Part I: PWM Speed Control and Locked-Rotor Detection

Introduction

This section presents a fan monitoring circuit that can be used in conventional MIC502-based circuits employing pulse-width modulation (PWM) fan speed control. The circuit relies on detecting motor commutation to indicate fan operation and does not require a three wire fan with a tachometer output.

Theory of Operation

The circuit detects fan operation by sensing the commutation of the fan motor. Commutation occurs four times per revolution as the motor windings are switched on and off by the fan's internal electronics. As can be seen in the oscillograph of Figure 1, the current through the fan is interrupted briefly when commutation occurs. This high dI/dt is fairly easy to detect with a differentiator circuit. If the fan stops turning for any reason, commutation ceases as well. Comparator U1a in the circuit of Figure 5, is configured as a rising-edge detector. R3, the current sense resistor, converts the current through the fan into a voltage. The combination of R4 and C1 on U1a's inverting input cause this input to lag behind the noninverting input as signal swings occur. This results in the output going high for positive dV/dt, that is, rising edges. As can be seen in Figure 1, U1a outputs a brief pulse each time commutation occurs.

These pulses must be blanked in order to avoid a false indication of fan operation. Although some fans exhibit very clean current waveforms at commutation, others tend to ring when commutation occurs or when switching on and off. This ringing follows PWM turn-on and may also be detected by the edge-detector circuit. Some means must be employed to prevent false indications of motor commutation due to this phenomenon.

A fan monitoring circuit can make use of the fact that the high dI/dt events occur at or near the PWM edges. If the fan current waveform is only sampled in the center of the PWM on-time, t_{ON}, only commutation events will be detected. Comparator U1b generates a window that is always centered within t_{ON}. It does this by comparing the level of the MIC502's triangle wave oscillator to a fixed reference voltage. (Recall that the MIC502's PWM output is generated by a comparator and triangle wave oscillator.) The oscillator swings between 40% and 70% of the power supply voltage. U1b compares the voltage at CF to a reference level set at 35% of the supply voltage. Whenever the fan is running, the point at which V_{CF} = $V_{DD} \times 0.40$ represents the center of the PWM on-time. Resistor divider R1-R2 sets the reference level. (This is why R1 and R2 must be moderately-high-precision resistors.) Whenever V_{CF} is below the reference level, U1b's output is high. U1b's output will be high for a short period that is always centered within t_{ON}. See Figure 2.
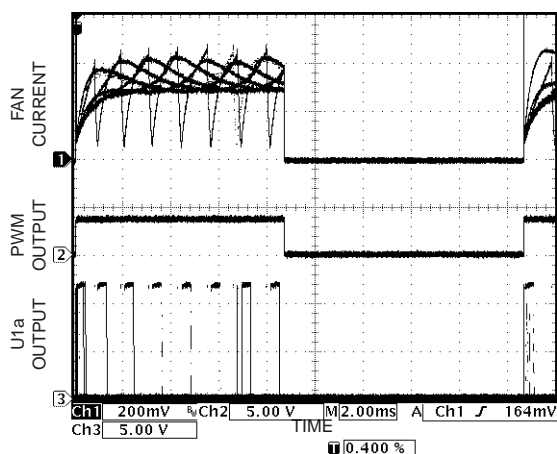

Figure 1: Detecting Commutation

Sensing fan commutation is a very reliable method of determining fan rotation. (It can also be used to measure RPM.) However, there are a few issues to be dealt with in the case of PWM speed control. As the PWM turns on and off, fan current, I_{FAN}, does also. This produces high edge rates that are difficult to distinguish from commutation events. Since the circuit employed here senses positive edge rates, it will generate an output pulse each time the PWM turns on. This can be seen on the far right side of Figure 1, lower trace.
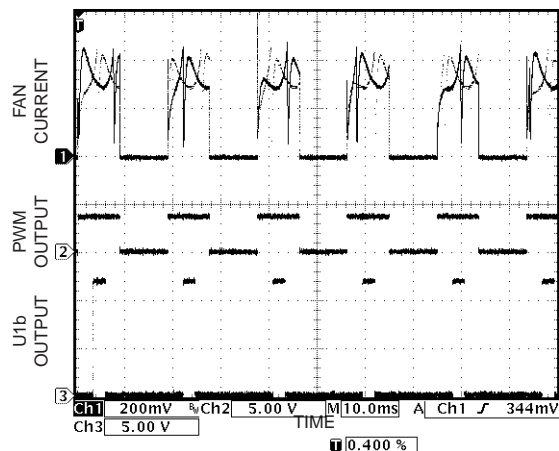

