acoustic energy. Therefore good electromechanical coupling is desirable. The same is true of the receiver transducer, which converts mechanical energy that has been propagated down the line into electrical energy. This demands that the magnetic flux link the whole winding and again a closely wound coil is desirable.

Consideration was given to winding the coils directly on the nickel ribbons, but there are many problems associated with this design. First of all the ribbon must be annealed, and winding the coil on the fragile annealed ribbon without work-hardening it would be extremely difficult to achieve. Second, each coil must be wrapped around two ribbons which must be in perfect alignment for welding. Third, the sharp edges of the magnetostrictive ribbon cut into the coil insulation and cause shorted turns. An insulated layer could be used but then a bobbin might as well be utilized. In addition the wire must be wound under some tension which may hamper magnetostrictive movement. In addition the coils must be in longitudinal alignment within ten per cent of the coil length, (± .005 for our design), to provide adequate push-pull performance. This will add to the problems of ribbon alignment.

A bobbinless coil design would correct most of the above disadvantages. However, during ribbon insertion there is still the danger of cutting into insulation and causing shorts. Also the mounting of the coils rigidly to prevent lead wire breakage and maintain alignment would pose difficult design problems.

The final design consisted of a conventional round bobbin having a center hole slightly bigger than the magnetostrictive ribbon width. The diameter on which the coil is wound is larger than the bore only by an amount necessary to maintain rigidity and minimize production problems. Designing the shape of the bobbin to that of the ribbon configuration was considered, but the bobbin is so small and the wall so thin that the part could not be molded.

c. Number of turns. In general, increasing the number of turns of magnet wire on the transducer coils will increase the amplitude of the output signal. This is true because the magnetostrictive ribbon is not in saturation, and with proper magnet biasing, an increase in field intensity will increase the magnetostrictive effect of the nickel. It is important to understand, however, that design limitations were present which restricted the number of turns that could be used, and a compromise had to be made. To begin with, as the number of turns is increased the inductance of a coil will go up.

An increase in the inductance of the transmitter coils increased the rise time of the input current pulse. A final value of 180 turns was specified for the transmitter coils. This was felt to be the maximum number of turns permitted with the existing transducer and amplifier design, and yet achieve the rise time required for a properly shaped trapezoidal input pulse. The sharper the rise time, the less effect will noise originating on the line have on the output signal-to-noise ratio of the recovered pulse. However, the sharper the rise time, the more average power is necessary to drive a pulse of the same peak amplitude through the line and its associated electronic circuitry. Since the two limiting cases are a rectangular input pulse and a triangular input pulse, a suitable compromise is the trapezoidal pulse.

The upper limit to the number of turns on the receiver coils is such that the resonant frequency of the coils together with their stray capacitances is appreciably above the operating frequency of the delay line. In the case of our delay line design, the upper limit for the number of turns on the receiver coils was 350. Once a satisfactory transducer design was achieved it was found that operation could be improved by tuning the electromechanical circuit with a capacitor shunted across the transducer coils. A shunt damping resistor was then used across the receiver coils to provide critical damping.

d. Wire Size. A number 48 AWG magnet wire was chosen to wind the coils. This size of wire was chosen as a compromise between maintaining wire strength to reduce production winding problems present when working with fine wire, and minimizing coil height to insure tight magnetic coupling between coils and ribbon to reduce flux fringing.

Further consideration of finer wire sizes is recommended and would show that there will be less inductance for a given number of turns of coil winding and a resultant faster rise time. Thus, it would be possible to increase the output of our existing delay line by placing additional turns on the transmitter coils, and yet retain the required rise time of the input pulse.

Belden's Celenamel magnet wire, which is essentially a cellulose acetate insulated copper wire, was chosen for the delay line coil winding because it can be easily soldered without removing the insulation by stripping. This wire is reputed to be a fast soldering wire at the lowest solder temperatures. It is superior to plain enameled wire with respect to abrasion and solvent resistance, and is resistant to thermal degradation at 105°C. Its heat aging characteristics are equal to those of Formvar, and it has excellent insulation resistance. Another wire that should be investigated is Rea's Solvar magnet wire, which is available at the same price. It is also self-stripping, is generally equal to the other properties mentioned above, and is capable of operating at temperatures up to 120°C. continuously.

