7
Motion encoders

7.1 APPLICATIONS

Motion encoders are used to convert linear or rotary motion to an analog voltage or a digital code. A variety of motion encoders is available that use many different sensor technologies in a wide size range. Applications include shaft position and speed readout, machine tool control, robotics, servomechanisms, industrial controls, and magnetic media handling. Two basic types are available, absolute and incremental.

7.1.1 Absolute

Absolute encoders output a unique code for each position. An example is an optical rotary encoder which divides 360° of rotation into 1024 parts. A 10 bit output is produced by light sources shining through ten stripe patterns onto ten photosensors. To eliminate the need for accurate edge alignment, the stripe pattern coding is often Gray code rather than straight binary.

7.1.2 Incremental

A 1024-count optical incremental encoder has a single stripe pattern and a single photosensor instead of 10, and calculates absolute position by counting stripes. Absolute position is established by moving the encoder to a limit, or an index output using a second photosensor can be used to reestablish reference position on the fly. A third sensor is used if bidirectional operation is contemplated. Despite the added complexity of establishing absolute position, incremental encoders are considerably simpler than absolute, and have become more popular.

7.2 TECHNOLOGY

Optical stripe encoders

Optical stripe encoders (incremental encoders) are available at low cost if the required resolution is on the order of 100 – 400 counts per turn. Accuracy is excellent, and unpackaged devices are available for incorporation in user-designed mechanics.

Packaged devices with moderate count resolution (512 counts per revolution) are available at less than $10 (MOD5500, BEI Motion Systems, CPD, San Marcos, CA (619)471-2600). As resolution requirements increase, the cost increases to about $30 for a 10,000 count encoder or $65 for a 50,000 count encoder. Maximum stripe densities of over 400,000 counts/revolution are available, but cost over $1000. Also, logic to handle these high counts is expensive: a 20,000 count encoder at 6000 rpm generates 2 MHz clock pulses. This is too fast for direct input to general-purpose microcomputers, so most systems provide a multibit up-down counter to interface to the computer, or use a more expensive DSP computer capable of handling high input frequencies.

A simple radial stripe pattern is usually used. With one sensor, speed can be measured but not direction. With two sensors, direction can be measured also, and if sine and cosine shaping is provided, the distance between stripes can be interpolated for higher resolution. Without sine-cosine shaping, the square wave outputs of two sensors provide double the resolution. These encoders, without interpolation, are used in computer mice, trackballs, and other speed- and position-measuring devices. With analog interpolation for higher resolution, higher effective counts for servomechanisms and accurate position transducers are available.

In closed-loop position servomechanism applications, optical stripe encoders are normally used with either a dedicated PID (proportional-integral-derivative) motion control integrated circuit such as the National LM628, or as an input to a DSP-type computer programmed with a feedback control routine. The DSP (digital signal processing) computer is programmed with the PID algorithm or a fuzzy-logic motion control algorithm.

Binary-coded optical encoders have true absolute position output but are more expensive. A 16 bit (0.0018%) absolute optical encoder costs about $1000 (qty. 1, Teledyne-Gurley, Troy, NY (518)272-6300), a 12 bit (0.0025%) absolute encoder costs $399 (qty. 1, CP-850-12BCD from Computer Optical Products, Chatsworth, CA (818)882-0424).

LVDT

LVDTs, or linear variable differential transformers, are rugged and reliable. They are magnetically coupled and AC excited, capable of accuracy exceeding 0.1%, and are noncontact. The principal drawbacks are the high current consumption and the difficulty of fabricating large magnetic structures; most LVDTs are linear. LVDTs are inherently three-dimensional structures and are difficult to build on a printed circuit substrate.

LVDTs are popular sensors, and an integrated circuit is available which is designed for LVDT interface, Analog Device's AD698.

Resolvers

Resolvers, from vendors such as Litton's Clifton Division, Blacksburg, VA (800)336-2112, look much like an AC motor. A wound rotor is excited by AC and generates AC signals in two stator windings, mechanically disposed at 90° to each other. The stator windings produce sine and cosine waveforms as the rotor is rotated. Higher resolution multipole resolvers produce 16x or 32x cycles per revolution by using many windings and slotted armatures. A typical size 11 (2.5 cm diameter) resolver has an accuracy of ±7 min.

Typical operating temperature range can be –20 to 120°C, and environmental extremes of humidity, shock and vibration, oil mist, coolants, and solvents do not affect operation. Resolvers are rugged and capable of good performance, but no low cost versions are available.

Potentiometers

Linear and rotary motion sensing with positioning accuracy requirements of one part in 1000 can be done with potentiometers. With a precision conductive plastic pot, specs are:

- $10-100 \times 10^6$ cycles life
- 0.1° backlash
- 0.05% linearity or better (trimmed), 0.005% resolution; 5-10% linearity untrimmed
- High-speed capability to 10,000 rpm
- 0.03% rms noise; about 0.15% p-p
- $3 (10 K) if user provides bearings and packaging; else $5 and up

The main drawback of potentiometers for precision sensor use is the noise caused by the rubbing contact. The quietest available resistance material is conductive plastic, but its noise is many times its resolution, and it will limit performance in high resolution wideband servo systems. The typical high frequency peak characteristic of a PID servo amplifier will cause the output to saturate due to the potentiometer noise before an acceptably high gain can be reached.

Backlash in packaged potentiometers is caused by looseness of fit of bearings and the compliance of the wiper arm working against the coulomb friction at the contact point. When a potentiometer is used as the position sense element in a high gain closed loop position servo, backlash can cause an oscillatory limit cycle behavior when the system is nominally at rest.

Photopot

A "photopotentiometer" replaces the precious-metal wiper used in precision potentiometers with a photoresistor. A precision resistive potentiometer element is coupled to a collector ring using a deposited photoresistive element. The photoresistor is illuminated using a slit aperture which rotates or translates. This device solves the contact noise problems of metal-wiper potentiometers, but at a cost of complexity and power supply current. Linearity is 1.5–3%. Rectilinear models are available (from Silicon Sensors, Inc., Dodgeville, WI, (608)935-2775) to 10 cm length, and rotary models with 2–3 cm diameter.

Summary of position transducers

Table 7.1 compares the position transducers.

Table 7.1 Position transducers

Encoder type	Abs inc	Sin/cos available	Resolution	Supply current	Advantage	Disadvantage
Capacitive	A/I	yes	infinite	0.1 mA	absolute, inexpensive	good mechanics may be needed for accuracy
Hall effect	A	no	infinite	5 mA	low cost	inaccurate
LVDT	A	no	infinite	20 mA	rugged, decent accuracy	rotary not available
Optical stripe	I	yes	50,000 counts	20 mA	accurate, good linearity	incremental, high power, needs counter
Optical absolute	A	no	14 bits	50 mA	absolute, binary output	cost
Photopot	A	no	infinite	20 mA	infinite resolution	one vendor
Potentiometer	A	yes	infinite	0.1 mA	inexpensive	noisy
Resolvers	A	yes	infinite	200 mA	rugged	expensive

Abs/inc

Absolute transducers such as a potentiometer continuously output current position in analog or digital form; incremental transducers like an optical stripe encoder output a pulse each time an increment of position is reached.