Figure 2: Window Generator

The nature of this scheme places one stipulation on the overall circuit operation: The finite size of the sampling window requires that t_{ON} always be longer than the sampling window, t_{SAMPLE}. Since the sampling window is always centered within t_{ON}, forcing t_{ON} to be longer than t_{SAMPLE} ensures that there will always be some dead space between the beginning and end of the sampling window and the PWM edges. This means that we have now forced the minimum PWM on-time, and therefore the minimum fan drive level, to

be greater than t_{SAMPLE}. This requirement should have little effect on most applications, since a very low fan duty-cycle is of little value in practice. Most circuits either establish a minimum fan drive level or go into sleep mode at low system temperatures. Using the component values shown in Figure 5, the minimum practical fan duty-cycle is approximately 25%. Below this point, the circuit may give false indications of fan operation; i.e., it may not detect a stalled fan due to the PWM edges being at or inside of the sampling window. The optimum reference level is determined by observation of the fan current waveform during PWM operation. It may be raised or lowered as needed to insure adequate blanking of the PWM turn-on and turnoff events while allowing the widest speed control range.

The outputs of U1a and U1b are effectively ANDed by connecting them together with a single pull-up resistor, R5. (The LM339's outputs are open collector and may be tied together.) The resulting signal will be high only when commutation is detected within the sampling window. As shown in Figure 3, pulses are only generated when commutation occurs near the center of the PWM on-time. These high-going pulses are monitored by a missing pulse detector built around comparator U1c. As long as pulses continue to arrive via diode D1, capacitor C2 remains charged, holding the inverting input of U1c above the noninverting input. The noninverting input is fixed at 17% of the supply, approximately 2.0V for a 12V supply, by resistors R6 and R7. The output of U1c will normally be low. If no pulses arrive, C2 will discharge via R8 until U1c changes state. U1c's output will then be pulled high by pull-up resistor R9. This high voltage level is applied to the MIC502's VT2 input via diode D2. When this occurs, the MIC502's output will turn on and remain on until U1c's output returns low. (R10 and D2 are optional components that may or not be required depending on what other circuitry is connected to the VT2 input.) Figure 4 illustrates the operation of the missing pulse detector function. The voltage on C2 declines until a commutation event is detected. (Note that the slope of the voltage on C2 is exaggerated by approximately 2:1 due to the loading of the oscilloscope probe.)

Driving VT2 high before asserting an error signal solves the final issue unique to monitoring fans driven by PWM and avoids false error indications. In certain cases, the rotation of the fan and the on-time of the PWM may become "out of phase" in such a way that all the commutation events occur during the PWM off time, t_{OFF}. Obviously, commutation cannot be detected during t_{OFF}. This situation is indistinguishable from an inoperative fan. Driving VT2 high serves to upset the phase relationship between the fan and the PWM by driving t_{OFF} to zero. If the fan is operating, a commutation event will soon be detected, and the circuit will reset without having indicated a fault. If a pulse does not arrive soon, it may be assumed that the fan is indeed inoperative, and a fault should be indicated. The last component of U1, comparator

U1d, operates much like U1c and serves as a timer. If U1c's output remains high for more than a few seconds, capacitor C3 charges above the reference level set on U1d's positive input by R12-R13, and the output goes low, indicating a fault. Pull-up resistor R14 may be required depending on what circuitry is interfaced to U1d's output. Using the component values shown in Figure 5, a locked rotor condition will be detected within 2 to 3 seconds. Increasing the size of C2 will increase this time constant.

