TELEDYNE PHILBRICK Application Note

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modular V/F's and F/V's: simple solutions to everyday conversion problems

Prior to 1972, economical voltage/frequency/voltage conversion was often an enigma to the design engineer. Developments since then have opened a wide range of low cost applications for these devices.

by Frank Goodenough, Teledyne Philbrick

Modular voltage to frequency and frequency to voltage converters have not been on the scene a long time. The original data sheet for the Teledyne Philbrick Model 4701, one of the first converters in modular form, is dated February 1972. Prior to this time, V/F's could be obtained in rack mounted form or on p-c cards from a variety of companies at a cost of $300 to $3000 each. Even in this form, the V/F represented an economical solution to diverse types of problems and many companies incorporated their own V/F designs into proprietary products. V/F's and F/V's continue to be available in various small packages for aerospace and industrial tachometry applications.

The unique ability of these devices to solve everyday problems while operating alone or together has remained relatively unpublicized. A discussion of major voltage to frequency (V/F) and frequency to voltage (F/V) applications will show the design engineer how to maximize usefulness, how to improve response time, how to tailor performance to specific input/output requirements, and how to solve a wide range of problems.

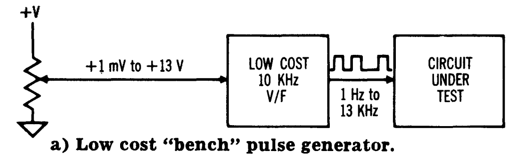
Applications for these devices break down into three major categories: systems using V/F's alone, systems using V/F's with F/V's, and other configurations using F/V's alone.

V/F applications

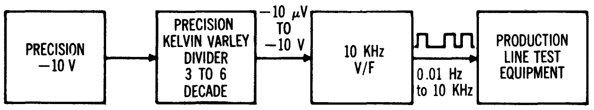
The basic function of a V/F used alone is to transform a variable dc voltage (usually 0 to 10 V) into a pulse train whose repetition rate is a direct linear function of the dc input voltage. Consequently, the converter can be used to build a variety of pulse frequency generators. For example, any engineer can have his own personal pulse generator for less than $25 by merely connecting the input through a potentiometer to the $+V_{CC}$ pin (Fig. 1a). Using a socket for the V/F, he can substitute a higher frequency unit and extend his maximum frequency to greater than 5 MHz. A simple IC flip-flop at the output provides a symmetrical square wave, while a 555 or a one shot provides variable pulse width.

Our engineer can build a precision pulse generator with a settable frequency range (and resolution) of greater than a million to one by replacing the potentiometer with a 3 to 6 decade Kelvin Varley divider, such as an ESI Model 1311 Dekapot or RV 622A Dekavider. The linearity of the divider, which can be better than one part per million, is maintained by taking advantage of the high input impedance ($>$ 100 megohms) available at the negative voltage input terminal of some V/F's. Accuracy is obtained by applying a precision -10 V to the divider and trimming the V/F full scale output to exactly 10 kHz (Fig. 1b). This technique lends itself to the design of special purpose production test equipment.

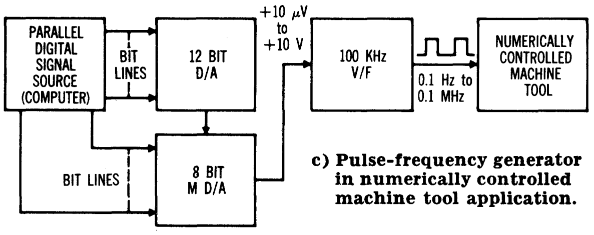
It is often necessary to convert a parallel digital signal source obtained from a computer or register to a frequency. A V/F can be used to perform this function by inserting a D/A between the digital source and the converter (Fig. 1c). This technique is used to slew the X, Y and Z axis motors in numerically controlled machine tools, to control the speed of individual rollers in printing presses, and to provide input signals for automatic testing of various systems or semiconductors.



a) Low cost "bench" pulse generator.



b) Precision wide range (6 decade) pulse generator.



c) Pulse-frequency generator in numerically controlled machine tool application.

Fig. 1. V/F in a variety of pulse generator applications.