4. <u>Magnetostrictive Ribbon</u>.

a. <u>Material</u>. Pure nickel was selected as the magnetostrictive medium because of its availability and its relatively good magnetostrictive properties. In addition it is a good corrosion resistive material. It was originally planned to investigate other magnetostrictive materials, such as

Permendur and Hiperco, but such plans were dropped when it became apparent that nickel was entirely satisfactory for this application. Most of the work was confined to "200" nickel, a highly refined, relatively pure nickel (99+%). Nickel "205", a similar 99% nickel material, which was inadvertently selected due to confusion in manufacture identification systems, was not considered as good for this application because of its lower resistivity. Heavier currents and temperatures were consequently required to produce optimum annealing conditions, and led to the formation of excessive scale on the surfaces of the nickel. Since this condition was considered detrimental to performance, "200" nickel was specified for the final delay line release.

b. Configuration. Because of skin effects discussed below under section c, the need for a thin magnetostrictive nickel material limited configuration to ribbons, thin-walled tubing or bundles of fine wires. Fine-wire bundles achieve highest magnetic efficiencies, but their use would create problems in attaching them to the delay line wire and in dampening the unwanted signals. Thin-walled tubing have the same disadvantages to a lesser extent. Ribbon was selected because of its availability, lower cost, and because of the ease with which it can be welded and dampened.

However, because thin-walled tubing has many advantages over ribbon, an investigation of this magnetostrictive shape is recommended. First it is easier to get a close fit to a round coil aperature. Second it would be mechanically stronger and more self-supporting. Third, nearly 100% more nickel could be placed inside the same diameter coil designed for our two-layer ribbon system. This would result in increased efficiencies and higher output. The ends of the tubing could be flattened to provide an area for welding and dampening without theoretically producing impedance discontinuities. Yet, a few disadvantages to tubing as a magnetostrictive medium should be mentioned. Investigators in this field claim that ribbon-shaped elements have inherently better frequency response than do tubes, although the frequency response can be improved by slotting the tubes. In addition, the frequency response of a tube will exhibit attenuation bands. The width and position of these bands are a function of the radius of the tube and the Poisson ratio of the tube material.

c. Ribbon size. Two mil thick by twenty mil wide nickel ribbon was specified as the final size of the transducer ribbon. In the final design four ribbons were specified: two attached to the top of the end of the line wire and an identical arrangement at the bottom of the wire to produce the push-pull effect. A ribbon thickness of .002 was specified to insure good frequency response by reducing eddy current losses. If the thickness of the ribbon inside the transmitter and receiver transducers is great in comparison to the skin depth, eddy currents will modify and distort the resulting output waveform by a factor proportional to $1/\omega$ with a phase lag of 90°. Annealing the ribbon increases the permeability of the nickel and enhances this effect. This phenomena will be discussed further under the section on annealing. Studies conducted with 5 mil thick ribbon were finally abandoned because of the difficulties encountered in eliminating this eddy current effect. Better results were achieved by controlled annealing of the two mil thick nickel ribbon. In addition, higher pulse amplitudes were achieved. Another distinct advantage of the two mil thick ribbon over the five mil ribbon is the reduced ratio of cross-sectional area to periphery. Since dampening of unwanted and reflected pulses at the ribbon ends can be achieved only on the periphery of the ribbon, the lower the ratio of cross-sectional area to periphery, the more efficient the damping of the mechanical signals.

The selection of the 20 mil width for the nickel ribbon was a compromise between good magnetic coupling between ribbon and coil for high pulse repetition frequencies with narrow tapes and high output amplitudes with wider tapes. The 20 mil width allowed a coil design which was well matched to the pulse width and pulse repetition rate required for the application.

The use of multiple ribbons---two in this case through each coil---increases the magnetic efficiency of the transducer operation and increases output amplitude. The amplitude increases in proportion to the number of ribbons in the coil, and although not in a direct proportion, is nearly so. Additional increases in output amplitudes could be achieved by the use of three or more layers of ribbon. The results desired, of course, must be weighed against the multiplying difficulties to be encountered in welding techniques, ribbon alignment, and dampening of unwanted pulses.

d. Annealing. The annealing of the nickel ribbon is without a doubt one of the most important aspects to be considered in achieving successful delay line performance. This is certainly not difficult to comprehend when it is understood that most of the losses that occur in the delay line system are in the vital area of the transducers. The efficiency of the transducer action between coils and ribbon is determined by the electro-mechanical coupling factor. This figure of merit for a magnetostrictive material is a function of the permeability and the magnetostriction coefficient. Both are affected to a great extent by the annealing parameters and the control of these areas.