Sin/cos

Incremental transcoders output two signals in quadrature which are used for keeping track of direction as well as position. Most versions are digital and use square wave outputs which resolve to half a stripe, but if the outputs are analog and sine and cosine shaped, interpolation between counts can determine a fine position with resolution limited by noise and stability.

7.3 CAPACITIVE MOTION ENCODERS

There are no commercially available modular capacitive motion encoders known to the author, except for capacitive proximity sensors designed for go-nogo proximity detection. But capacitive position sensors are easy to design, the electrode plates can be made as a part of an existing printed circuit board, and no special tooling or hard-to-get parts are needed. These sensors can easily be integrated by the designer on printed circuit boards or integrated circuits and can replace other types of purchased or packaged units.

Good accuracy and resolution are possible with capacitive encoders; one laboratory [de Jong et al., 1994] describes a rotary angle sensor of 50 mm diameter using printed circuit board construction with repeatability of 9 arc seconds, or 17 bits.

7.3.1 Electric potential sensors

Most capacitive position sensors measure the capacity of a system of conducting plates or other shapes. Improved performance for motion detection applications is possible by instead considering the problem as that of measuring electric potential by capacitive coupling. Consider a resistive sheet with an AC voltage imposed and a capacitive plate sensor nearby (Figure 7.1).

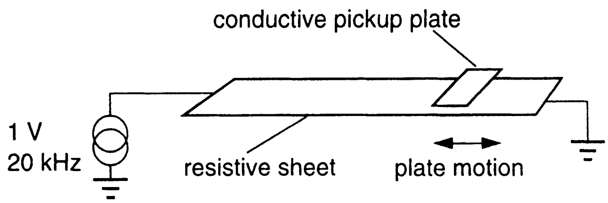


Figure 7.1 Resistive position transducer

Assume the sheet resistance is hundreds of ohms so that the 1 V AC signal produces a linear field just above the surface of the sheet. If the pickup plate is closely spaced, it will pick up the voltage at the surface of the sheet by capacitive coupling. In Figure 7.1, as it moves from left to right, the voltage will change from almost 1 V to zero. The absolute value of the coupling capacitance is relatively unimportant in a properly designed system, as the pickup plate voltage accurately tracks the voltage of the resistive sheet if the pickup is well guarded (Figure 7.25) and if the amplifier input impedance is very high.

This principle can be used to build a class of position sensors which measure fields rather than capacitance. In the case above, in fact, the challenge is to pick up the field capacitively but to eliminate the effects of stray capacitance so that the position measurement is independent of spacing.

Effects of stray capacitance

The model above suffers greatly from stray capacitance. The bottom of the pickup plate is coupled to the resistive sheet with a capacitance of, say, 0.8 pF with a 1 cm^2 area, but the back of the plate will couple to infinity with about 0.2 pF. This reduces the signal by 25% and makes signal amplitude very dependent on spacing. Demodulator designs which are less sensitive to amplitude are possible, but at the cost of a dozen small parts.

If the pickup is in an unshielded enclosure, electric fields generated by radio broadcasts, fluorescent lamps, and 60 Hz wiring will couple easily to the very high impedance pickup amplifier, and stray capacitance to clock-frequency signals will cause a position error with increase of spacing.

Stray capacitance noise pickup can be handled by shielding. As the pickup amplifier is almost totally insensitive to inductive noise, the electric field only must be stopped, and virtually any thickness of conductive material will suffice; see Section 12.3, "Shielding." But capacitance to the back of the pickup plate will be larger if a nearby shield is used, which leads to increased spacing sensitivity; a driven guard is preferable, or a feedback amplifier as shown in Chapter 4.

7.3.2 Alternate ways to generate a linear electric field

Resistive sheet

The resistive sheet in Figure 7.2 could be created by using a screened conductive plastic rectangle on PC board electrodes, with several hundred ohms/square resistivity. This sensor measures pickup displacement in the x direction and can be designed to have good rejection in the y and z directions and in the three tilt axes.

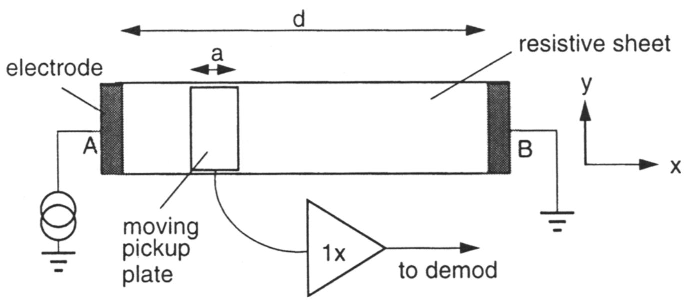


Figure 7.2 Resistive sheet

Note that the pickup is underlapped (or overlapped) so that inadvertent pickup plate displacement in the vertical (y) axis will not affect the detected position. If the pickup is the same width as the resistive sheet, a small displacement in the vertical direction will reduce the pickup area, and if any stray capacitance is present this vertical displacement will reduce the signal and change the reported position. Overlap or underlap by an amount equal to the maximum expected mechanical misalignment plus three to five times the spacing will combat this effect. Tilt around the z axis (into the page) is handled by overlap or underlap. Tilt around the x axis produces no output change, at least first order, and the effect of tilt around the y axis is minimum if $a << d$.

Metallic conductors

A metallic conductor pattern can be used as well (Figure 7.3).

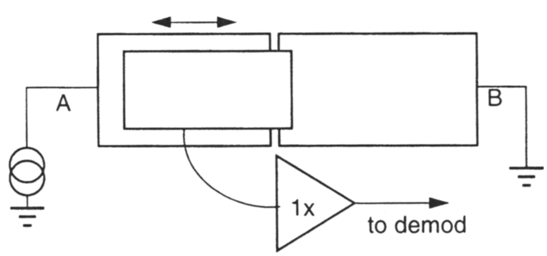


Figure 7.3 Conductive plate, square pattern

This has an advantage over the resistive sheet (Figure 7.2) as the plates can be simply copper areas on a printed circuit board and the pickup area is larger, but a serious disadvantage for accurate sensors as the mechanical sensitivity to pickup plate tilt around the vertical axis is worse due to the increase in pickup plate width. As the right side of the pickup, for example, tilts closer to the substrate because of poor mechanical stability and the left side tilts away, the voltage coupled to the pickup decreases, and the sensor will report a nonexistent change in position.

These plate patterns are drawn as linear transducers, but can easily be applied to a rotary transducer. Wrapping the rectangular plates around a center point produces a rotary pattern reminiscent of air-spaced tuning capacitors (Figure 7.4).