Since its introduction during World War II, the operational amplifier has been the device of choice when precision integration of analog voltages is required (Fig. 2a). The use of this device has proven to be an excellent technique when integrate and/or hold times are less than a few minutes, but components become expensive and performance degenerates rapidly when these times are exceeded. However, Fig. 2b shows a V/F, counter, and D/A converter substituted for the op amp. In this configuration, instead of accumulating charge in a capacitor, counts accumulate in the counter.

Counting can continue for seconds, hours, days, or even years, if enough counter stages are provided. And, when put into the hold condition by disconnecting the counter from the V/F, the count is held indefinitely with no change in the output. (If the count is transferred to a latching relay register, even power loss will not cause the loss of the held number). If a BCD counter is used, a numerical display can be used in parallel with the D/A to provide an indication of the integral of the input voltage. A fixed precision time base can be added to provide repeated integrations. If provision is made for resetting the counter and transferring the count to the display register, an integrating digital voltmeter has been constructed (Fig. 3). This device offers three unusual features. It has the ability to resolve a 10 μV input change when the V/F input voltage is between 10 μV and 10 V; this is equivalent to a resolution of 20 bits. When connected to a thermistor, as in Fig. 3, the device becomes a thermometer capable of resolving a temperature change of 0.001° Celsius over a 200° range. In addition to temperature change measurement, this ability to resolve small voltage changes over a million to one dynamic range is required in virtually all analytical and medical instruments, including gas chromatographs, spectrometers, spectrophotometers, and blood analyzers.

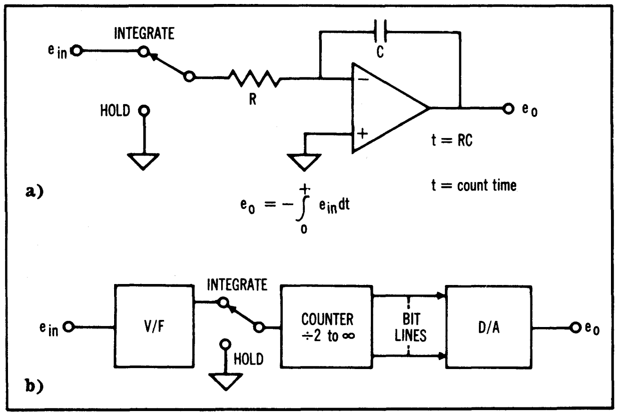


Fig. 2. Comparison of op amp and V/F used as integrators.

A second feature, complementing the first, is impulse noise rejection superior to that of the dual slope integrating A/D converter. The final feature is the ability to easily separate or isolate the V/F output from the counter input. The many forms this separation can take are illustrated in Fig. 4, where a combined A/D converter/data link is shown.

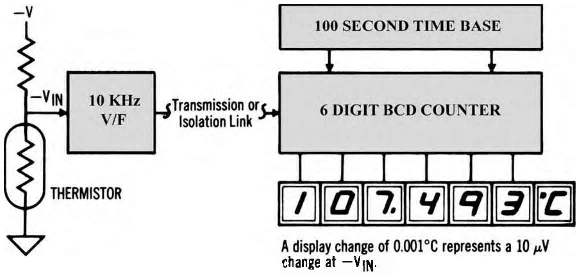
Add an F/V to monitor voltage

On the right side of Fig. 4 is an F/V as an output device that offers an alternative to the counter. Along with the F/V, a variety of precision analog data transmission links is shown: these include the use of light, RF, copper wire, magnetic tape, or water as the transmission medium. With the exception of wire and water, all of these may be used to isolate voltage. The coming of age of low loss, low cost fiber optics has provided a particularly practical option. F/V's with fiber optic data links have performed such varied functions as monitoring the filament voltage on high power radar klystrons, measuring the tempertaure inside high voltage transmission transformers, and transmitting signals through the walls of nuclear reactor containment vessels.

The laser/air path has been used to obtain data from a million volt linear accelerator. Using a 1 MHz device, this type of link can carry 100 kHz information. Dedicated telephone lines have been used to transmit 10 kHz V/F output several miles, from a remote site to a laboratory, at low cost. If the signals must pass through non-dedicated commercial telephone lines, however, they should have their bandwidth limited to 30 Hz to 2500 Hz, thus limiting output frequency to the telephone system bandwidth. In all these transmission techniques, maximum noise immunity will be obtained if the V/F output pulse is converted by a flip-flop to a symmetrical square wave, thus putting maximum energy into the line and minimizing bandwidth.

