The Multiplier-Type Ring Modulator

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Introduction-Robert A. Moog

Vibrations of the air in the frequency range of 20-20,000 cycles per second are perceived as sound. The unit of frequency is the HERTZ (Hz): 1 Hz = 1cycle per second. The WAVELENGTH of an acoustical vibration is the distance in space spanned by one cycle, and is inversely proportional to the frequency. The WAVEFORM is a graph of the instantaneous amplitude of the vibration versus either space or time. The SINE waveform is a special waveform which consists of only one frequency. All other waveforms may be synthesized from sine waves of various frequencies, or from noise bands which can be mathematically described as continuous frequency distributions of sine waves. The SPECTRUM of a sound event is a listing of the frequencies of both the sine waves and the continuous noise bands that comprise it. The entries on this list are known as COMPONENTS. A BAND is a segment of a spectrum and is defined by its CENTER FREQUENCY, the frequency which lies at the center of the band, and its BANDWIDTH, the frequency range spanned by the band. UNIT BANDWIDTH is a band 1 Hz wide.

A VOLTAGE is a quantity of electrical force that is directly analogous to air pressure. Sound adds rapid but small variations to the average air pressure; similar variations can occur about an average voltage. The average value (over a certain time) of a voltage is known as the DIRECT, DC, or BIAS component of that voltage. The variation which that voltage undergoes about its average value is known as the SIGNAL or AC component of that voltage. When signal voltages are referred to, STANDARD VOLTAGE LEVEL is the average variation of a voltage for which most audio equipment is designed. This level is roughly 1 volt RMS. RMS stands for root mean square, the name of a mathematical procedure for determining the average of a varying voltage. A VOLTAGE-CONTROLLED device is a device whose operating characteristics may be varied by changing the magnitude of an applied voltage. Thus, a voltage-controlled oscillator is an oscillator whose output frequency depends upon the magnitude of an applied control voltage.

A MODULATOR is a device which varies the characteristics of the signal according to the nature of an applied carrier, or control voltage. Note that this use of the word is different than the usual musical use. A RING MODULATOR is such a device with two inputs and one output. In a MUL-TIPLIER-TYPE RING MODULATOR, the output voltage is directly proportional to the voltages at the inputs. The instantaneous amplitude of the output is therefore proportional to the product of the instantaneous amplitudes of

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the two inputs. In order to produce this type of proportionality, it is necessary to use NON-LINEAR circuit elements, which are elements that change their characteristics according to the magnitude of the voltage applied to them. The PROGRAM INPUT for a ring modulator is usually audio material which is to be processed, while the CARRIER INPUT is a generated signal or a signal otherwise more precisely controlled. Basically, however, the two inputs for the ring modulator are equivalent. The output of a ring modulator will generally contain additional frequency components which are not present in either input. These are known as MODULATION PRODUCTS or SIDEBANDS. UNWANTED MODULATION PRODUCTS are those which would not be present if the accuracy of multiplication were complete.

A GATE is an electrical switching circuit which is opened or closed by the application of a bias voltage. The QUIESCENT condition of a circuit is that which exists in the absence of an applied input signal. HETERODYNING is the production of a particular sideband through the modulation of two signals.



Fig. 1. (Top) Basic ring bridge circuit of a ring modulator. (Bottom) Lattice network presentation of basic ring modulator circuit with potentiometers to improve balance.

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Basically two types of ring modulators are known: switching-type ring modulators and multiplier-type ring modulators. The switching-type is widely used in industrial control applications and has been discussed in some detail in the literature.¹ Because of its inherent distortions, this device is not suited for musical systems, for which the multiplier-type offers definite advantages.

All ring modulators comprise as their functional non-linear elements four diodes arranged in a ring configuration, or when redrawn, in a lattice configuration (Fig. 1). The carrier signal is introduced across two points of the bridge through the input transformer while the program input is introduced at two other points directly, one of which is grounded. The output signal is taken off two other points that are symmetrically related to the carrier input terminals. Usually the transformerless input is used for the program or control signal because of its extended frequency-handling capability from DC to very high frequencies. Its range is then limited only by the type of desired output and the limitations of the output transformer.