The final selection of the annealing method, temperature,time and other prevailing conditions, was specified only after a great deal of time and effort had been expended. Yet it is felt that many additional gains may be realized with additional intensive investigation.

First of all it must be understood that an annealing process after receipt of the raw material is mandatory. Although the nickel is ordered in a bright soft-annealed condition, it is not at all satisfactory for our application. Even if the nickel had been properly annealed prior to our receipt, the work-hardening affects of winding the ribbon onto the shipping spools would be disastrous to good performance. Satisfactory performance of our pilot production lines only after a thorough education of the workers involved and a persistent overseeing of the methods used in handling the annealed ribbons will attest to that. In addition it is also mandatory for the ribbon strips to possess an unusual degree of straightness to prevent the possibility of work-hardening as they are assembled and threaded through the small coil apertures and positioned in the dampening pads. This straightness is not provided in the conventional reel form received by the supplier, and it is doubtful that we could achieve this unless we ordered the nickel cut in straight strips at additional cost. Thus, during the annealing process we apply a small tension on the ribbon to straighten it.

Two processes to anneal the ribbon were studied. The first annealing process consisted of passing an A.C. current down the ribbon while applying a light tensile load to provide the necessary straightness. The end areas of the ribbon to be welded to the delay line wire were provided with heat-sinks to draw off the heat and prevent oxides from forming. By this technique these areas remained bright and were suitable for resistance welding without extensive surface preparation. The oxides that are produced on the surface of the nickel during air annealing, although not suitable for welding, are acceptable, providing the oxide does not become flaky as it can at higher temperatures.

The specified annealing conditions were arrived at by varying temperature, time, and tension in carefully controlled tests until the nickel achieved that combination of permeability and magnetostrictive coefficient that produces optimum ribbon performance. Optimum ribbon performance is here defined as that ribbon performance in which the mechanical pulses produced on the ribbon by the transducer coils have the maximum amplitude attainable with negligible or no distortion due to the skin effect.

In general, lower annealing temperatures do not remove the stresses in the work-hardened raw material. The result is a ribbon with remanant characteristics, or a memory, which when assembled in a delay line will remain magnetized even after the biasing magnet is removed. The end result is a transducer assembly that is difficult to adjust for optimum performance and one which is detrimentally affected by degaussing and stray magnetic fields. As the annealing temperature is increased the work-hardening stresses are removed, permeability increases, and as would be expected, increased pulse amplitudes can be achieved in the nickel. As higher and higher annealing temperatures are reached, permeability increases with corresponding increases in signal amplitudes. However, the higher permeabilities of the nickel, as mentioned earlier in this report, increase the eddy current skin effects and pulse degradation results. As temperatures are raised further, this effect increases and there is actually an amplitude decrease due to the extreme distortion of the pulse. There is a temperature somewhere between these two extremes where optimum ribbon performance is realized.

Tensile loading applied to the ribbon during the annealing process actually reduces the permeability that is achieved at a given temperature. A low tensile load just capable of producing a straight ribbon is considered best for this application. However, optimum ribbon performance, as defined above, can be achieved at higher tensile loads, but higher temperatures must be used. This is because tension not only reduces permeability, it reduces skin effects proportionately. Thus, a heavier load applied during a corresponding higher temperature can still reduce the higher permeability down to the optimum ribbon performance point. Generally this is not good practice for two reasons. First, the higher temperatures increase the danger of excessive scale on the ribbon, Second, the ribbon begins to creep at higher temperatures and heavier loads, which produces a permanent stretch that results in loss of signal amplitude.

The time of anneal becomes a factor for two opposing reasons. The longer annealing time increases the effect of creep, mentioned above, and slows down the annealing process which costs money. Conversely, a longer annealing time enhances larger grain growth, which at a specified annealing temperature increases permeability and improves magnetostrictive properties. Thus, a compromise must be made and will affect all that has been considered above.