Matched V/F and F/V pairs can be configured to provide versatile data links adaptable to all types of transmission media. There are many different techniques for transmitting more than one piece of analog data over these V/F/V links. These techniques basically break down into frequency division multiplexing (FDM) and time division multiplexing (TDM). When using V/F's in TDM, either analog or digital multiplexers may be used.

The analog multiplexer lends itself to the transmission of multiple channels of high accuracy, low frequency data or, conversely, low accuracy, high frequency data, depending on the sampling rate. It also offers the unique capability of transmitting high accuracy, high frequency signals whose characteristics are changing slowly. For example, operating at a one sample per second rate into a 1 MHz V/F, one channel might carry a sinusoidal waveform that changes from 20 kHz to 30 kHz, and from ±2 V to ±3 V over a five minute period. The remaining channels could carry similar signals or slowly varying dc levels. When time is available for manual evaluation of the data, the use of an oscillograph recorder provides a minimum cost system.



A display change of 0.001°C represents a 10 μV change at $-V_{IN}$.

Fig. 3. V/F as high resolution DVM, A/D or thermometer.

Channel (word) separation is provided by a 50% duty cycle data waveform. Frame sync is provided by an 11 V (1.1 MHz) signal (higher than any data voltage). A +7 V offset at the current input of the V/F (frequency output is 700 kHz when input V is zero) makes transmission of the 30 kHz sine wave possible.

Applications as varied as process plants and aircraft test instrumentation require that data from many separate sensors be brought together for multiplexing and retransmission to a third location for processing and analysis. Such a system can be imple-