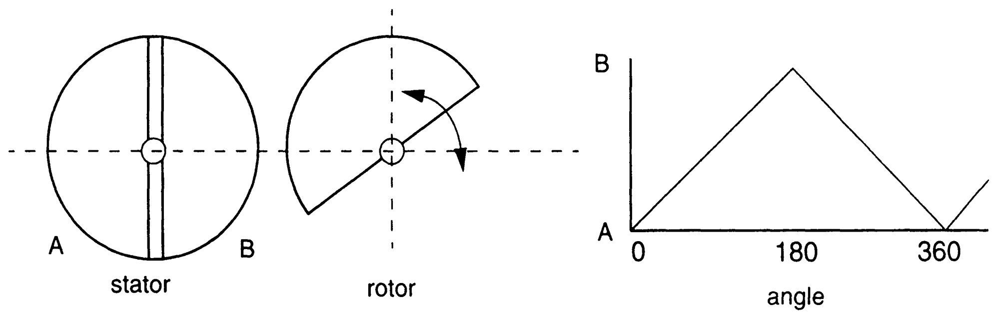


Figure 7.4 Rotary sensor

Adding another similar rotor segment is shown in Figure 7.5.

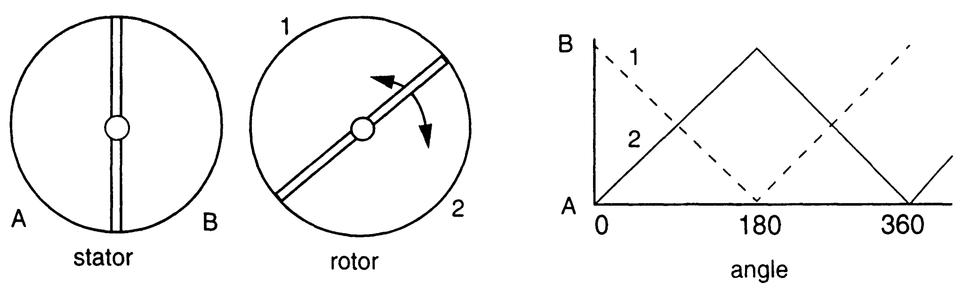


Figure 7.5 Differential rotary sensor

Although needing an additional amplifier, this geometry allows ratiometric detection and is insensitive to spacing, and is insensitive to tilt when the rotor is near 90° intervals, but not when the rotor is near 45°, 135°, etc.

These rotary sensors could have some applications as a rotary transducer, but they have an ambiguity of 180° and are probably not as useful as the sine/cosine plate approach detailed later. A better rotary sensor, with increased linear range, no ambiguity, and with more resistance to tilt, is made by wrapping the V-ramp pattern (Figure 7.8) into a circular pattern.

The ramp pattern shown in Figure 7.6 is equivalent to the resistive sheet (Figure 7.2) if the pickup plate is accurately aligned. It acts as a capacitive divider, so that electrode *A* is coupled tightly to the pickup plate with the pickup at the left end, and *B* is coupled with the pickup at the right end. A high impedance or feedback-type amplifier is preferred to minimize spacing sensitivity, and overlap rather than underlap reduces unwanted sensitivity to *y*-axis displacement.

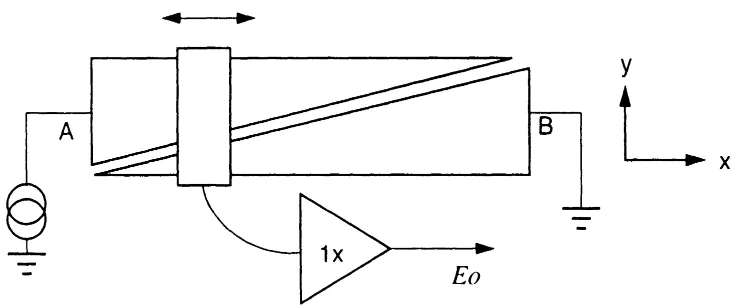


Figure 7.6 Conductive plate, ramp pattern

In the equivalent circuit (Figure 7.7), *C*1 is the area common to the pickup plate and the stator section *A*, *C*2 is the area common to the stator and *B*. *C*1 will increase linearly as the pickup moves to the left, and *C*2 will decrease. The voltage at the center tap (the pickup plate) with *Cstray* small is

$$Vp = Vs \times \frac{C1}{C1 + C2} \qquad 7.1$$

or *C*1/*Ct* where *Ct*, the sum of *C*1 and *C*2, is a constant. This equivalent circuit also shows that the capacitive pickup is at least first-order immune to changes in capacitance due to environmental effects: the output is related to a capacitance ratio rather than an absolute capacitance.

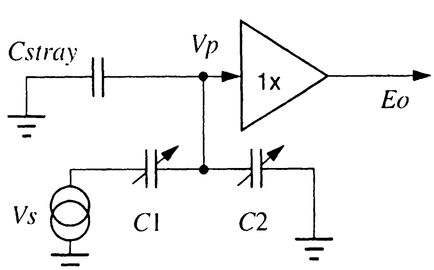


Figure 7.7 Ramp pattern, equivalent circuit

The ramp pattern above (Figure 7.6) suffers from tilt in two axes. Tilt in the vertical (y) axis was discussed and is minimized by using a smaller pickup width. Tilt around the horizontal (x) axis also causes a large change in reported position. The modified ramp pattern (Figure 7.8) shows a simple way to combat this effect.

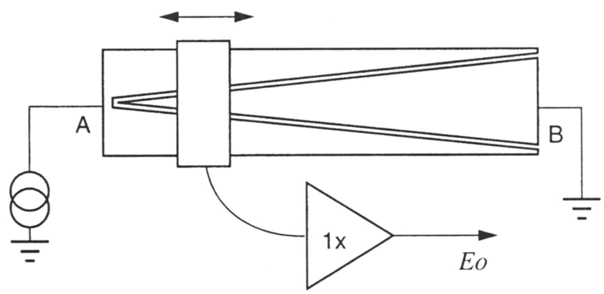


Figure 7.8 V ramp

With this geometry, the plates are symmetric and horizontal-axis tilt is nulled out.

Improved linearity

The V pattern above can be further improved. The simple V pattern produces a nonlinear response (Figure 7.9).

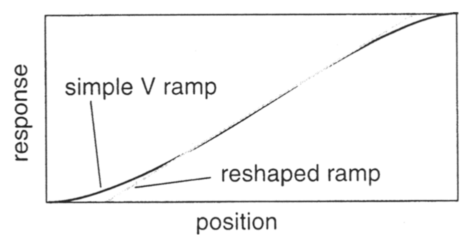


Figure 7.9 Nonlinear response

Reshaping the ramp fixes this (Figure 7.10).

