CHAPTER - I

INTRODUCTION AND SURVEY

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1.1 INTRODUCTION

Any electronic system can be fundamentally divided into a number of blocks. A filter circuit is such a block which is almost invariably in-corporated in the system. A filter can be considered as a frequency selective network whose main purpose is to separate an unwanted signal from a mixture of wanted and unwanted signals. In this way, it shapes the frequency response of the electrical system. Secondly, because of the rejection of the unwanted signals, the filter increases the signal to noise ratio for the system. In general, any circuit that produces a prescribed frequency response characteristic and whose most common objective is to pass the certain frequency band and to reject all other frequencies, can be considered as a filter. In such a capacity, the filters are being used, in one form or the other, for a long time.

1.2 SURVEY OF LITERATURE

In the earlier days most of the filter circuits developed used components like resistors, capacitors and inductors. These filters are commonly known as passive filters. Their most important drawback is the loss of signal. The synthesis of these filter circuits is extensively discussed in the literature and many text books$^{(1-8)}$.

With rapid developments in the field of semiconductor devices, particularly, the IC technology, the use of active devices in the circuit design became the common approach. Such circuits are called active filters. Such circuits have many advantages over their passive counterparts. The filters used nowadays are almost invariably the active filters.

The theory of filters originated with the works of Campbell and Wagner$^{(9)}$ on electric wave filters. Campbell and Zobel considered the design of filter based on "image parameters" which fundamentally depends on image or iterative impedances. Modern filter design is based on the selection of the filter transfer function to satisfy the specification and then the realization of this function by synthesis techniques.

The pioneering work done by SALLEN and KEY$^{(10)}$ and other workers on the synthesis of the second order network using the transistor as a active element, was the beginning of the new era in the field of "Active filter". Due to tremendous development in IC technology, the OP-AMPS are produced with better and better performance. They have the advantage of small size, excellent electrical characteristics and low cost. The number of active building blocks and their synthesis techniques were discussed by many authors(11,12).

The active filters employing R-C networks in conjunction with active elements such as NICs,(13-17) controlled voltage sources, Gyrators(18-21) and F.D.N.R.(22,23) were proposed by different authors. Limitations of the network synthesis using NIC were considered by a few authors. A number of articles giving extensive discussion on the theory of active filters can be found in the literature.(24-33)

Latter on SMITH and SEDRA(34) (1968) gave the concept of current conveying. ARONHINE(35), SENANI(36) and other workers(37-38) have shown that the current conveyers may be used to implement all the transfer functions with a high input impedance and independently controllable voltage gain.

Due to rapid development in computers, many software computer packages are available for the analysis of the active filters such as DIANA, DINAP, SPICE, ISCAP, SCAR, TCAP etc. KUO(39) et.al. and other workers(40,41) have used these computer programs in the analysis of switched capacitor filters.

M.A. SODERSTRAND and K.L. LEE(42) are the pioneers in the Computer Aided Design (CAD) and analysis of the active-R filters.

Initially, the parasitic capacitance associated with the active devices, particularly, operational amplifier, was considered undesirable. In order to avoid its effect, many compensation techniques were developed. However, BUDAK and PETRELA(43) (1972) suggested that the same parasitic capacitance can be utilized to design filter circuits without the use of external capacitor.

M.A. SODERSTRAND(44) (1972), RADHAKRISHNA RAO and SRINIVASAN(45-47) (1973-1976) are the pioneers in the use of operational amplifier pole. They have suggested that the pole of an operational amplifier could be used to design an active-R filters with only resistors. MITRA and AATRE(48) (1976), HO and CHIU(49) (1976), SOLIMAN and FAWZY(50) (1977) and ANANDA MOHAN(51) have realized the active filters using the operational amplifier pole while NANDI(52) (1976-78) has contributed towards the realization of the grounded capacitors using operational amplifier pole.

SCHAUMAN(53,54) (1975-76) has developed a general second order active-R filter. SODERSTRAND(55) (1976) has suggested a simplified version of second order Active-R filter circuit which realizes all the low pass, high pass and band stop responses simultaneously at three different points. BRAND and SCHAUMAN(56-59) (1975-78) have proposed the design method for the monolithic analog active-R filters which is suitable for a low pass and band pass functions at two different output terminals. VENKATESHWARAN(60) and SOWRIRAJAN(61) (1979) have described Multi-function Active-R filter. SHARMA and DULLU(62,63) (1981) have realized the band pass filter without external capacitor. KIM and RA J.B(64,65) (1977-79) have suggested an active-R circuit which realizes all filter functions. MITRA and A.K. AATRE(66) (1976) have discussed the low sensitivity and high frequency active-R filters. SOLIMAN and FAWZY(67) have suggested a universal active-R biquad circuit which is adjusted to realize a high pass characteristics. It is a the special case of SCHAUMAN'S Active-R filter. AHMED M.T., SIDDIQUI(68,69) (1978-79) and JAVED(70) M.T. (1983) have described active-R biquads to realize second order filter functions. J.C.M. BERMUDEZ(71) (1983) has reported a general second order active-R network by which two different active-R biquads can be realized as the special case.