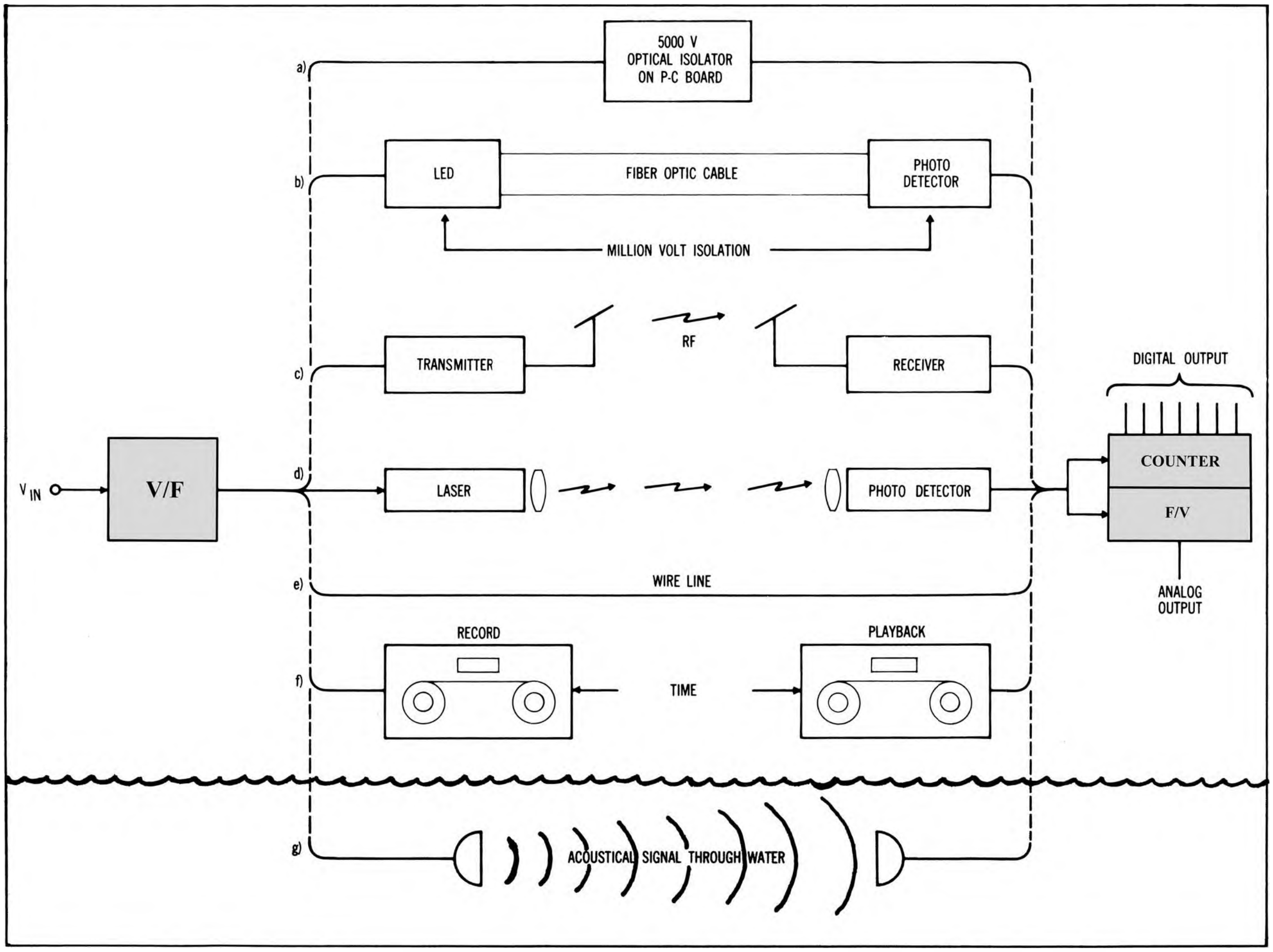


Fig. 4. Alternative modes of analog data transmission or voltage isolation, using a paired V/F and F/V.

mented by providing a 10 kHz V/F at each transducer, and putting the outputs on shielded twisted pairs to a digital multiplexer. Frame sync is provided as in the previous system, by operating one V/F with a fixed 11 V input while the others operate from 0 to +9 V.

Channel or word identification is provided by a 50% duty cycle. In addition, a 1 V offset into each V/F results in a 1 kHz pedestal on every word, regardless of signal level, making automatic demultiplexing possible. To transmit the data into a computer, the output of the data link is connected to both a counter and an F/V. The output of the F/V is fed into a pair of comparators, one of which looks for the 12 V frame sync signal, while the other looks for the 1 V word sync pedestal. The output of the two comparators controls the counter and tells the computer when data is good and which channel it is coming from. A 16 channel system, such as that shown in Fig. 6, can be built for less than $2000.

A frequency division multiplex system, similar to that used for aerospace telemetry during the 1950's and early 1960's, uses a V/F per data point on the transmit end of the link and an F/V per point on the receive end. Each V/F is offset to operate at a different zero voltage input frequency. The output is deviated ±1 kHz with a ±1 V input signal. Each pulse train output must be converted to a sine wave, via a square wave producing flip-flop and a low pass filter. The sine waves are linearly mixed in an op amp and fed to the data link. At the receive end, band-pass filters separate the channels and F/V's regenerate the data. Each channel has an information bandwidth from dc to approximately 300 Hz. This technique lends itself particularly well to the use of low cost magnetic tape recorders for the recording of data at remote sites or on moving vehicles. It has been used on automotive test tracks.

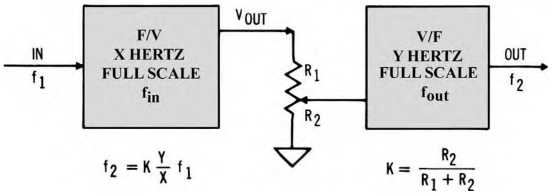


Fig. 5. F/V/F Infinite resolution frequency multiplier/divider.

In another type of application, it is often necessary to multiply a variable frequency by some fixed or variable number. This is virtually impossible to accomplish using conventional circuit techniques. It can be easily implemented, however, using F/V/F techniques (Fig. 5). Merely convert the frequency to a voltage with an F/V, scale it with a fixed or variable attenuator, and drive a V/F. The multiplication factor can be either integer or fraction. If the V/F output is set at a frequency lower than the F/V input, the circuit performs frequency division without the usual constraint of division by integers