In industrial control applications the output waveform of the ring modulator is usually of no particular consequence, since, for instance, a servo motor does not care whether it is driven by a distorted or undistorted AC voltage. Therefore, the selection of diodes for these applications is not very critical, as long as they perform the required switching function. For this reason silicon diodes or copper oxide rectifiers are quite popular, and their choice will be tailored to the threshold level required.

A typical waveform resulting from the processing of two frequencies through a switching-type ring modulator is shown in Fig. 2. Here λ_1 is the wavelength of the lower frequency f_1 and λ_2 is the wavelength of the higher frequency f_2 . The resulting sidebands are comprised of the frequencies f_2-f_1 , f_2+f_1 , $3f_2-f_1$, $3f_2+f_1$, $5f_2-f_1$, $5f_2+f_1$, and the further odd harmonics of f_2 , minus and plus f_1 . For musical purposes such a waveform is of very limited usefulness, since it sounds scratchy and unpleasant. Therefore, some people who have used this type of ring modulator in musical systems have recommended and are employing lowpass filters at the output in order to make the sound somewhat more pleasant.²

Problems of this type are not experienced with the multiplier-type ring modulator. This modulator uses specially selected diodes of a type which, at normal signal levels, operates in the "square law" region, and which therefore produces extremely accurate multiplication.

The output waveform resulting from the processing of two sine waves through a multiplier-type ring modulator is shown in Fig. 2.³ The output frequencies

¹ Basil T. Barber, "Servo Modulators, Part One," Control Engineering, Aug. 1957, 65; Barber, "S.M., Part Two," C. E., Oct. 1957, 96; Barber and L. S. Klivans, "S.M., Part Three," C.E., Nov. 1957, 122; Klivans, "S.M., Part Four," C.E., Dec. 1957, 90 (with comprehensive tables and 84 references).

² L. Heck and F. Buerck, "Klangumformungen in der Rundfunkstudiotechnik, insbesondere durch Anwendung der Frequenzumsetzung," Elektronische Rundschau, Jan. 1956.

³ See also Harald Bode, "Sound Synthesizer Creates New Musical Effects," *Electronics*, Dec. 1, 1961.



Fig. 2. (Top) Typical output waveform of switching-type ring modulator. (Bottom) Typical output waveform of multiplier-type ring modulator.

are f_2-f_1 and f_2+f_1 when the input frequencies are f_1 and f_2 . Thus the output waveform may also be regarded as the sum of two new frequencies f_2-f_1 and f_2+f_1 beating together. A well designed and carefully built multiplier-type ring modulator results in an extremely small amount of unwanted modulation products.

Before discussing some applications of this device, it may be of interest to take a closer look at the electrical functions of a complete instrument that has been developed to be compatible with modern electronic music studio installations.

Basically a multiplier-type ring modulator as shown in Fig. 1 could be used as a passive, self-contained circuit or system module. However, since its output voltages are appreciably below the standard voltage levels of an electronic music system when the diodes are operating in their optimum range, an output amplifier would certainly be required. Furthermore, when the modulator is operating in the low portion of the available dynamic range, especially in pauses between events, a low level carrier feed-through may become audible. In order to prevent the carrier from being heard at all in the quiescent state, a gate is provided in the path between the carrier input terminals of the overall device and the corresponding input terminals of the ring bridge, as indicated in the block diagram of Fig. 3. This gate is activated to pass the carrier signal only when the program level exceeds a predetermined threshold voltage, which can be selected by setting the gain control

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Fig. 3. Simplified block diagram of multiplier-type ring modulator with carrier input gate, threshold control preamplifier, rectifier, ripple filter, Schmitt-trigger, and output amplifier.



Fig. 4. Single channel Bode multiplier-type ring modulator built by the R. A. Moog Co.

of a preamplifier in the program signal path. This is followed by a rectifier, a ripple filter, and a Schmitt-trigger circuit (a circuit which has two stable states depending upon the voltage supplied to its input, and which directly supplies the bias voltages for opening or closing the gate in the carrier voltage path).