SUN-ZHI-XIAO(73-74) (1980-83) has suggested a new active-R biquad with four output terminals realizing LP, HP, BP, notch and all pass functions. A voltage tunable active-R filter has been designed by NEWCOMB and S.T. LIEU(75)

(1984). E.A. TALKHAN, M.N. IBRAHIM and A.S. NOUH(76) have designed an integratable tunable active-R band pass filter. KAPUSTIAN, BHATTACHARYA and SWAMY(77,78) (1978-79) have discussed the frequency limitations of active-R filters. OSOWSKI S.(79) have realized voltage transfer function using active-R network where as VENKATMANI and VENKATESHWARAN(80) (1982) have discussed the active-R multifunction circuit synthesis.

SODERSTRAND(81-84) (1975-77) has suggested Active-R ladder without external capacitors and in (1978), he has suggested an active-R filter using CMOS technology.

MASARU ISHIDA, YUTEKA FUKAI and KEISUKE EBISUTANI(85) (1984) have discussed a novel Active-R synthesis of driving point impedance, based on single pole operational amplifier model, which simulates inductance, capacitance, F.D.N.R. and F.D.N.C.. ABUELMATTI M.T. and ALMASOURY(86-90) (1986) have reported a active-R versions of oscillators(91-95) and many other workers(96,97) have discussed active realization of RL impedances and resonators(98,99).

MC-GINTI(100) (1987) has described a design method for the monolithic implementation of a class of active-R filters which provides an alternative to the high speed digital filters.

SHAH and TANTARY (1987) have proposed an active-R version of a voltage controlled oscillator which utilizes the single pole characteristics of the operational amplifier. N. MOHAN and R.L. PATIL(101-104) (1989) have designed a second order low pass active-R filter which simulates the inductor and capacitors. Many other workers(105-116) have described the simulation of inductors and capacitors using operational amplifier pole.

The design process for several types of filters by interfacing with computer is suggested by HOWARD HUTCHING(117) (1990). J.V. VOSPER (1991) described synthesis of first order active-R all pass networks and their applications in the sinusoidal oscillator design. N. MOHAN and R.L. PATIL(119) (1992) have designed Ripple pass functions and their active-R realization. Nowadays, plug in card filters are available with LAPLACE(120) instruments (1992). These are the PC based filter cards. A.B. KADAM and A.M. MAHAJAN(121) (1995) have designed a second order active-R filter circuit which realizes all filter configurations.

Nowadays, a growing field of active filter is the switched capacitor (SC) active filter, is the product of fully integrated active filters compatible with MOS technology. The idea of active filter using switched capacitor and associated theory was developed as early as

1960's. In the decade of 1970's, it was found that SC filter was very promising method of implementing precision monolithic analog filters in MOS IC's.(122, 123)

W. BRUGGER(124) et. al (1981) have described the procedure for the design of cascaded switched capacitor filter. EDGAR SANCHEZ-SINENCIO(125) et. al (1984) have discussed the effects of proper switch phasing in SC filters to yield low gain-band width (GB) product dependence. K. NAGARAJ(126) (1989) has reported a novel switched capacitor technique for realizing a very large time constant. DAVID(127) et. al (1991) have suggested the design of high frequency switched-capacitor filters implemented using GaAs MOSFET technology.

1.3 BASIC FILTER CIRCUITS AND CLASSIFICATION

The filter specifications are given in terms of cut-off frequencies or passband and stopband. The passband is the frequency band of wanted signals and stopband is frequency band of unwanted signals. An ideal filter should pass the wanted signals with no attenuation and provide infinite attenuation for the unwanted signals.

Filters may be classified in a number of ways like

(a) Analog or digital

(b) Passive or active

(c) Audio (AF) or radio frequency (RF)

Analog filters are designed to process 'Analog' signals, whereas, digital filters process digital signals or discrete signals.

Depending upon type of elements used in their construction, filters may be classified as "passive" or "active". Filters are again classified according to the functions they perform, such as low pass, highpass, Band pass, Band elimination, amplitude equalizers and delay equalizers.

The four basic filter circuits and their ideal characteristics are shown in Fig. (1.1).

An ideal low pass characteristic is drawn in fig 1.1(a) with passband extending from $W = o$ to $W = W_c$ and stopband from W_c to infinity. W_c is called as the angular or radian cut-off frequency or simply cut-off frequency.