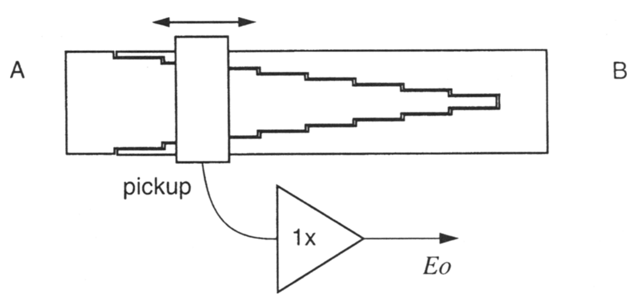


Figure 7.10 Reshaped ramp

The result is a linear relationship between position and output voltage.

With appropriate shaping, the electrodes can generate arbitrary nonlinear functions. With a rectangular pickup as shown, the electrode shape can be determined by an inverse convolution integral as shown in the next section.

CONVOLUTION

The linear ramp generated by the electrode pattern of Figure 7.10 can be predicted mathematically by the convolution of the pickup shape with the electrode shape. The convolution integral and its inverse can be used to create electrode shapes to generate arbitrary waveforms, with the most useful being linear and sine-cosine shapes for both rectangular and polar coordinates.

7.4.1 The convolution integral

Continuous functions

Convolution is an operation performed on two arbitrary functions, $f(x)$ and $g(x)$. The convolution of these functions, $c(x) = f(x) * g(x)$, is the area under the product of the two functions, plotted against the relative position of the two functions (Figure 7.11).

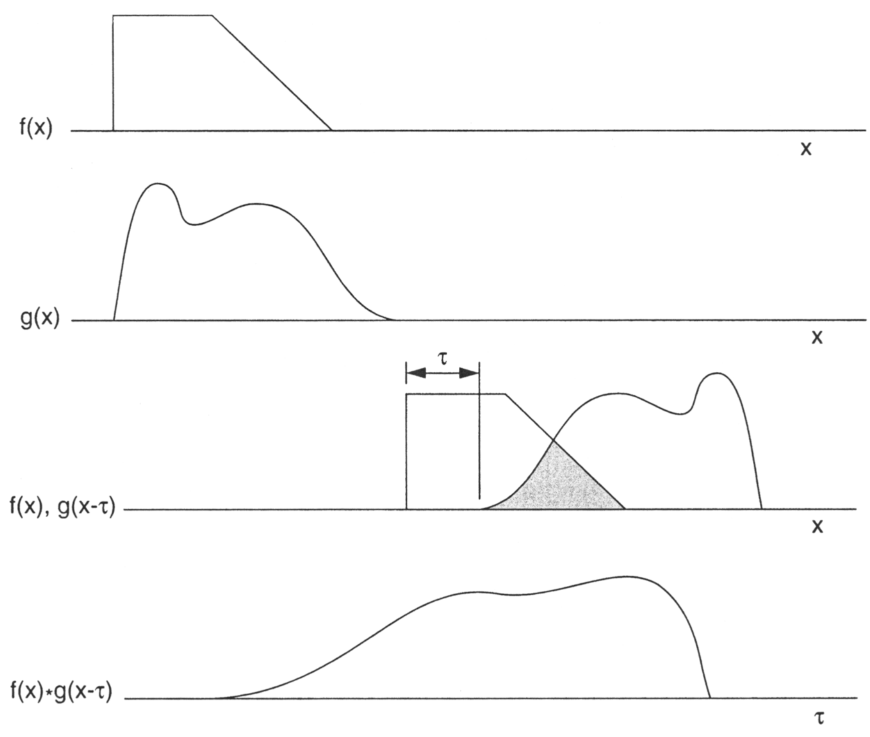


Figure 7.11 Convolution of two functions

The third graph shows $g(x)$ in terms of a dummy variable τ. Since τ is subtracted from x, the shape of $g(x)$ is reversed, and as τ increases from $-\infty$ to $+\infty$, $g(x-\tau)$ moves from right to left relative to $f(x)$. Note that either $f(x)$ or $g(x)$ could be restated in terms of τ, or $\tau/2$ could be added to $f(x)$ and subtracted from $g(x)$ with equivalent results. With τ as shown in graph 3, the region where $f(x) \times g(x)$ is not zero is shown shaded. Using τ as the independent variable the area under $f(x) \times g(x)$ vs. τ is the convolution, as shown in the bottom graph. Its equation is

$$f(n)^* g(x) = \int_{-\infty}^{\infty} f(x) g(x - \tau) d\tau \qquad 7.2$$

Two-dimensional convolution

Convolution is also defined for two-dimensional objects $f(x,y)$ and $g(x,y)$ by calculating the area under $f(x, y) \times g(x - x_1, y - y_1)$ with x_1, y_1 used as dummy variables adjusting the relative displacement of $f(x, y)$ and $g(x, y)$ in two dimensions.

7.4.2 Sampled data convolution

For sampled data systems, the continuous variable x is replaced by the discrete-time variable n and the continuous variable τ is replaced by a discrete-time version of τ, and convolution is then defined as

$$f(n)^* g(n) = \sum_{\tau = -\infty}^{\infty} f(n) g(n - \tau) \qquad 7.3$$

For every finite value of t, all nonzero values of $f(n)$ and $g(n - \tau)$ are multiplied and summed. For mathematics software programs such as Mathcad or MATLAB, with inputs $f(m)$ and $g(n)$ in discrete time (m instead of n to allow independent function lengths), an example calculation (using Mathcad) is

$M := 100$	define length of $f(m)$
$m := 0 \cdots M-1$	define range variable m
$N := 20$	define length of $g(n)$
$n := 0 \cdots N-1$	define range variable n
$f_{(M+n)} := 0$	set unused $f(m)$ between 100 and 120 to zero
$g_{(N+m)} := 0$	set unused $g(n)$ between 20 and 120 to zero
$K := M + N$	set $K = 120$
$k := 0 \cdots K-2$	define dummy range variable k
$\tau := 0 \cdots K-2$	define range variable τ to span overlap region

$$c_\tau = \sum_{k=1}^{\tau} f_k g_{(K+\tau-k)} \text{convolution } c_\tau \qquad 7.4$$

Here, τ is the variable which moves $g(n)$ relative to $f(m)$; k then scans through all legal values for each new relative position defined by τ. The convolution c_τ multiplies f and g at all values of τ, sums, increments k, and repeats the multiply/sum operation until $k = \tau$. As the input functions are padded with zeros, only values of k in the overlap region are nonzero. This fails in practice, as $K + \tau - k$ can assume values well outside of the range defined for $g(n)$ so that an out-of-range variable will be flagged. Equation 7.4 is repaired by adding truncation to limit range to legal values with a max/min operators, or in Mathcad the mod function

$$c_\tau = \sum_{k=1}^{\tau} f_k g_{\text{mod}(K+\tau-k,\, K)} \qquad 7.5$$

returns the remainder after dividing $K + t - k$ by K and also truncates to legal values.