A photograph of a single channel ring modulator of this type is shown in Fig. 4. The controls on the front panel are the threshold control for the

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adjustment of the minimum program level for opening the carrier gate, the squelch on-off switch for activating or de-activating the carrier suppression circuit, the ring modulator balancing adjustments (which normally remain untouched), and the pilot light and switch of the built-in power supply unit.

Among all signal processors the multiplier-type ring modulator takes a unique position, since it is capable of converting existing sounds into new (and pleasing) sounds with entirely different overtone spectra that do not resemble the original acoustical phenomena. A few examples will illustrate some typical applications of this sound processing tool and the results obtained.

Ex. 1: A 1000 Hz sine wave is applied to the program input and a 900 Hz sine wave to the carrier input. The output contains two frequencies, 100 Hz and 1900 Hz. If the magnitudes of the inputs are both 1.0 volt RMS, the magnitude of the total output of the described standard model will also be 1.0 volt RMS.

Ex. 2: The program input receives a 1000 Hz square wave and the carrier input receives a 900 Hz sine wave. A square wave contains an infinite series of discrete frequencies, all of which are odd multiples of the fundamental. The output therefore consists of two infinite series, one of which is the sum of the 1000 Hz square wave components and the 900 Hz sine wave, and the other of which is the difference.

Ex. 3: Program input is filtered white noise with a bandwidth of 0 to 100 Hz and carrier input is a 900 Hz sine wave. This noise spectrum contains equal energy per unit bandwidth from 0 to 100 Hz. The output of the modulator is a spectrum centered at 900 Hz, but containing an equal distribution of frequencies from 800 Hz to 1000 Hz. Note that the bandwidth of the output is twice the bandwidth of the program input. When sweeping the carrier frequency of this setup over the center portion of the audio range, the sound of a howling wind may be simulated. A similar but more complex effect will be obtained when the program input is white noise with a bandwidth of, for instance, 400 to 500 Hz. In this case a carrier of 900 Hz would generate two white noise bands, one from 400 to 500 Hz and one from 1300 to 1400 Hz. Naturally, "tuned" white noise may cover a lesser bandwidth and thereby result in more selective effects.

Ex. 4: The program material is supplied by a voltage-controlled oscillator which operates in the sine wave mode and is controlled by a keyboard. The carrier signal is supplied by a second voltage-controlled oscillator in the sine wave mode, controlled by the same keyboard and tuned relative to the first oscillator by a frequency ratio of 3:4, or any rational number. In case these integers do not have a common denominator, the resulting fundamental frequency and its overtones at the output will be of a very attractive quality due to slow timbre changes, which may result from an intentional detuning of the two input frequencies relative to the theoretical multiples of the fundamental frequency.

Ex. 5: Very interesting effects with the speaking or singing voice may also be obtained by feeding the fundamental voice frequency (obtained through

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a lowpass filter) into one input and the entire voice spectrum into the other. In this case the application of an efficient automatic gain control to the fundamental frequency (with the aid of a voltage-controlled amplifier) would be required, in order to retain the original dynamic properties of the input sounds.

Ex. 6: When feeding the program material (preferably music and very effectively, organ music) into the carrier input and a low frequency sine wave in the vibrato range (for instance, 6 Hz) into the program input, a special modulation effect will be created, and will be remarkably enhanced if the same program material is reproduced directly (without modulation) through a second amplifier and speaker system. The result will be a kind of spatial amplitude-phase modulation.

Ex. 7: Percussive sounds in the category of Trinidad drums are obtained when the sounds of bass drums, tom toms, temple blocks, wood blocks, claves, and maracas are fed into the program input and an audio frequency in the lower to middle audio range into the carrier input.

Ex. 8: When the program material is heterodyned into a higher frequency range, say 10,000 to 20,000 Hz (with the aid of an oscillator of appropriate frequency feeding into the carrier input), and the new spectrum is passed through a narrow band filter in said frequency range, and the filtered frequencies heterodyned back into the audio range by applying the same oscillator frequency to the carrier input of a second ring modulator, the effect of a tunable filter is obtained when the oscillator frequency is changed.

From these examples, which merely scratch the surface of the possible applications of the multiplier-type ring modulator, it will become evident that this instrument is a very powerful tool for the electronic music composer, and that the variety of results obtainable is as limitless as the imagination of the user.