The passive single pole low pass filter with its frequency response characteristics is sketched in fig. (1.2). The passive low pass filter allows input signals from dc ($jw = 0$) to some cut-off frequency where the output amplitude is reduced to 0.707 (-3dB) of the dc amplitude.

Then transfer function can be written as,

$$\frac{V_o}{V_{IN}} = \frac{1/RC}{S + 1/RC} \quad \ldots. \quad (1.1)$$

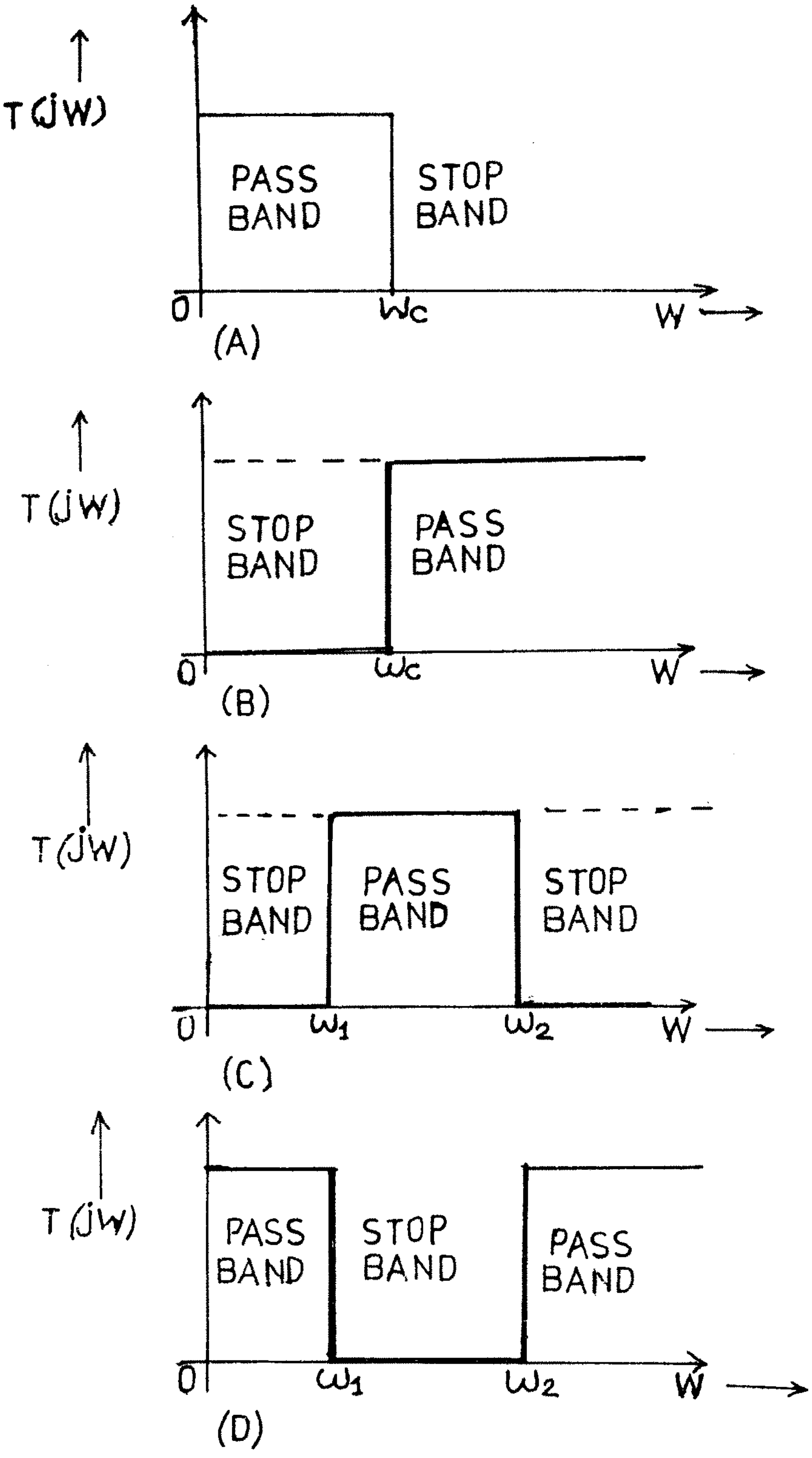

FIG. (1.1): IDEAL CHARACTRISTICS OF
(A) LOW PASS. (B) HIGH PASS.
(C) BAND PASS. (D) BAND STOP FILTER.

A zero transmission exists at infinity as the capacitive resistance is zero at t = ∞/. It is found that the transfer function has a lower power of 'S' in the numerator than in the denominator and it tends to zero as 'S' becomes infinity.