The second process considered was a bright anneal in our hydrogen-nitrogen atmospheric furnace. This process utilized a special tensioning fixture to achieve the required straightness. Temperature and time of anneal were based on data from earlier tests. It was determined that the hydrogen-nitrogen atmosphere provided a surface with adequate brightness, free of oxides, to readily weld the nickel onto the Ni-Span C wire. Unfortunately, it was found that none of the samples that were annealed were suitable for our application. Different annealing temperatures were tried and tensions varied, but little correlation could be found between the results of these combinations and those from the first annealing process discussed. Many of the nickel ribbon samples evidenced an excessive amount of remanance. Pulse distortion was excessive in some samples and most showed somewhat disappointing pulse amplitudes. The annealing was conducted by the Production Engineering Department; thus it was difficult to evaluate these studies and assign contributary causes for the overall poor results. Proper attention may not have been given to the control of the various factors, which would make "zeroing in" virtually impossible. Perhaps the tensioning fixture, which consisted of a relatively large mass, was not in the furnace for a long enough time to come up to the annealing temperature. Thus it would act as a heat sink for the nickel ribbon, and produce erroneous results with respect to the existing temperature data. It may be that the nickel was subjected to relatively slow heating and cooling rates which may have produced poor results. This normally is not believed to have any effect on the properties of annealed nickel, but annealing under tension may produce changes.

There is a theory, simply stated, that the passing of a heavy current down a magnetostrictive material such as nickel ribbon creates a concentric magnetic field surrounding the ribbon which would tend to align the magnetic domains of the nickel in a direction favorable to magnetostriction. If this theory were correct the lack of an advantageous magnetic field within the furnace during annealing could explain the lower pulse amplitudes achieved in the nickel with this second process. However, I feel a great more investigation is necessary in this area before any conclusions can be drawn and the validity of this theory can be proved. For example, this theory is more easily understood if the current in the ribbon is d.c.; more difficult to comprehend if the current is a.c. Most of the work accomplished in the area of current annealing at the time of the delay line release utilized a.c. currents, although a few d.c. studies were run. No differences between the two types of current annealing could be detected in the few tests conducted. I understand Bob Ragen's group has gone further into this area; perhaps they have reached some conclusions.

In summary, the furnace anneal has several attractive advantages. Namely, it produces ribbons relatively free of oxide, and it can handle more ribbon at one time, making it a practical economical production process. The big disadvantage is in control capabilities. However, before this process can be discarded as unworkable, I feel more careful and intensive study should be made.

A third annealing process was considered, but little effort was applied to determining its feasibility. This process consisted of the induction heating of the nickel strips.

There are a number of areas directly related to the annealing process in which investigation is strongly recommended. Cursory probes in some of these areas indicate further work would yield impressive improvement in line performance. These areas are briefly discussed below.

(1) In the current annealing process, time, current, and tension were specified on the basis of producing a balanced non-distorted pulse in the nickel. It is known

that the peak amplitude of this pulse is about half the peak amplitude of the distorted pulse at higher permeabilities. Also it has been found that this distortion can be compensated for by a slight adjustment of our end-on receiver biasing magnet. Although this results in a peak amplitude loss, it was observed that the pulse amplitude was still greater than that of the balanced pulse with no magnet compensation. In addition, there is a theory that the pulse distortion caused by skin effects would be corrected to some extent by the distortion produced in the pulse by line dispersion. If this were true, a canceling effect could be achieved. At any rate, this is an area where it is most apparent that an increase in delay line output could be obtained.

(2) Investigators in the field of magnetics have discovered that higher permeabilities can be obtained in ferromagnetic materials by magnetic annealing, or annealing materials in the presence of a magnetic field. Closely associated to the current-conducting magnetic field theory discussed under current annealing, it is proposed here that studies be conducted to determine the effects of external magnetic fields, both in intensity and direction, on the magnetostrictive ribbons.

(3) Further studies could be conducted on the

nickel from a sonic propagation standpoint. It is known that annealed nickel is a lossy material with a low mechanical Q as compared to nickel in a work-hardened condition. Since the ribbon must be annealed only in the area under the coils, perhaps improvement in delay line output could be realized by work-hardening the ribbon length between the transducer coils and the weld junction. It is difficult to imagine much improvement in this area as this length is short compared to the line length. However, it is mentioned here as worthy of some investigation.

(4) Other magnetostrictive materials could be studied. Investigators have found other materials, such as Permalloy, Permendur, and Hyperco favorable in certain magnetostrictive applications.