Another way to calculate the convolution of discrete-time functions is to use the fact that the inverse transform of the product of the complex Fourier transforms of the input signals approximates the convolution.

Inverse convolution

The convolution operation shows the designer of area-variation capacitive sensors what the output signal will look like with predefined electrode shapes. If a particular output signal is needed, this forces a cruel sort of trial and error, exacerbated by the curiously nonintuitive nature of the convolution integral's graphical results. With the inverse convolution operation **iconv**, electrode design becomes more deterministic. If a desired output $c(\tau)$ is defined and one plate $g(x)$ is defined, the other plate $f(x)$ can be calculated by

$$f(x) = \textbf{iconv}\,[(c(t),\, g(x))] \qquad 7.6$$

This operation may be handled with discrete variables using an element-by-element divide

$$f_m = \frac{\sum_{k=1}^{\tau} f_k g_{\text{mod}(K+\tau-k,\, K)}}{g_0} \qquad 7.7$$

with the obvious restriction that some definitions of f_m and c_τ may not produce a legal g_n. Another obvious restriction is that g_0 should be nonzero; in fact it should be much larger than the limiting precision of the hardware handling the calculations to avoid roundoff errors. Equation 7.6 is used for inverse convolution in Mathcad and was used for the following graphs; another popular mathematics program, MATLAB, has a direct **iconv** operator.

Another way to solve convolution or inverse convolution problems is to use the convolution property of Fourier transforms, where two functions to be convolved are Fourier transformed, multiplied, and inverse Fourier transformed.

7.4.3 Examples of inverse convolution

Equation 7.6 is used to create the following examples (Figure 7.12) of inverse convolution, where one input signal g_n and the convolution c_τ are given and the other input f_m is calculated

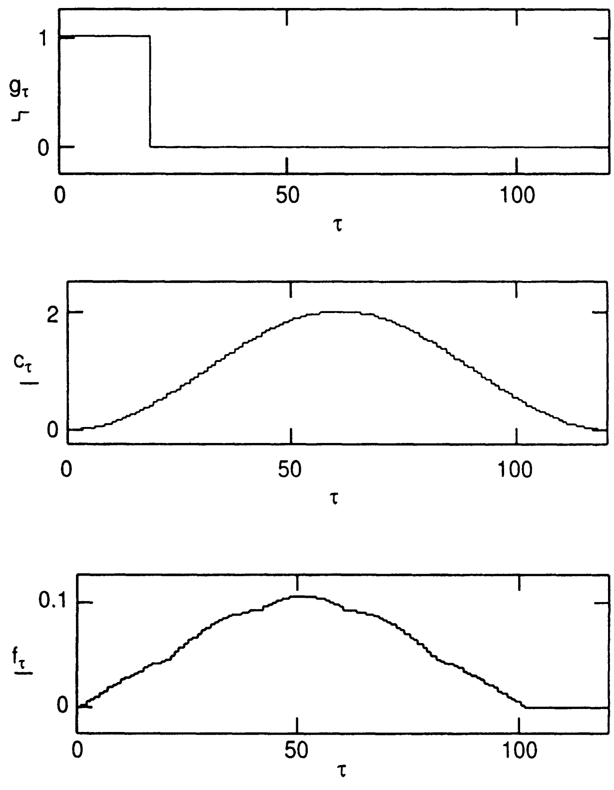


Figure 7.12 Sine wave output

The input g_τ is defined as shown, representing a rectangular pickup plate, and the desired sinusoidal output c_τ is defined as sin(n). The input function g_τ is graphed vs. range variable τ instead of n so that the full 120 count shape is shown. The inverse convolution equation 7.6 is used to calculate the required shape of the other electrode f_τ, so that if a rectangular pickup plate with width 20 slides linearly over a fixed electrode shaped like f_τ, the output waveform will be the desired sinusoid, c_τ. More examples are shown below (Figures 7.13–7.15)