The second order gain transfer function that realizes low pass characteristics is

$$\frac{V_O}{V_{IN}} = \frac{b}{S^2 + as + b} = \frac{W_p^2}{S^2 + (W_p/Q_p)S + W_p^2} \quad \ldots\ldots \quad (1.2)$$

An ideal high pass characteristic is shown in Fig 1.1(b). with passband extending from W_c to infinity and stop band from 0 to W_c. The passive single pole filter and its response characteristic is shown in Fig (1.3). It passes input signals with unity gain from infinity (Very high) to cut-off frequency where the output amplitude gets reduced to 0.707 (-3dB) of the high frequency amplitude. The transfer function is,

$$\frac{V_O}{V_{IN}} = \frac{S^2}{S + 1/RC} \quad \ldots\ldots \quad (1.3)$$

Secondly, the gain transfer function for high pass characteristic is,

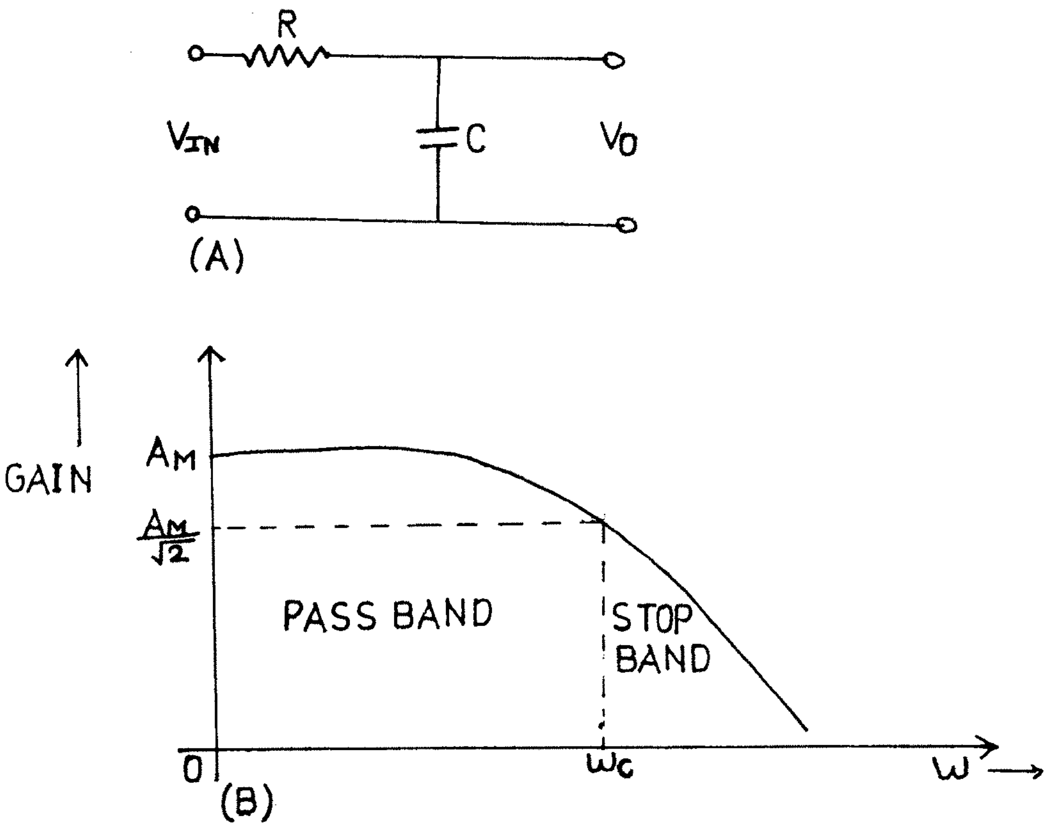

FIG.(1·2): PASSIVE SINGLE POLE LOW PASS FILTER.
(A) CIRCUIT DIAGRAM (B) FREQUENCY RESPONSE.