Figure 6 is a modification of the basic circuit which adds a few components to support the MIC502's sleep mode. Transistor Q2 functions as a switch which only discharges C2 via R8 when the MIC502's PWM output is on. Thus, when the MIC502 enters sleep mode, or is otherwise shut down, the missing-pulse detector is disabled. To insure that U1c maintains the correct state when Q2 is off, R17 holds the noninverting input of U1c at a voltage higher than the inverting input. This action depends on the fact that the current through R17 and the input bias current of U1c are much smaller than the current which flows in the R6-R16-R7 voltage divider.
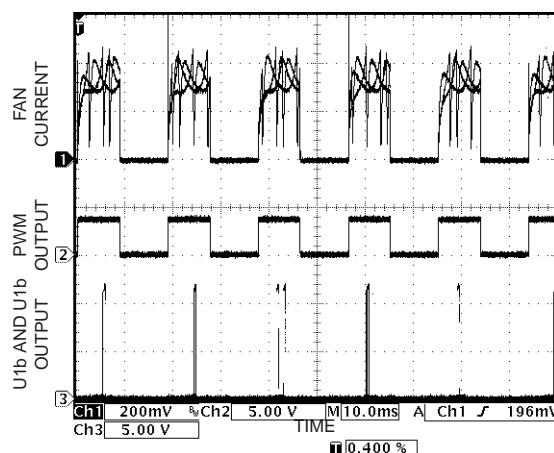

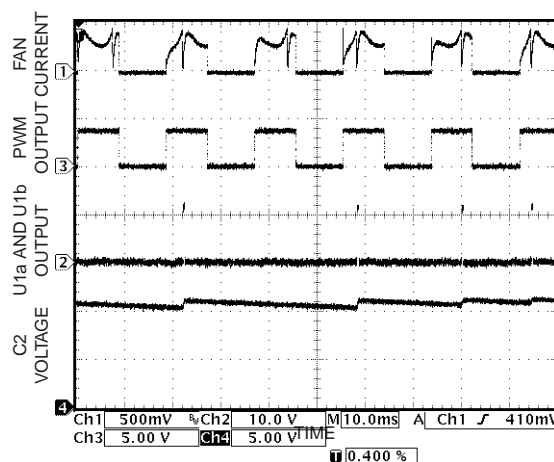**Figure 3: Commutation Detector Signal Filtered by Window Generator.**

Figure 4: Missing Pulse Detector Operation

Designation	Description
U1	LM339 quad comparator IC
D1, **D2**	1N4001 silicon diode
R1	13k 1%, 1/8W resistor
R2	7k 1%, 1/8W resistor
R3	2.2Ω 5% 1/4W resistor
R4, R6, **R10**	100k 5% 1/8W resistor
R5, R9	2.2k 5% 1/8W resistor
R7	20k 5% 1/8W resistor
R8	10M 5% 1/8W resistor
R11	3.3M 5% 1/8W resistor
R12, R13, **R14**	10k 5% 1/8W resistor
C1	150pF capacitor
C2, C3	0.1µF capacitor