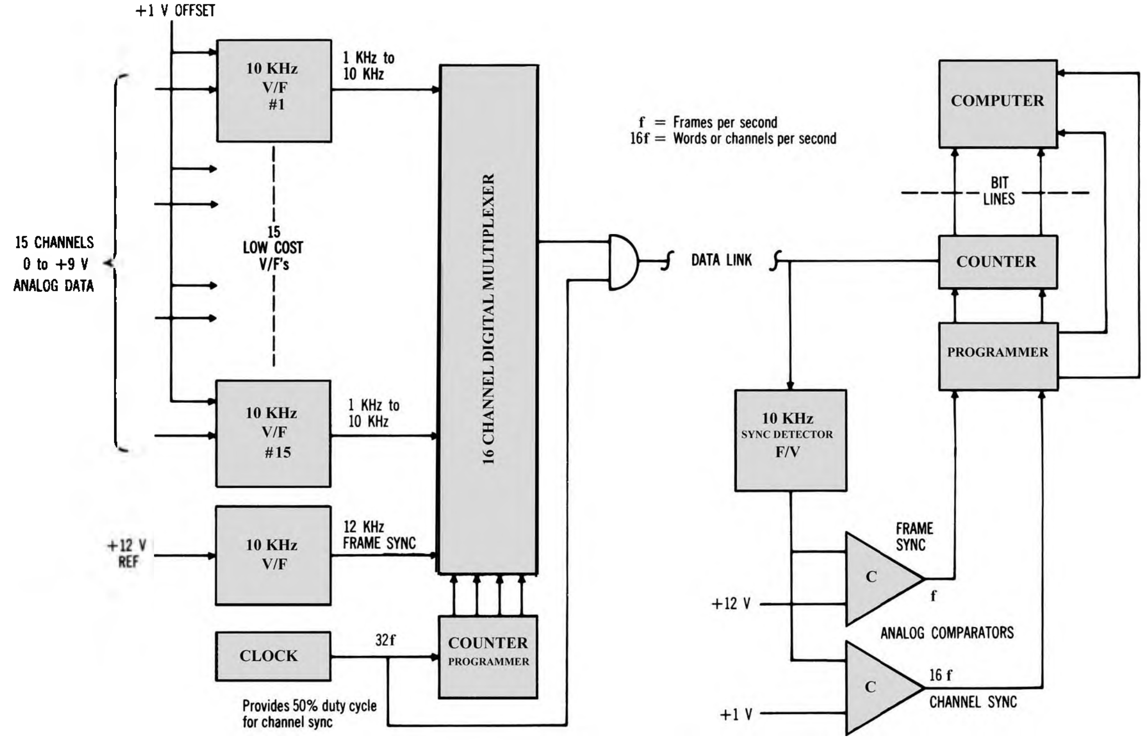


Fig. 6. V/F to digital time division multiplex analog data link using digital mux and de-mux.

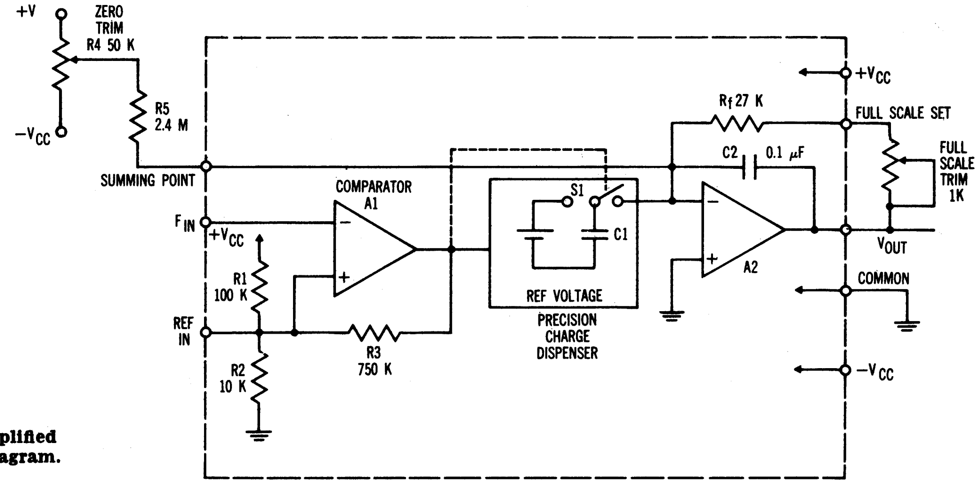
APPLICATION TIPS

The purpose of this section is to indicate the inherent flexibility of these devices and the ways in which they can be operated successfully without the addition of redundant active and passive signal conditioning components. If the designer is advised of these possibilities, he can save himself considerable time and expense.