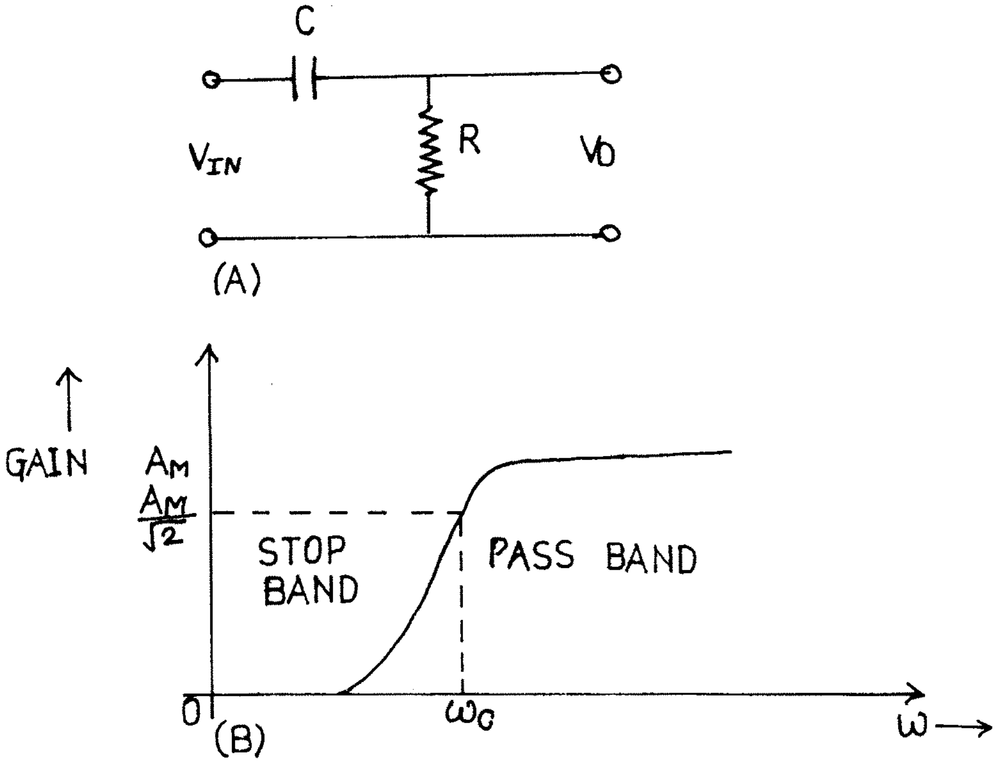

FIG.(1·3): PASSIVE SINGLE POLE HIGH PASS FILTER.
(A) CIRCUIT DIAGRAM (B) FREQUENCY RESPONSE.

$$\frac{V_O}{V_{IN}} = \frac{S^2}{S^2 + aS + b} = \frac{S^2}{S^2 + (W_p/Q_p)S + W_p^2} \quad \ldots\ldots \quad (1.4)$$

This gain transfer function has a pair of complex poles and a double zero at the origin.

The ideal band pass frequency response characteristics is shown in fig 1.1(c) in which radian frequencies extending from W_1 to W_2 are passed while the frequency bands from 0 to W_1 and W_2 to infinity are stopped. Band pass filters are classified in two categories as narrow band or wide band. The single pole band pass filter and its response characteristic is sketched in Fig. (1.4). Its gain transfer function is given by

$$\frac{V_O}{V_{IN}} = \frac{aS}{S^2 + aS + b} = \frac{(W_p/Q_p)S}{S^2 + (W_p/Q_p)S + W_p^2} \quad \ldots\ldots \quad (1.5)$$

This function has a pair of complex poles in the left half of 'S' plane and zero at the origin. At low frequencies the loss increases as S, that is at 20 dB/decade. The frequency response rises from zero at the origin to peak near the pole frequency, then a zero of transmission ('S' is a numerator and S^2 in denominator) at infinity draws the response back down to zero as the