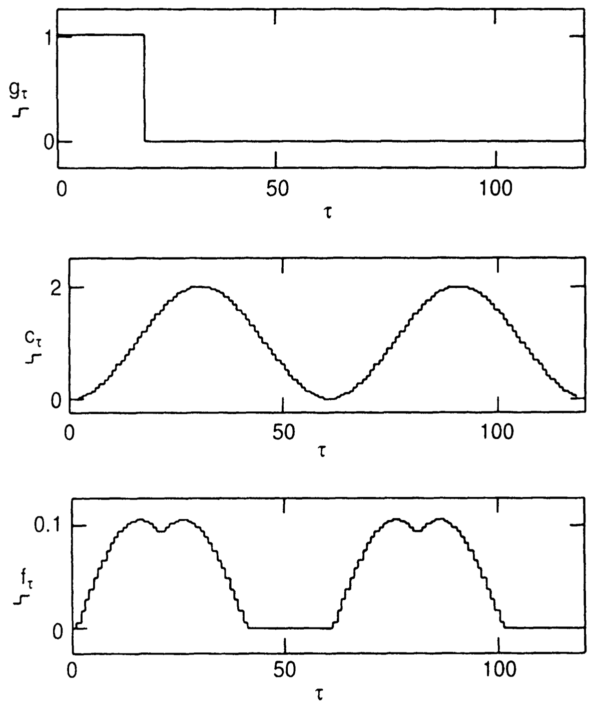


Figure 7.13 Two-cycle sine wave

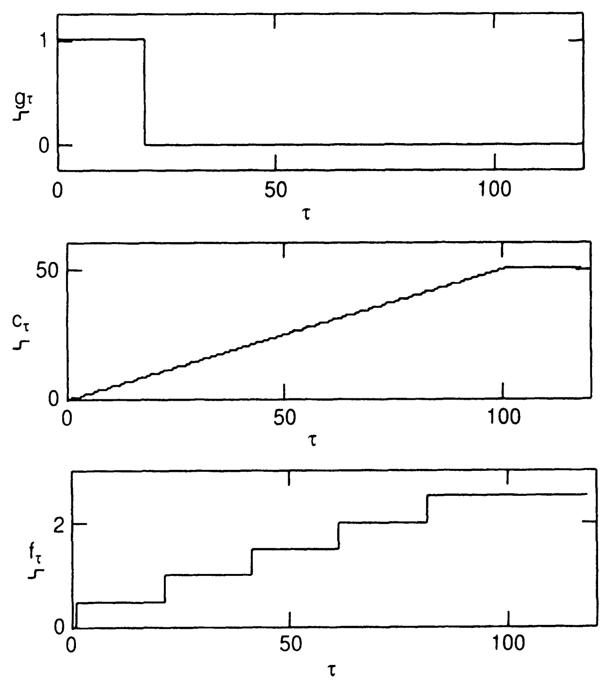


Figure 7.14 Linear ramp output

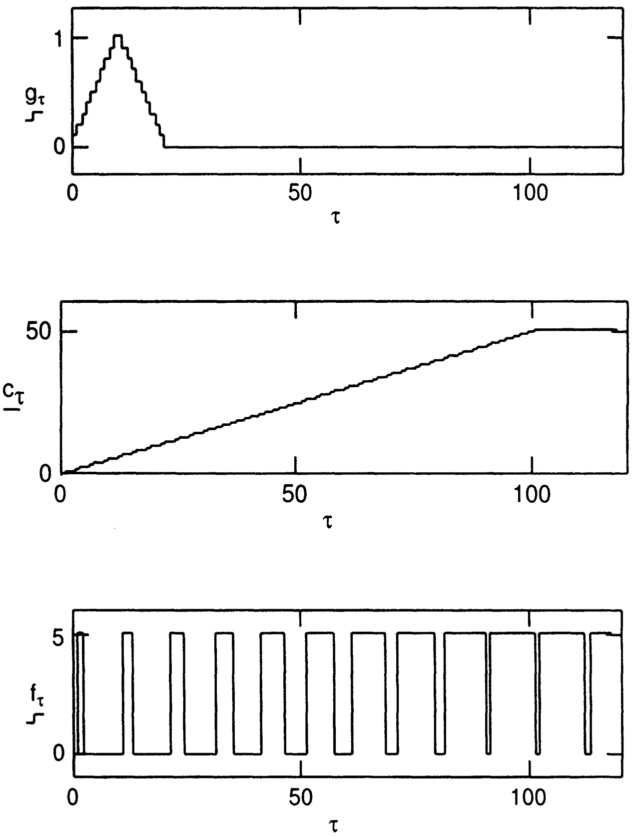


Figure 7.15 Triangular pickup plate

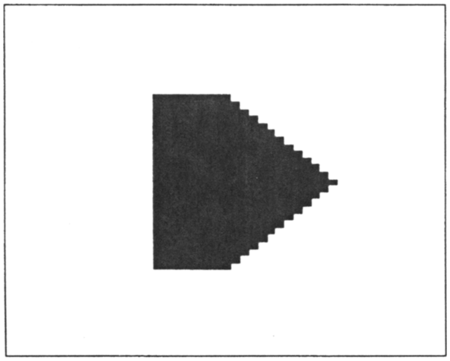
Here, a triangular input and a ramp output are chosen, and the shape of the other input f_τ is calculated. If a nonrectangular pickup is used, as above, the convolution may not yield an exact description of the proper shape of electrodes, as a two-dimensional inverse convolution should properly be used. The example above happens to work, as $f(n)$ is rectangular, but in general it will not and a y-axis variable would needed to be added to the calculation as in the two-dimensional convolution examples below.

Two-dimensional convolution

Examples of two-dimensional convolution and deconvolution using Fourier transforms are shown in *The Mathcad Treasury of Methods and Formulas*, 2nd edition, an online book of mathematical techniques (see "Convolution, 2D" in the index). With these methods, the convolution of two two-dimensional shapes A and I by the equation

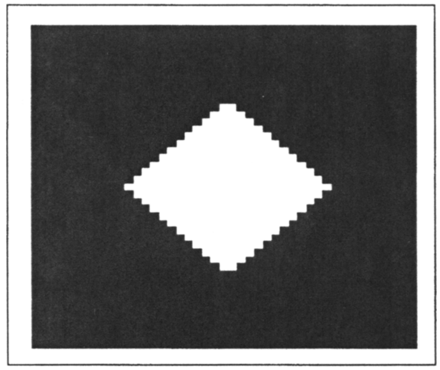
$$I2 = \mathrm{icfft}(\mathrm{cfft}(A)(\mathrm{cfft}(I))) \qquad 7.8$$

is shown, using Mathcad's surface graph for display (Figures 7.16–7.19).



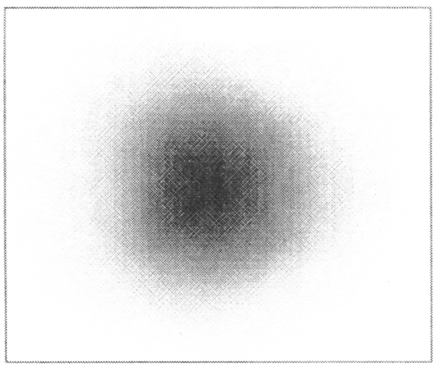
I

Figure 7.16 Shape *I*



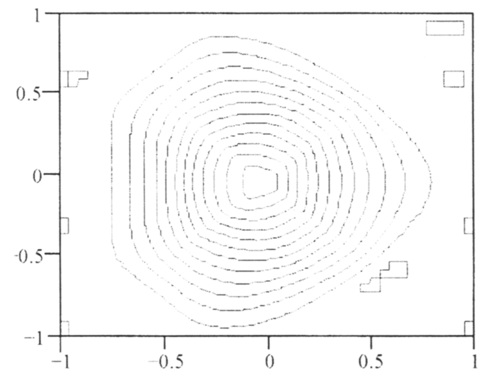
A

Figure 7.17 Shape *A*



I2

Figure 7.18 Convolution of *A* and *I*



I2

Figure 7.19 Contour plot of convolution of *A* and *I*

As with the one-dimensional convolution, if the desired output *I*2 is known and one input *A* is known, the other input *I* may be derived using deconvolution

$$I = \text{icfft}\left(\frac{\text{cfft}(I2)}{\text{cfft}(A)}\right) \qquad 7.9$$

The terms icfft and cfft are the inverse complex Fourier transform and the complex Fourier transform. Deconvolution works only if the desired output is realizable by convolution. If only one data point in the desired output is wrong, the mathematics does not converge and a totally bizarre solution is produced.

7.4.4 Rectangular to polar conversion

Any of these rectangular graphs in x - y coordinates could be converted to r - ϕ polar coordinates using the standard transformation

$$r^2 = x^2 + y^2$$

$$\tan\phi = \frac{y}{x}$$

A rectangular plate transforms to a pie-shaped plate in polar coordinates (Figure 7.20).

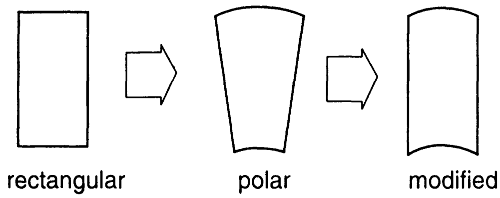


Figure 7.20 Pickup transformation

Note that the pickup plate can be pie shaped, as the polar coordinate transformation would suggest, but sensitivity to runout is smaller with the modified rectangular pickup shape.

7.5 PLATE GEOMETRY

The stray capacitance situation is improved if the pickup plate is enclosed by the stator plates. When the pickup moves away from one stator, suffering a loss of capacitive coupling, it moves closer to the opposite plate. The increase from one plate compensates for the decrease from the other, if the pickup is approximately centered. The pickup can be completely enclosed by the stator, either in the cylindrical geometry shown in Figure 7.21 or using two stator plates (Figure 7.22).