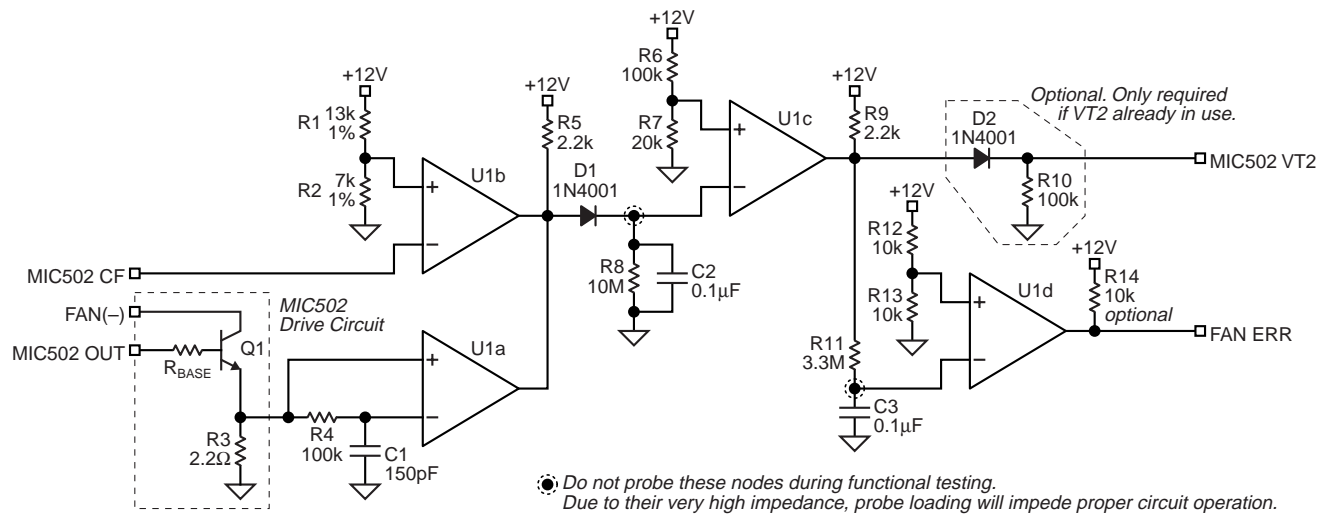**Table 1a. PWM Locked-Rotor Detector Circuit Basic Circuit Parts List**

Schematics

Figure 5 shows the basic PWM fan monitoring circuit.

Figure 6 is the same circuit plus additional components to support sleep mode.

Parts Lists

Parts for Figures 5 and 6 are shown listed in Tables 1a and 1b. **Bold** items are optional depending on overall circuit configuration. See text. R_{BASE} and Q1 are not listed since they are part of the standard MIC502 fan drive circuit.

Designation	Description
Q2	2N2222 bipolar transistor
R15	100k 5% 1/8W resistor
R16	2.0k 5% 1/8W resistor
R17	10M 5% 1/8W resistor

Table 1b. PWM Locked-Rotor Detector Circuit Sleep-Mode Addition Parts List

Figure 5: PWM Locked-Rotor Detection Circuit

Figure 6: PWM Locked-Rotor Detection Circuit With Sleep Mode Support

Component Selection

Most of the components used are noncritical low-cost types. Substitutions can generally be made without adverse effects. Most of the resistors are standard 5% tolerance. Note that R1 and R2 are higher precision 1% tolerance. C1, C2, and C3 can be standard ceramic capacitors. Note that excessive leakage in C2 and C3 will degrade circuit performance by making the time constants shorter. Some additional comments should be made regarding some of the components:

U1: The LM339 quad comparator was chosen because: it is commonly available from multiple suppliers, thus low cost; it has adequately low input bias current; it includes the required number of comparators; its outputs are open collector; its input range includes ground; and it has a wide power supply operating range. Other comparators with the same or better performance can be used.

Q2: The characteristics of Q2, a small-signal NPN bipolar transistor, are not particularly critical. The 2N2222 used here has a breakdown voltage, $V_{(BR)CEO}$, of 30V; a minimum gain of 30; comes in a TO-92 or SOT-23 package; and can dissipate 625mW. Any comparable device should be adequate.

C1: The value of C1 is not particularly critical. A wide range of values is generally acceptable. Higher values will result in a more sensitive differentiator, i.e., for a given waveform the output pulses will generally be longer. If needed to insure reliable operation with a given fan, C1 may be increased. Decreasing C1 is not recommended. (Note that changes in the values of R3, R4, and C1 all interact. Higher values of R3, R4, and/or C1 result in a more sensitive differentiator.)

D1, D2: Although 1N4001 silicon rectifier diodes are shown above, virtually any small-signal rectifier will work. The highest reverse voltage that could ever be applied is 12V and the forward current will not be more than about 6mA. D2 and R10 are only required if other circuitry (besides the locked-rotor detection circuit) is connected to VT2. Otherwise, there is no requirement to isolate the circuit, and the output of U1c may be connected directly to VT2.