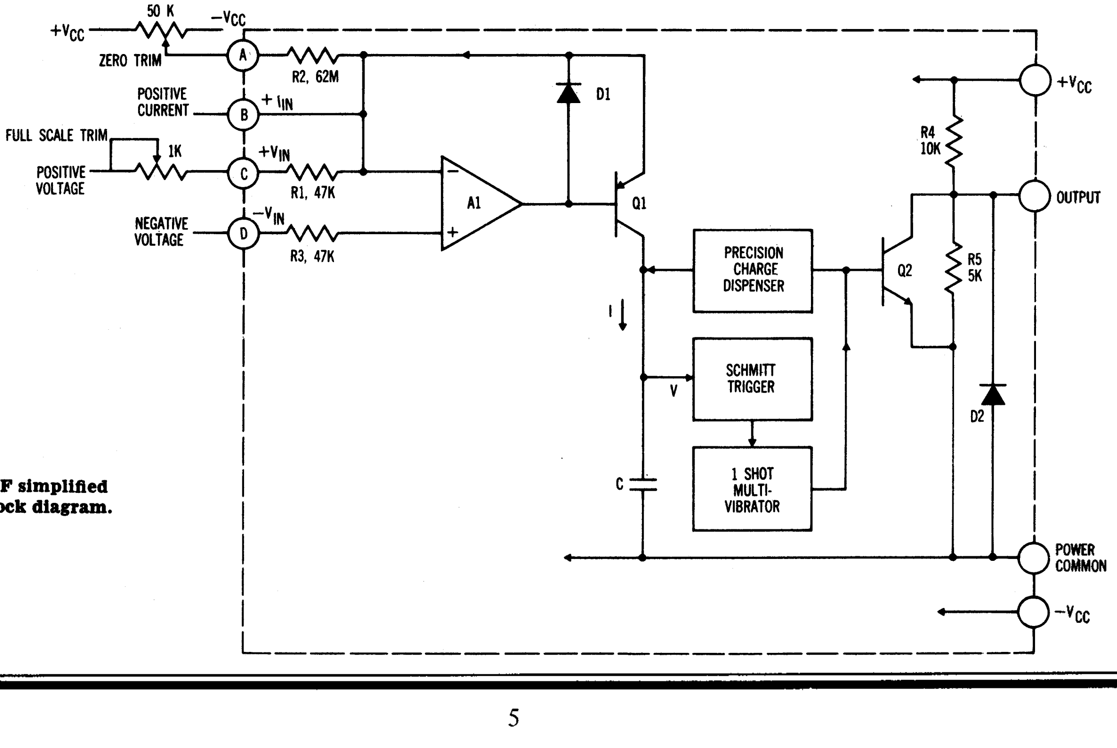
Modular F/V's and V/F's can be dropped into a circuit without adding any external components, if 0.5% full scale accuracy and 5 to 20 mV of offset is acceptable. Such is usually the case in low cost systems or ones in which there are system trims. The lack of trim has no effect on relative accuracy, which can approach 1 part in 100,000. If trimming is desired, only a pair of low cost trimming potentiometers is needed.

While additional components are not absolutely required, the input and output circuits of both types of device are designed to provide a broad range of signal conditioning with the addition of a few passive components. To take full advantage of this capability, the user should understand how the devices work. Figure A is a block diagram of a typical F/V with zero and full scale trim pots connected. Essentially, this circuit operates as a pulse averaging discriminator. As such, it converts any voltage waveform at the F_{IN} pins that exceeds the level at the REF_{IN} pin to a constant width, constant height, train of pulses. It then provides an output voltage that represents the average of the energy in the pulses. The higher the frequency, the more pulses in a given period of time, and the greater the average voltage.

The F/V input circuit is designed for optimum performance (maximum noise immunity) with a TTL input pulse. With the addition of several passive components, however, it can be conditioned to perform reliably



A. F/V simplified block diagram.



B. V/F simplified block diagram.

with input signals between 20 mV and several hundred volts, including small ac voltages imposed on large dc voltages.

The output circuit of the F/V is more versatile than the input circuit. For example, the full scale frequency for a 10 kHz F/V can be set at any frequency between 100 Hz and 20 kHz, by using an external feedback resistor between the summing point pin and the output pin. This capability has been used for range switching, which provides +10 volts for any desired frequency between 100 Hz and 20 kHz. If a 100 kHz device is used, full scale can be set anywhere between 1 kHz and 200 kHz.