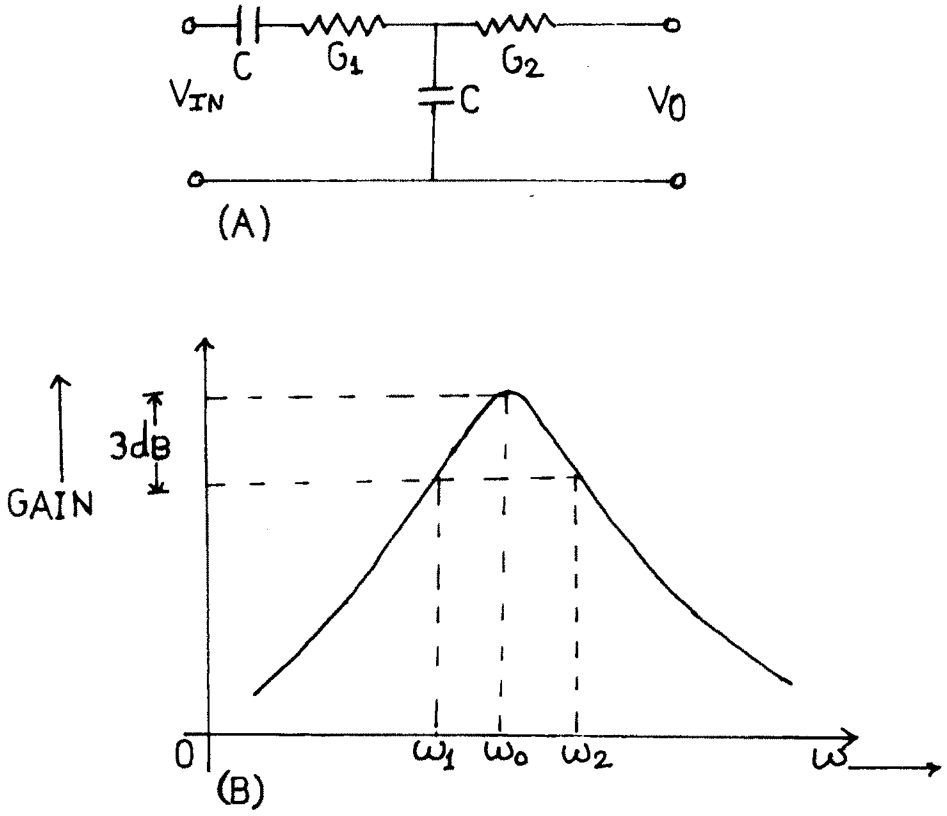

FIG. (1·4): PASSIVE BAND PASS FILTER.
(A) CIRCUIT DIAGRAM (B) FREQUENCY RESPONSE.

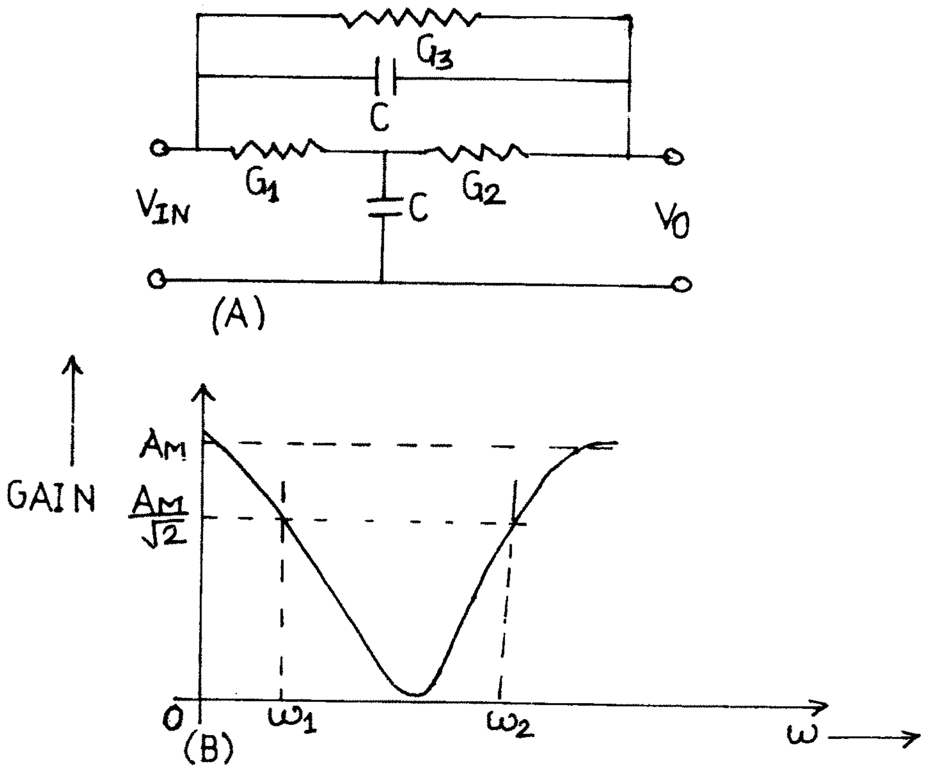

FIG.(1·5): PASSIVE BAND STOP FILTER.
(A) CIRCUIT DIAGRAM (B) FREQUENCY RESPONSE.

frequency becomes high. The bandwidth is the difference between the lower and upper (-3dB) 0.770 points.

Finally, the ideal band reject characteristic is shown in fig 1.1(d). Where the radian frequencies W_1 to W_2 are stopped and frequency bands from 0 to W_1 and W_2 to infinity are passed.

The single pole band reject filter and its response characteristic is sketched in fig. (1.5). The second order transfer function for band stop characteristic is,

$$\frac{V_o}{V_{IN}} = \frac{S^2 + d}{S^2 + as + b} = \frac{S^2 + W_z^2}{S^2 + (W_p/Q_p)S + W_p^2} \quad \ldots \qquad (1.6)$$

This function has complex poles in the left half of 'S' plane and complex zero on the jw axis. Also the pole frequency is equal to the zero frequency. The losses at low frequencies and at high frequencies approach unity while the loss at zero frequency is infinity.

1.4 BASIC ACTIVE FILTERS

Due to vast developments in IC technology, the operational amplifiers are being fabricated with better quality and excellent performance. This led to the extensive use of operational amplifier, in the design of active filter. Further, with high volume of the production, the active devices have become cheaper than passive components nowadays. The most of the active filter structures are realized by embedding an operational amplifier in RC network in feedback configuration as shown in fig. (1.6).