5. Dampening Pads.

This area of the magnetostrictive delay line design, is important because it directly affects the signal-to-noise ratio of the line. The transmitter transducer emits a sonic stress wave in two directions in each magnetostrictive ribbon. For this application one wave has to be dampened, as it would appear in the output as a spurious signal, or noise, reflected from the ribbon end. At the receiver transducer the main pulse must also be dampened once it has passed through the transducer coils, for it will be reflected from the ribbon ends and appear as signal noise.

The dampening method used was practical and conventional. The two push-pull sets of ribbons at each transducer are sandwiched between layers of a rectangular sheet of elastomer. Each entire assembly is then clamped under pressure by a top metal plate. The thicknesses of the individual sheets of rubber were selected to obtain optimum ribbon alignment with respect to the transducer coils. Where each set of dual ribbons enters the dampening pad assembly, the individual ribbons are separated to form a narrow V. This is done to decrease the ratio of cross-sectional area to periphery and achieve more efficient dampening of the acoustic pulses.

Selection of a dampening pad material must be a compromise between two conflicting requirements. First, the material must present a low impedance to the pulse at the point where it enters the dampening medium, and thus provide a good acoustic match. This is necessary to prevent reflections from occurring at the junction, and generally requires a material with rather poor dampening qualities. Second, the material must have good dampening and absorbing qualities to eliminate the unwanted pulses over a reasonable length of pad. Silicone rubber was selected as the dampening pad material because of its temperature stability, and because its softness and tackiness provided a good compromise. Polyurethane and rubber foams provided excellent low impedance properties, but did not achieve sufficient dampening characteristics. Neoprene and natural gum rubbers were better dampening materials, but produced reflections because of a poorer acoustical impedance match.

Other delay line manufacturers have gone to a two-step technique to overcome this problem by inserting teflon strips, a material of better absorbing qualities, in the back section of the dampening pad assembly. A few of our earlier experimental lines were built utilizing this technique. A slight improvement was noted, but since acceptable signal-to-noise ratios were being achieved without the use of the teflon strips, this design was not included in the pilot production release.

Another technique that was tried was to release the front pressure on the dampening pad assembly to improve the impedance match, and clamp down harder on the rear end of the pads to increase pressure and compensate for the loss of attenuation at the front end. This method was not successful for the elastomers tested, because their dampening characteristics are not lineal with respect to pressure. Pressures were soon reached in the dampening pad system where additional forces did little to affect an increase in dampening of pulses. The practical use of this technique would have to be utilized in a material with exceptional absorbing capabilities, or the length of the dampening pads would have to be extended, (not always practical), so that increased pressure at the rear area of the pads would suffice to suppress the unwanted pulses.

In fact the silicone rubber of our present dampening system was designed to use its full dampening capabilities, and further increase of pressure may only prove detrimental to line performance. Excessive pressure on the nickel ribbon would submit the nickel to work-hardening in various areas under the pad. The result would be the formation of minute discontinuities which would increase the level of signal noise. In addition, excessive pressure of the dampening pads may pull the ribbon along its entire length, and the resultant work-hardening would reduce signal amplitude.

6. Biasing Magnet System.

a. Transmitter Magnet. Normally a biasing magnet is not necessary at the transmitter transducer to produce mechanical impulses in a simple one coil-one ribbon magnetostrictive delay line system. The electrical energy pulse present in the coil will provide a magnetic field associated with it which will produce a magnetostrictive effect in the ribbon. There is an advantage of a biasing magnet, however, in this simple system, which is also an advantage in the more complicated push-pull system utilized in our delay line design. This advantage is that the transducer can be adjusted by means of the biasing magnet to operate at the most favorable operating point on the nickel ribbon strain versus magnetic field curve. This is because the static magnetic field produced by the biasing magnet is much stronger than that produced by the transducer coil; thus small signal operation can be assumed, and the magnetostrictive effect can be considered lineal. Of course, for both the transmitter and receiver transducers, it must be assumed that the operating point is well below the magnetic saturation point of the magnetostrictive material.