For many rpm and flow applications, the input frequency will vary only over a narrow range, say 5000 Hz to 10,000 Hz. When this is the case, the user may want the F/V output to vary between 0 and +5 V, rather than the expected +5 V to +10 V. Since the output of the F/V is an op amp with summing point available, it is an easy matter to subtract 5 V from the output by providing an offset voltage to the summing point through a resistor. Changing the feedback (full scale setting) resistor can provide 0 to +10 V for 5000 to 10,000 Hz input. Additional manipulation of the feedback resistor and offset voltage can provide ±10 V output for a narrow range of input frequency.

As with the F/V, the modular V/F can be used as received from the vendor without the addition of any external components. Shown in Figure B is the block diagram of such a typical V/F. for normal operation, pin D, the $-V_{IN}$ pin (sometimes called the REF_{IN} pin), is connected to common and the zero to +10 V signal is connected to pin C, the $+V_{IN}$ pin. Zero trimming is implemented, as shown in Fig. B, with a potentiometer to pin A, and full scale trim with a potentiometer in series with the input signal.

Some V/F's have a current input pin (B) that makes the measurement of current possible. But of more importance, it makes scale changing and offsetting possible. A given V/F can provide its full scale signal output (for 0 to +1 V into the current input) in series with the appropriate resistor. This information is given on data sheets and varies from one model to another. Offsetting is accomplished by applying a fixed signal to the voltage or current input, providing a particular frequency output for no signal input. It makes a variety of signal conditioning possible, but it is of utmost importance in increasing V/F response time.

The response time of a V/F for a step input is some small fixed time (by definition of frequency $t = 1/f$) plus the period between two pulses of the new frequency. Thus, a change from a low frequency to a high frequency is very fast, but a change from a high frequency to a low frequency is very slow. For a 10,000:1 input voltage change, the response time is 10,000 times faster for an increase in voltage than for a decrease in voltage.

If a 1 V offset is provided, the difference in response time will be only 10:1. A 9 V offset will reduce response time change to only 10%. This lowered response time does not come free, however, as the dynamic range of the V/F is decreased by the same factor as the response time is increased.

On some V/F's, the $-V_{IN}$ (D) can be used for a 0 to $-V_{IN}$ or 0 to −10 V input signal. When available, this input point has a high input impedance and makes it possible to operate with differential input signals.

The output of a V/F is a fixed width TTL (0 and +5 V) pulse. However, with the addition of only one resistor between the output and $+V_{CC}$, the pulse height can be increased for operation with HNIL or CMOS logic.

only, as demanded by digital frequency dividers. Substitute an analog function multiplier/divider, a log amp, or multiplying D/A converter for the resistive divider, and the range of possible applications becomes much wider.

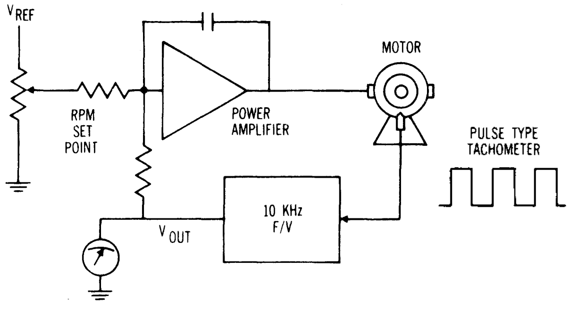
Using an F/V alone

In many respects, applications for a F/V as a stand-alone device are more natural and have been around much longer than those where voltage to frequency conversion is required. Periodic events abound in nature and information concerning their periodicity is constantly needed. The use of an F/V operating alone for rpm and flow measurement and control is illustrated in Fig. 7a: the F/V converts the signal from a pulse train output rpm transducer (tachometer) to a voltage that either appears on a meter or strip chart, or controls the speed of a shaft. Variable reluctance, optical, magnetic reed switch, and cam operated switch rpm transducers all produce a frequency as an output signal to which the F/V can adapt. The monitoring or control of shaft speed is particularly important in industries where a continuous run of material must pass over or around different size rollers, operating at different rpm's. Such applications occur in paper mills, textile plants, printing presses and magnetic tape handling. A plastic fiber plant, for example, may have several thousand of these rotating shafts.