In the RC network the active element is a operational amplifier connected as a voltage controlled Voltage source (VCVS) described by L.P. HUELSMAN(133) (1971). The VCVS will be assumed to have ideal characteristics i:e. infinite input impedance, zero output impedance, zero reverse transmission and ideal phase shift (either zero or 180°). The voltage gain required will be generally low and will be determined by the synthesis method used in the various cases.

1.4.1 ADVANTAGES OF ACTIVE FILTER

(1) SIZE CONSIDERATION

Active filters are generally smaller in size than their LC counterparts due to elimination of inductors. Further reduction in size is possible with micro-electronic technology. The RC components and operational amplifiers are fabricated in a single IC Chip with the use of hybrid technology. Again the active filters can be.reduced to very small size by using microscopic technology that the weight is further reduced.

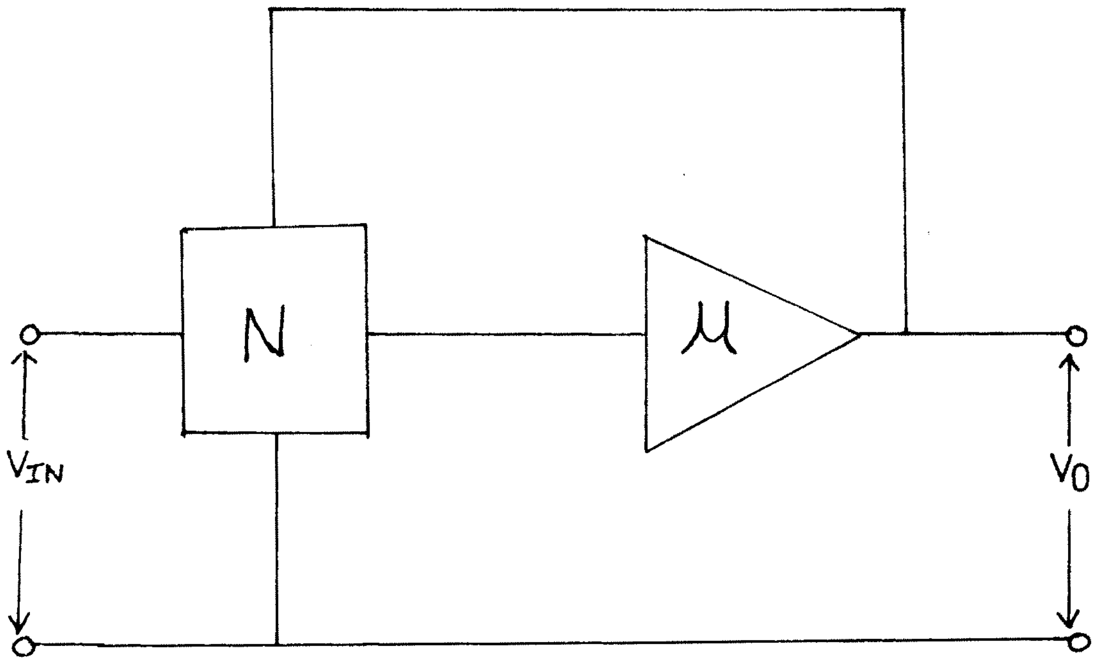

FIG.(1.6): GENERAL CONFIGURATION OF ACTIVE FILTER.

(2) CIRCUIT RELIABILITY

It is because of the smaller size, the active filters have reduced parasitic effect which increases the reliability and circuit performance(128).

(3) ECONOMICS AND EASE OF MANUFACTURE

Typically, active filters are more economical than passive filters because of the availability of cheaper operational amplifiers and the absence of costly inductors. It is not possible to integrate an inductor. Passive filters are designed using resistors, capacitors and inductors. Such circuits are more expensive. On the other hand active filters have the distinct advantage that they can be easily assembled and fabricated in microminiture form using the integrated circuit technology. So in large quantities, the cost of the integrated circuit can be much lower than its equivalent passive filter.

(4) GAIN AND FREQUENCY ADJUSTMENT FLEXIBILITY

Since operational amplifier is capable of providing a gain, the input signal is not attenuated as it is in a passive filter. In addition the active filter is easier to tune or adjust.

(5) **NO LOADING PROBLEM**

It is because of the high input impedance and low output impedance, the active filter is free from the loading problem.

(6) The design process is simpler than that of passive filters due to reduction in components.

(7) Active filters can realize wider class of functions.

(8) Active realization can provide voltage gain whereas passive filters exhibit a significant voltage loss.

1.4.2 DISADVANTAGES

The active RC realizations have some drawbacks such as, finite bandwidth of the active devices which places the limit on the high frequency performance. Hence the most of the active-RC filters are used upto approximately 30 kHz. This is useful in voice and data communication.