In our push-pull transmitter transducer system the biasing magnet is mandatory, because the "push" ribbon must expand in response to a current pulse in the coil. Without the biasing magnet this is impossible, for nickel is always a negative magnetostrictive material, which means it always constricts in response to a magnetic field, regardless of polarity. Thus, the biasing magnet provides a static constriction in the nickel ribbons, which, dependent upon the direction of changing current in the coils, produces a "pull" effect with an increase in magnetostrictive constriction, and a "push" effect with a relaxation or decrease in magnetostrictive constriction. The push-pull effect is used to convert from a longitudinal (ribbon) sonic energy mode to a torsional (delay line wire) sonic energy mode.

The design of the transmitter biasing magnet is conventional and similar to those existing in other manufactured delay lines. The magnet is 1/8-inch in diameter and 1/4-inch in length, and is polarized with its north and south poles at the ends. The magnet is positioned in the transducer assembly with its length parallel with the ribbon, and centered with respect to the transducer coils. In this position the lines of flux produced by the magnet most easily couple with the nickel ribbon and produce a uniform field of single polarity under the coil.

There is one important difference between our transmitter transducer design and that of conventional delay lines. Our design incorporates a movable magnet holder which allows adjustment toward or away from the magnetostrictive ribbon. This design requires less control over the magnetic properties of the biasing magnet, and provides an easy method for adjusting each delay line for optimum performance.

b. Receiver Magnet. The biasing magnet is necessary at the receiver transmitter for two important reasons. First, it provides the magnetic field necessary to generate voltages across the ends of the receiver coils. A mechanical pulse, traveling down each of the push-pull ribbons, passes underneath the pair of receiver coils, and changes the permeability of the nickel with a resultant magnitude change of the flux linking the coils and the ribbons. The changing flux generates an output signal voltage across the coils.

Second, the biasing magnet is uniquely and exclusively positioned in our delay line system to produce a static magnetic field within the nickel-coil area, which, because of its ununiformity and polarity, corrects the line dispersion present in the pulse. The magnet is positioned end-on with respect to the coils, and its holder is designed to allow adjustment in a parallel direction with respect to the ribbons to obtain optimum dispersive correction. An additional adjustment is incorporated in the holder design to allow an adjustment perpendicular to the ribbons to achieve a maximum output pulse amplitude. For simplicity and cost reduction considerations the receiver biasing magnet is identical to that in the transmitter transducer design. Additional studies are recommended to investigate changes of the shape and size of the receiver magnet toward improving dispersion-correction capabilities which, though adequate, would improve signal-to-noise ratios.

7. Mode Converter Junction.

The mode converter junction consists of the weld joint between the nickel ribbons and the delay line wire, which converts the longitudinal stress pulses to torsional pulses, and its support system.

a. Weld Joint. Design considerations in this area include minimizing reflections to improve output amplitudes and signal-to-noise ratios, and proper alignment of the nickel ribbons with respect to the wire for low loss conversion and pulse transmission. Aside from the selection of proper ribbon and wire sizes to obtain correct theoretical impedance matches, as discussed under section 1, the following areas were considered.

(1) Weld technique. Work in this area consisted almost exclusively of achieving a proper joint by standard resistance welding techniques. Capacitive discharge welding was selected over a.c. current welding primarily because of the inherent advantages in the faster weld times available. Bonding techniques using adhesives were considered more unreliable and difficult to control. The new welding techniques using electron-beam guns and lasers

utilize expensive equipment not warranted for our application.

In order to evaluate the welding technique, measurements were made of the efficiency of the weld as a function of weld energy, in watt-seconds, and weld pressure. Efficiency was determined by reflection measurements made on a series of welds at varying energy levels and weld pressures. Weld consistency was determined by reflective measurements on a series of welds made under identical conditions. Optimum results were found to be a compromise between weld strength and exclusion of excessive weld puddle, which represents an impedance mismatch. In addition, a weld puddle of considerable area reduces the efficiency of the hinging action between ribbon and wire, and feeds transverse waves back along the ribbon.

In our application, it was found that all four ribbons would not weld completely to the line material in one weld pass. Repeated weld passes did not improve the weld joint. The inside ribbon strips next to the Ni-Span C line wire attained a highly desirable weld with the wire as discussed above. The outside ribbons, however, produced weak highly unsatisfactory welds with the inside nickel strips. Increasing energy levels and pressures until the outer nickel layers were sufficiently welded, produced excessive puddling between the inner ribbon layers and the material. Thus, it is necessary to perform the welding in a two-step operation. First the nickel pairs are welded together. Then the pairs are welded to the wire. Unfortunately this requires additional ribbon handling and increases welding problems. Further investigation into other welding techniques may be practical to eliminate the two-step operation.