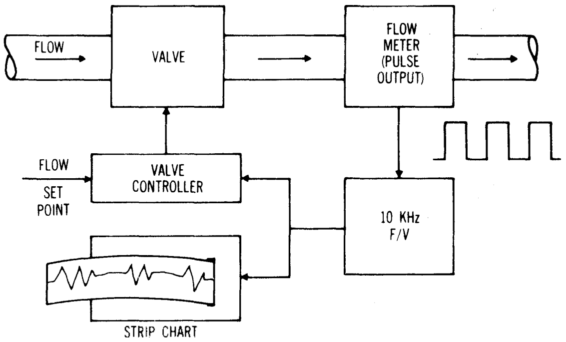
A vital parameter in any type of process plant, ranging from water treatment to oil refining to sewage disposal, is the measurement and control of fluid flow (liquid or gas), as illustrated in Fig. 7b. Turbine, vortex shedding, doppler, and fluidic flow transducers all produce an output pulse train whose repetition rate is a direct function of flow rate.

The turbine flow meter is simply a "wind mill" in the flow path. The rpm of its shaft is a direct function of volumetric flow rate and therefore easily adapted to pulse output rpm transducers. Major disadvantages of this type of meter are the wear of moving parts and the inability to handle lumpy materials such as wood pulp in a paper mill. The vortex shedding flow meter is ideal for this latter type of application, since it consists of nothing but a narrow, rigid barrier in the flow stream. As the fluid passes the barrier, vortices or eddies are produced at a rate that is a function of flow. These are detected by acoustic or thermal techniques that produce a pulse train output. In addition to rate of flow in pipe, this technique has been used to measure ocean currents and the relative speed of sailing vessels through water.

The weak point of the vortex shedding flow meter is the obstruction of the flow path it creates. This type of meter is particularly difficult to implement in very large pipes, and impossible for wide aqueducts or streams. The doppler flow meter is ideal for such applications. A constant sinusoidal



a) F/V as motor speed control.



b) F/V as flow meter/controller.

Fig. 7. F/V "stand-alone" applications.

acoustic signal is directed across the flow path at about a 45° angle. The signal is picked up on the opposite side of the flow path. If the 45° angle is upstream, the received frequency will be higher, and if downstream, lower, due to doppler shift of the frequency. The frequency difference between the transmitted and received signals is, in either case a direct function of flow rate.

A rather interesting F/V application is the monitoring of a band of frequencies. The F/V can provide an alarm if an input frequency goes outside the band or if it comes into the band. The former configuration has been used to monitor the pulse rate of intensive care patients. If their pulse rate becomes too low or too high, an alarm is sounded. The latter configuration can be used in a manner similar to a scanner, using one or more latching window comparators to look for F/V output voltages that represent particular frequency bands. The inherent noise rejection of the F/V insures that the comparator will operate from a signal rather than noise. Applications range from a simple CB monitor to sophisticated radar or sonar countermeasures.

When it is necessary to measure the difference between two frequencies, as in doppler frequency measurement, a pair of F/V's alone will do the job nicely. Each F/V converts one of the frequencies to a voltage. The output of one of the F/V's is connected through a scaling resistor to the summing point of the second F/V. The output amplifier of the second F/V will subtract the two voltages, providing an output voltage that is a function of the frequency difference. This same technique can measure differences in shaft rpm or flow rate.

We have discussed a wide range of applications in the section above. To choose the proper converter for a particular application, one must know and understand the most important specification parameters. The two most critical specs to consider are nonlinearity and full scale temperature coefficient. These two parameters determine the relative accuracy of these devices. Absolute accuracy is strictly a function of how close to a National Bureau of Standards voltage and frequency reference the input and output are trimmed or measured to at full scale, and how close to zero the zero input/zero output is trimmed. V/F's are usually trimmed to a certain low frequency at a few millivolts input signal.

The input/output X/Y plot of an ideal V/F or F/V is a straight line. Nonlinearity is the deviation from that straight line, expressed as a percentage of full scale input or output. Thus a V/F/V with 0.01% nonlinearity has a relative accuracy of one part in 10,000. However, it can still resolve voltages to one part in a million. That is, 10 μV changes can be measured over a million to one range (10 μV to 10 V) with an accuracy within 0.01%. This nonlinearity is inherent and does not change when the device is trimmed for zero and full scale accuracy.

Full scale temperature coefficient is the factor that defines the change in relative accuracy with temperature, expressed in ppm per degree Celsius. It will vary between 100 to 200 ppm (for a low cost device) to 5 ppm on the best units available. The choice of a device is strictly a function of required accuracy and ambient temperature.

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