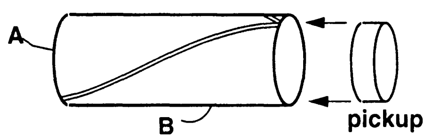


Figure 7.21 Cylindrical plates

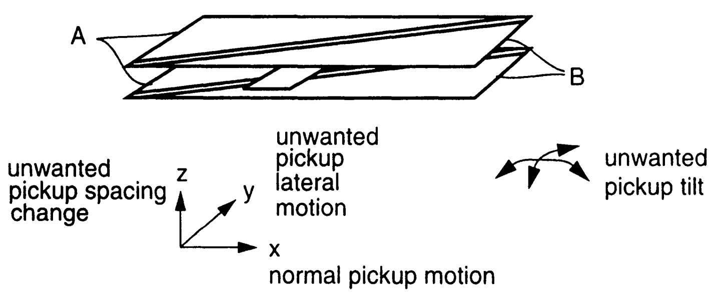


Figure 7.22 Two stator plates

Another benefit is 2× increased capacitance. Here, also, the reshaped ramp of Figure 7.10 will give better linearity.

7.5.1 Spacing change effects

Plate geometries where the pickup is surrounded by fixed, close-spaced stator are more resistant to spacing changes. With the single-stator geometry of Figure 7.6 or Figure 7.8, the performance as spacing varies can be seen by looking at Figure 7.7. The stray capacity, *Cstray*, is constant with spacing while *C*1 and *C*2 change as 1/spacing. For a 10% spacing change and a *Cstray* which is the same as the total pickup capacitance *Ct*, the apparent position will change by about 10%. This can be fixed in several ways.

In the two-stator-plate geometry of Figure 7.22, the stray capacitance to ground *Cstray* will be minimum. Also, the stator-to-pickup capacitance will be relatively constant as the pickup plate is displaced up and down, especially for small displacements about the centerline. Larger displacements with a low-Z amplifier cause an increase in total capacitance *Ct* (*Ct* = *C*1 + *C*2) which interacts with the pickup amplifier's input capacitance. This graph shows the capacitance *Ct* vs. z displacement of the two-stator-plate geometry (Figure 7.23).

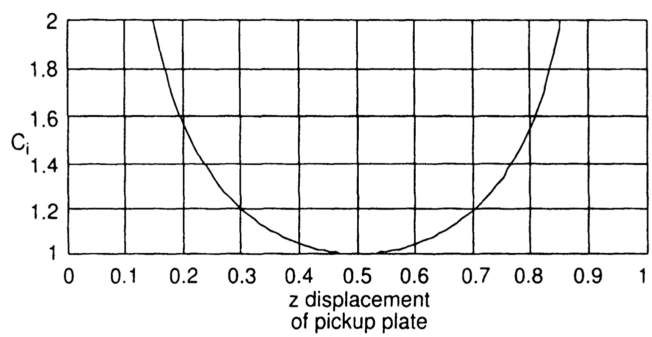


Figure 7.23 z displacement, two stator plates

If the spacing is held within 20% of the center, the variation of total capacitance is held to less than 5% (Figure 7.24).

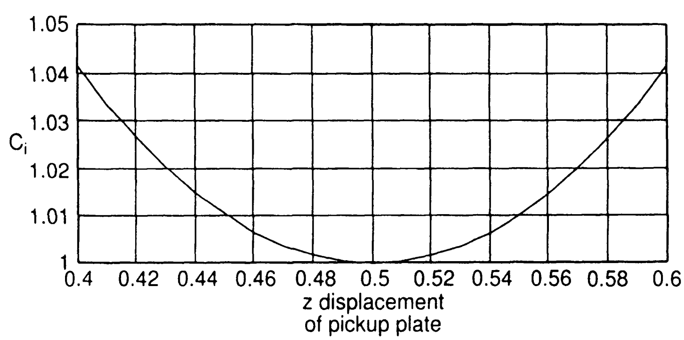


Figure 7.24 z displacement, two stator plates, near center

With large displacements, say, half of the total spacing, as the pickup comes close to either stator plate the total capacitance is dominated by the spacing of the closer plate and changes as 1/spacing, but when the pickup is close to centered, the nonlinear effects cancel over a fairly broad range and vertical axis tilt is first-order compensated. For this to work well, the sum of stray capacitance and amplifier input capacitance should be much less than *Ct*.

This geometry first-order compensates for tilt in all axes. If the pickup underlaps the stator, translation is also first-order compensated in all axes except the desired x axis.

Guard the pickup

If the pickup is shielded from "looking" at any ground potential (or any harmful noise potential) by a conductive guard plate (Figure 7.25) which is bootstrapped to the pickup's potential, *Cstray* will be effectively nulled, as seen in Chapters 3 and 4.

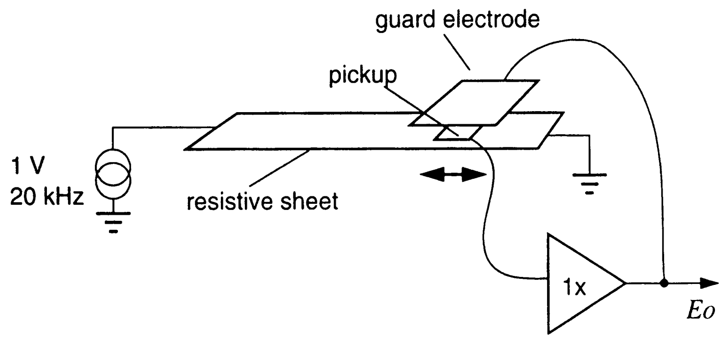


Figure 7.25 Guard electrode

The guard in this example travels with the pickup plate; it is typically larger than the pickup plate, and it shields the pickup plate from stray electric fields and capacitive coupling. If the pickup plate can look in any direction and see either the stator plate or guard, stray capacitance will be totally nulled, provided a zero input capacitance amplifier is used. If the connection between pickup and amplifier is shielded, the shield is connected to the guard so the shield's capacitance does not degrade waveshape. This is a very effective way to null out stray capacitance without adjustment, and with no bad effects on waveshape (Figure 7.26).

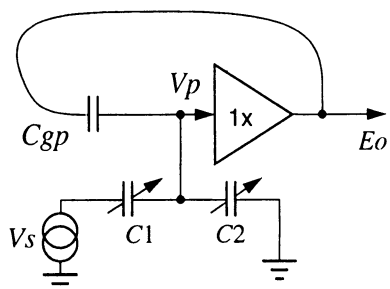


Figure 7.26 Guard electrode equivalent circuit

Cgp is the capacitance between the guard electrode and the pickup plate. The capacity of *Cgp* is larger than the stray capacitance it replaces, but since the voltage across it is forced to be zero by the 1× amplifier, *Cgp* conducts no current. The stray capacity is effectively removed. As the 1× amplifier is typically a low output impedance type, the guard electrode presents a stiff barrier against noise also. If the amplifier gain is, say, 0.99 instead of 1, the effect of *Cgp* will not be completely nulled, but it will be reduced by a factor of 100. *Cgp* will reduce amplifier high frequency gain and rise time.