R3: The optimum value of R3 will vary with the size of the fan. Higher running current will result in more signal amplitude across a given size R3. The 2.2Ω value used here has been successfully used with fans in the 80mA to 200mA range. In order to dissipate the least amount of power in R3, its value should be reduced to the minimum level that results in reliable circuit operation. (Note that changes in the values of R3, R4, and C1 all interact. Higher values of R3, R4, and/or C1 result in a more sensitive differentiator.)

R4: The value of R4 is not particularly critical. However, 100k is a reasonable, practical value. Higher values would call for a smaller C1 and might allow parasitic effects to dominate circuit operation. Lower values would call for a corresponding higher value of C1. For a given C1, higher values of R4 will generally result in a more sensitive differentiator, i.e., for a given wave-

form the output pulses will generally be longer. (Note that changes in the values of R3, R4, and C1 all interact. Higher values of R3, R4, and/or C1 result in a more sensitive differentiator.)

R10: D2 and R10 are only required if other circuitry (besides the locked-rotor detection circuit) is connected to VT2. Otherwise, there is no requirement to isolate the circuit, and the output of U1c may be connected directly to VT2.

Layout Guidelines

Noise on the power supply rails can adversely effect the circuit's operation. Some fans generate objectionable power supply noise when they commutate or otherwise switch on and off. If needed, bulk capacitance should be placed across the fan's power supply to remove switching noise. Enough bulk capacitance should already exist in the case where these circuits are used inside power supplies. For the most part, standard circuit layout rules apply. The following items are recommended:

- Add bulk capacitance as needed to insure that fan switching noise is not present on the circuit's power supply rails.

- Bypass all IC supply pins to ground with 0.01μF capacitors placed as close to the IC as possible.

- In noisy environments, the MIC502's VT1, VT2, and VSLP pins should be bypassed to ground by 0.01μF capacitors placed as close to the IC as possible. The reference nodes for comparators U1b, U1c, and U1d (noninverting inputs), should be similarly bypassed. Noise on any of these nodes can cause erratic operation.

- The fan is provided with low-impedance connections, i.e., wide PCB traces, directly to the power supply.

- Power and ground connections are as short as possible.

- The circuit layout is as compact as possible and as far away from noise sources as possible.

- The power and ground connections for the fan are separate from that of the other circuitry. To minimize ground loops and/or ground bounce, these connections should be made as far upstream as possible, preferably to the bulk capacitance.

If erratic operation is encountered after all of the above guidelines have been followed, the cause may be due to one of the following items:

1. A test probe or lead wire is attached to one of the circuit's high impedance nodes. These sensitive nodes are marked in the schematics above. Remove all test probes, lead wires, etc., and do not touch these nodes while testing.

2. Contaminants on the circuit board are creating conductive paths that upset one or more of the high impedance nodes. These sensitive nodes are marked in the schematics above. A thorough cleaning of the PCB should eliminate the problem.

3. The circuit is picking up noise from adjacent circuitry. Deactivate the suspect circuitry during testing to positively identify this as the cause. If this is found to be a problem, locate the circuit as far from the noise source as possible or add shielding.

4. One or more of the components is defective, the wrong value, or wired incorrectly.

If noise is found to be a problem, one option for reducing the circuit's sensitivity is to reduce the high-value resistors, R8, R11, and R17. This will require a proportional increase in the size of the associated capacitors, C2 and C3. For example, if the value of R8, R11, and/or R17 is reduced by half, the capacitance of C2 and/or C3 should be doubled. This will maintain approximately the same time constants. The values of these components were originally chosen to minimize capacitor size and cost. (Note: R8 and R17 should be the same value.)

Part II: A Drive Circuit for Maintaining Tachometer Signal Integrity With Optional Locked-Rotor Detection

Introduction

This section presents a pair of circuits that can be used with the MIC502 to preserve the tachometer signal output on fans so equipped. These circuits utilize linear fan speed control. Although linear speed control involves certain trade-offs in terms of power dissipation and speed control range, it is necessary to avoid the "chopping" effect of PWM speed control on the tachometer signal.