(2) Mechanical Assembly. In the mechanical assembly it is necessary to cut the wire and ribbon as near to the actual weld as possible. This is because any material extending beyond the weld joint will act as a reflective termination surface. It was found that a great deal of pulse distortion due to weld reflections superimposed on the main pulse could be eliminated by grinding the ribbon ends flush at the welds. This grinding must be accomplished carefully to prevent a weakening of the weld joint.

(3) Ribbon Alignment. Experiments have shown that there will be spurious reflections if the ribbons become bent just before the point at which the weld occurs. It is thus important to ensure parallelism of the ribbons at all times. It is also important that the ribbon pairs are welded exactly opposite to each other on the wire so that the best advantage can be made of the push-pull effect.

For the reasons discussed in (2) and (3), the weld operation should be performed in adequately designed fixtures.

b. Mode Converter Support. The relatively fragile weld junction must be properly supported to protect it from excessive shock and vibration. In addition, physical movement of the joint with respect to the fixed transducer location is detrimental to line performance. (A final line adjustment in production consists of repositioning the weld junction with respect to the transducer until optimum amplitude of the output pulse is achieved.) The support must be capable of firmly holding the weld joint in a fixed position and yet not dampen or distort the signal pulse measurably. This was achieved satisfactorily by a special bracket and silicone rubber pads. Some delay line manufacturers use instead, silicone rubber tubing. Although release precluded further investigation, I would like to recommend polyurethane foam as a potentially good mode-converter support material.

8. Recommendations:

In conclusion, briefly listed below is a summary of the areas previously mentioned in which investigation should yield the most improvement in delay line performance.

a. Further investigation of music wire with respect to its low loss, high mechanical Q properties.

b. Consideration of different sizes of delay line wire diameters with regard to sonic pulse propagation in the wire. Care must be taken to eliminate the affects of associated parameters.

c. Investigation into the feasibility of using finer magnet wire sizes for the winding of the transducer coils. Reduced coil inductances would allow more turns on the coils and increase output amplitudes.

d. Investigation of thin-walled nickel tubing as the magnetostrictive medium to increase coupling efficiency and gain higher output amplitude.

e. A study of the feasibility of utilizing nickel ribbon annealed for peak signal amplitudes rather than balanced non-distorted pulse operation.

f. A study of the effects on magnetostrictive ribbon annealed in external magnetic fields.

g. Further investigation of other magnetostrictive materials including other nickel products, Permalloy, Permendur, and Hyperco.

h. A study of the shape, size and strength of the receiver magnet toward improving dispersion correction capabilities.

W. E. Wells

WEW:mb

8/14/64
N. WISEMAN

1. DELAY TIME: 4.95 MS ± 100 ns

2. MAXIMUM PULSE REPETITION RATE: 500 KC, RZ MODE.

3. INPUT COIL: 2 REQUIRED, FREE AIR MEASUREMENT

   a) 180 ± 2 turns, # 48 "STRIP EASE" MAGNET WIRE

   b) INDUCTANCE – 17 ± 1.7 μh (WITH OUT RIBBON)

   c) R_{dc} – 18.5 ± 2 Ω

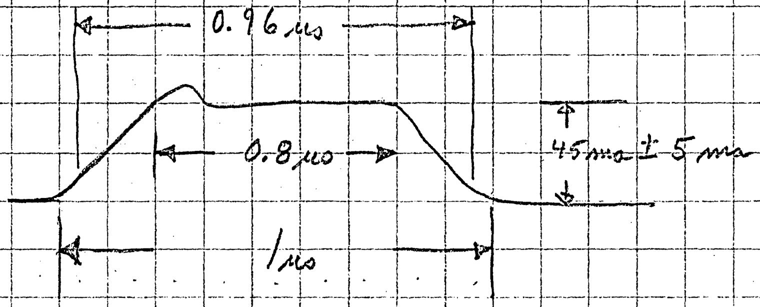
4. ASSEMBLED LINE INPUT CHARACTERISTICS:

   a) Z_{IN} @ 500 KC – 180 ± 20 Ω

   b) INDUCTANCE – 52 ± 10 μh

   c) R_{dc} – 37 ± 4 Ω

5. THE FRIDEN LINE DRIVER, DRIVING THE ASSEMBLED LINE SHALL HAVE THE FOLLOWING INPUT CURRENT WAVEFORM:



6. OUTPUT COIL: 2 REQ., FREE AIR MEASUREMENT

   a) 350 ± 2 TURNS # 48 "STRIP EASE" MAGNET WIRE

   b) INDUCTANCE – 64 ± 6.4 μh

   c) R_{dc} – 39 ± 5 Ω

8/14/64
N. WISEMAN

7. ASSEMBLED LINE, OUTPUT COILS

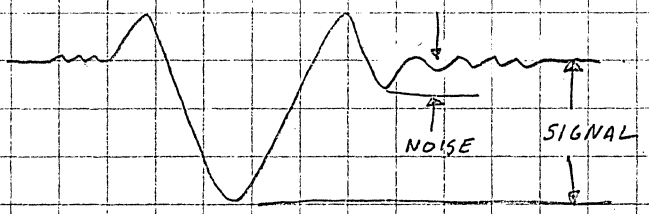
a) INDUCTANCE - 230 ± 30 µh

b) Rdc - 80 ± 8 Ω

8. OUTPUT VOLTAGE WAVEFORM, DELAY LINE TERMINATED WITH 1.5 K, 100 pf

a) MINIMUM OUTPUT VOLTAGE - 25 MV

b) THE DYNAMIC SIGNAL/NOISE RATIO MUST BE EQUAL TO, OR BETTER THAN 5:1 @ PRF OF 330 KC



9. DAMPING PAD EFFICIENCY - IE. RATIO OF LAUNCH PULSE TO REFLECTED PULS

a) NOMINAL - 12:1

10. LOSS FACTOR FOR THE TORSIONAL MEMBER:

THE NI SPAN-C USE IN THE LINE SHOWS A NOMINAL IMPROVEMENT OF 4:1 OVER THE MATERIAL AS RECEIVED. THE NOMINAL LOSS IN 100' OF WIRE WITH OUT SUPPORTS IS 5 db

11. Δ DELAY VS TEMP. - ONE SAMPLE MEASURED 7 PPM/°C FROM 25°C - 60
or .8 µsec In a 5 ms Line

12. NO SHOCK OR VIBRATION MEASUREMENTS MADE.
Haves group errors at 3½ Gs vibration

COMPONET	MATERIAL	DIMENSIONS	SPECIAL TREATMENT	VENDER
MAGNETOSTRICTIVE RIBBON	#200 PURE NICKEL	.002" x .020"	ANNEALED WITH 3 AMPS A.C. FOR 1 MIN.	DRIVER HARRIS CO. HARRISON, N.J.
TORSIONAL WIRE	NL-SPAN C	.025"DIA.-47'LONG (18 TURNS)	HEAT TREATED IN HYDROGEN & NITROGEN ATMOSPHERE AT 1225°F FOR 30 MIN.	ENGELHARD INDUSTRIES INC., H.A. WILSON DIV. UNION, N. J.
DAMPING PADS	25-30 DUROMETER SILICONE RUBBER	1.75" x .5" x .125"		C&R RUBBER PROD. SAN LEANDRO, CALIF.
WIRE SUPPORTS	25-30 DUROMETER SILICONE RUBBER	2" x .062"		C&R RUBBER PROD. SAN LORENZO, CALIF.
LINE RETAINER	25-30 DUROMETER SILICONE RUBBER	.25" x .25" x .031"		ALASCO RUBBER & PLASTIC, BURLINGAME, CALIF.
TRANSMIT COIL	#48 CELENAMEL	180 TURNS (17 mh± 10%)		FOX ELECTRONICS, SAN FERNADO, CALIF.
RECEIVE COIL	#48 CELENAMEL	350 TURNS (64 mh± 10%)		FOX ELECTRONICS, SAN FERNADO, CALIF.
MAGNET	CAST ALNICO	.125" DIA - .250" LONG		ARNOLD ENGINEERING CO., MARENGO, ILL.

NOMINAL DELAY = 4.95 MILLISEC. ± 100μS
MIN VOLTAGE OUT = 25 MILLIVOLTS
MIN SIGNAL TO NOISE RATIO = 5:1 (DYNAMIC)

GENERAL INFORMATION ON THE EC-130 DELAY LINE