Neutralizing capacitor

A technique common for vacuum tubes but not often used in semiconductor circuits is neutralization (Figure 7.27). Neutralization compensates for an unwanted input-to-output capacitance by feeding back an out-of-phase output signal to the input through a tunable capacitor, equal in value to the unwanted capacitor. An op-amp implementation is illustrated, as vacuum tubes are becoming difficult to obtain.

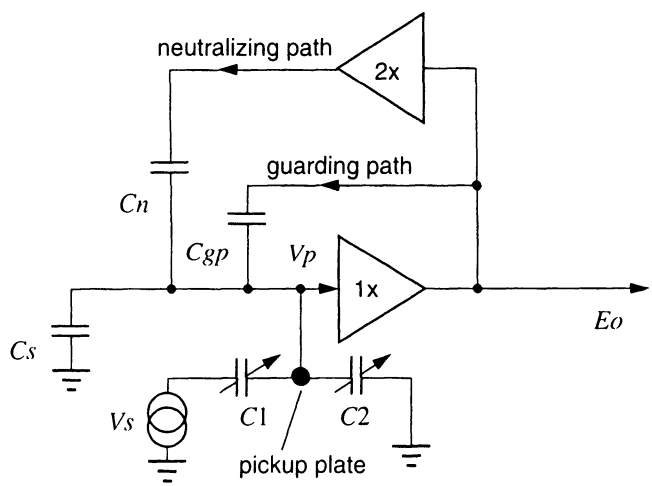


Figure 7.27 Neutralizing amplifier

Here, the bulk of the stray capacitance is compensated by the 1× amplifier driving the guard plate. The remaining stray capacitance (including amplifier input capacitance) is labeled *Cs*. A 2× amplifier provides positive feedback through *Cn*, the neutralizing capacitor. If *Cn* = *Cs*, the effects of *Cs* are removed, and the output voltage will follow exactly the position voltage at the center tap of *C*1 and *C*2. If *Cn* is too large, however, the output voltage will be larger than desired and become unstable, so this technique should be used with care and as a last resort if guarding fails to provide adequate performance. Guarding, as is seen in Chapter 10, cannot compensate for some types of internal operational amplifier parasitic capacitances and the neutralizing circuit may be unavoidable.

A single amplifier with a gain of slightly more than one could be used for both guarding and neutralization by allowing *Cgp* to serve both purposes, but the virtue of a 1× amplifier is that its gain can be made very accurate, while a higher gain will depend on resistor tolerance and will necessitate tuning the gain for good performance. The single-amplifier circuit is shown in Figure 7.28.

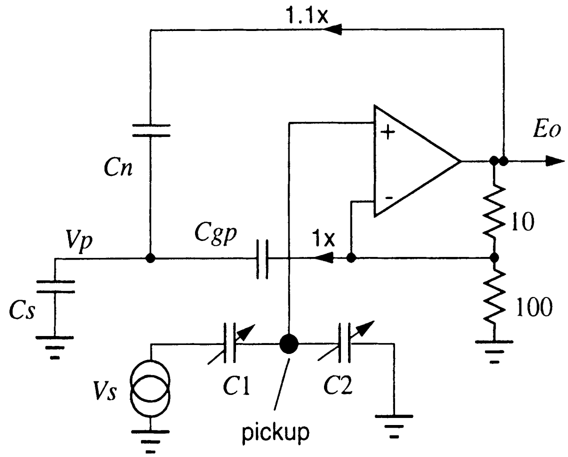


Figure 7.28 Neutralizing with one amplifier

In this circuit, the amplifier produces an accurate 1× output which is used for guarding, and a less accurate 1.1× output which is used for neutralizing. The value of 1.1× may be somewhat arbitrarily chosen between, say, 1.05 and 2. For a gain of 1.1×, *Cn*'s value must be adjusted to 10*Cs*, or optionally *Cn* can be fixed at about 10*Cs* and the amplifier gain tuned for proper neutralization. One minor drawback is that the guard voltage is not as "stiff" as before, with an impedance of 10 Ω, but this still should be acceptable. The amplifier, of course, must have adequate drive capability to handle the 110 Ω load.

7.5.2 Wireless coupling

Capacitive coupling to the pickup plate can be used to eliminate lead wires. The plate geometry discussed above needed three connections, two to the stationary stator plates and one (or two if a guard is used) to the moving pickup plate. All of these geometries can be reversed, that is, consider the pickup stationary and move the "stator" plates instead. This has an advantage, as the pickup is the most sensitive circuit element and shielded cable would be needed to connect to a moving pickup plate, while ordinary stranded wire is fine for connecting to moving stator plates.

Another option can eliminate the wire connection completely. With only slight changes in operation, the connection can be made by capacitive coupling rather than wires. The ramp plate geometry is redrawn in Figure 7.29 with capacitive coupling to the pickup instead of wire pickup.

The pickup now is capacitively coupled to the 1× amplifier through the capacitance between plate *C* and the extended lower section of the sliding pickup plate. This adds a small (about 1–10 pF) capacitance in series with the 1× amplifier. but if that amplifier has suitably low input capacitance, performance will not suffer.

If the amplifier input capacitance is comparable in value to the pickup capacitance, the amplitude will be cut in half, and an amplitude-independent signal design (see "90°

drive circuits" in Section 10.7.2) is needed. An alternate scheme is to use a feedback amplifier connection (see "Feedback amplifier" in Section 10.3.5).

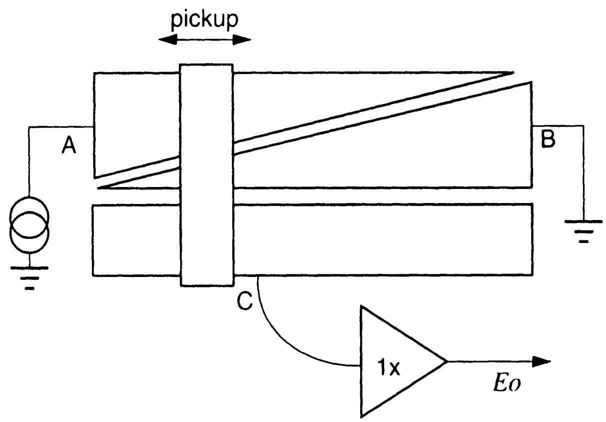


Figure 7.29 Capacitive pickup coupling

Another option is to reverse the roles: fix the pickup plate and couple the drive signal capacitively to the (moving) *A* and *B* plates. The moving shield method shown in Chapter 2 may also be wireless, as the shield is normally at ground potential.