Amplifiers are available with extended bandwidth with increased cost which will operate upto the frequency 500 KHz. The active-RC filters at low frequencies can become rather bulky because of capacitor sizes. The outputs of the filters built with operational amplifiers have a dc voltage offset which drifts with ambient temperature changes. The maximum pole frequency limit decreases with the pole 'Q' which defines the sharpness of the filter. On the other hand, passive filters do not have such limitations and they are capable of operating upto 500 MHz. This limitations occurs in active-RC realization because of the parasitic capacitance associated with the passive elements. The sensitivity is most important criteria for comparison of various realizations due to variation in circuit elements. It is found that the sensitivity of passive filter is much less than that of active filters. Finally, the active filters require power supplies while passive filters do not. Due to economic and better performance, the active-RC filters are used in voice and data communication systems. The passive filters are used as the basis for active simulation.

1.5 APPLICATIONS OF ACTIVE FILTERS

Modern communications and instrumentation systems are demanding more stringent filtering specifications(131). The active filters are widely employed in communication systems. The most important use is in connection with PCM-CODEC (pulse code modulation coder/decoder) chips for digitization of telephones. This requires perfect filter specifications in terms of sharpness of cut-off and passband ripple. Further applications in communications includes de-emphasis and pre-emphasis, aliasing, equalization, active impedance matching networks for repeaters and teleprinter low pass filters to suppress harmonics.

One more interesting communication application is in dual tone multi-frequency (DTMF) signaling as developed by Bell telephone laboratories for use in touch tone dialing and is destined to become standard in the American telephone market. It is also used in the associated systems such as the radio-telephone line on the metro-linear railway operating between New York city and Washington. The other applications of active filter are in instrumentation such as noise rejection in digital voltmeters, harmonic filtering in transformers, vibration and shock studies. They have their interesting use in the field of medical electronics where they have distinct advantages over passive filters in the low and sub-audio range. Many physiological signals fall within the three decade band below 20 Hz. For example : heart monitoring by electrocardiograph (ECG) and brain wave recording by electroencephalograph (EEG). The active filters overcome the problems of impedance matching inherent in the passive systems.

The further applications of active filters include control (e.g. servo-system design and process control equipment), Entertainment electronics (e.g. stereo amplifiers and musical synthesis) and pulse shaping (e.g. to avoid crosstalk in colour TV broadcasting equipment, sonar systems, telemetry, phase locked loops, oscillators, hum suppression, pre-filtering of analog to digital converters, spectrum analysis and seismological research).

Also, wave filters find many applications in telecommunication, physics and general electronic engineering. Some of the more important applications employed in purification of the wave form, Radio transmission and reception, carrier telephony and telegraphy and electrical wave filters in Acoustics (e.g. filters in Air ducts, silencers and tone guard).

1.6 ACTIVE-R FILTER

The passive filter consists of three basic elements as resistance, capacitance and inductance. However, due to tremendous development in IC technology, it is possible to produce operational amplifiers with better performance and low cost. The operational amplifier along with resistors and capacitors are generally used in Active-RC filters. Due to development in IC technology, there is tremendous reduction in size of electronic systems and it has become possible to eliminate, the costly and bulky inductors from the active filter design.

Initially, there has been a drive to utilize inherent circuit capacitances, thereby eliminating the use of external capacitors. Therefore, many circuits are developed with only resistors (without using LC components) which are commonly identified as "Active-R" filter. The operational amplifiers show roll-off at high frequency end of the frequency response curve. Therefore, it is possible to represent the operational amplifier by a single pole integrator model. This pole is useful in designing filters in which only resistors are the additional elements needed to construct a general second order filter circuit. SCHAUMAN has described the procedure of designing the second order 'Active-R' filter, in which the filter characteristics i.e. the cut-off frequency, center frequency, Q and bandwidth are directly related to the pole location and the dc gain of the operational amplifier. This means, they depend on the gain-bandwidth product of the operational amplifier.

The advantages of 'Active-R' filter realization are the higher frequency range, miniaturization in size, compact, light weight, ease of design and tunability. Further, it is found that the Active-R circuit has low sensitivities as compared to active-RC and passive filters.

1.6.1 Active-R Filter Design Procedure

The Active-R filter design technique is based on use of the "integrator model" for the compensated operational amplifier. Using this model, the operational amplifier can be treated as an inverting or non-inverting grounded integrator (selection of suitable circuit topology of a given filter function). The most important factor in designing the 'Active-R' filter is that the selection of Active-R circuit and finding the transfer function of the circuit. The next step in design procedure is the determination of element values. In this, gain transfer function of the circuit is compared with the standard form of filter transfer function. This provides designing equations. The solutions of these equations yield the required element values. The method is known as "coefficient matching technique". Thus using these values, one can design the required filter configuration.