Theory of Operation

Figure 9 illustrates a basic linear fan drive circuit. This circuit simply integrates and low-pass filters the MIC502's PWM output into a dc voltage level that can be applied to the fan. A bipolar transistor is used to supply the final current gain needed to drive the fan motor. The integrator is formed by R1 and C1. The resulting dc voltage is amplified by U1a operating as a noninverting amplifier with a gain of 3.2. Its output directly drives the base of Q1. The feedback voltage applied to the op amp's noninverting input is taken from the emitter of Q1, allowing the op amp to compensate for the voltage drop across Q1. Figure 7 illustrates the operation of the circuit, showing the PWM output of the MIC502, the voltage on C1, and the voltage applied to the fan. Note that in this example, the MIC502's operating frequency has been set to approximately 90Hz by using a 0.033µF capacitor on the CF pin. A higher operating frequency results in less ripple on the output of the integrator with a given R1 and C1.

The basic linear fan drive circuit of Figure 9 provides for a conventional tachometer signal output on fans so equipped. If the application also requires local locked-rotor detection, the circuit of Figure 10 can be used. A missing pulse detector circuit has been added to the linear drive circuit to monitor the tachometer signal. The missing pulse detector function is conveniently implemented in a second op amp of the same type as used in the linear drive circuit. (The op amp is essentially operating as a comparator in this application.) A single dual op amp and two transistors are thus the only active components needed. The TACH signal is applied to C2,

which acts as an edge-detector, turning on Q2 briefly each time a high-going transition occurs. C3 charges slowly via R6 to act as a timer. When Q2 turns on, C3 is effectively shorted to GND. If no transitions are detected, C3 will eventually charge up to the level of the 12V rail. The noninverting input of U1b is held at approximately 91% of the supply voltage by a resistor divider formed by R7 and R8. If the level on C3 becomes greater than 91% of the supply, the op amp output goes low, indicating a fault. The resulting fault signal can be wire-ORed with other open-collector signals. R9 may be required as a pull-up resistor. Figure 8 illustrates the circuit's operation. (Note that the slope of the voltage on C3 is exaggerated due to the loading of the oscilloscope probe.)
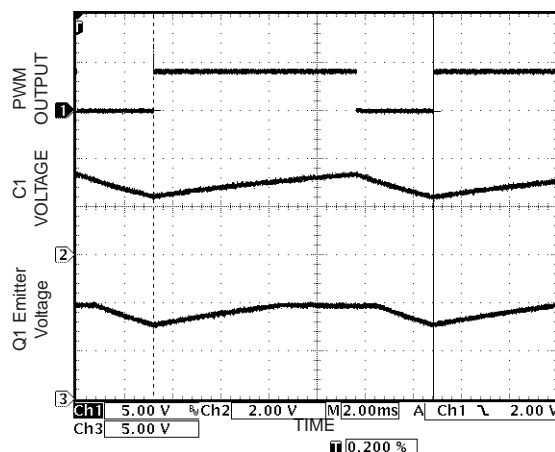

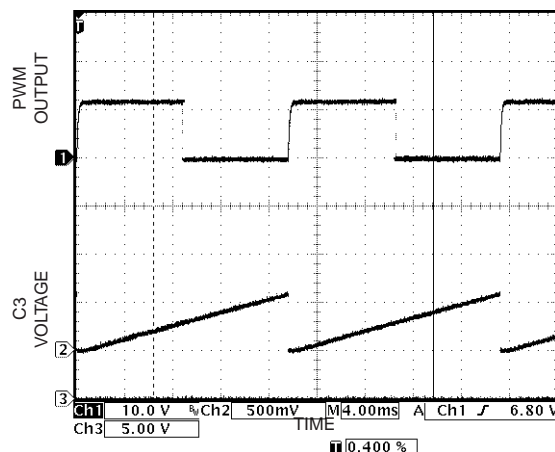**Figure 7: Linear Fan Drive Using Circuit of Figure 9**

Figure 8: Missing Pulse Detector Operation

Maximizing Fan Drive

One disadvantage of linear fan drive is the power dissipation that takes place in the pass element, a bipolar transistor in this case. In addition, it is difficult to apply maximum voltage to the fan because of limits on the op amp's output swing when powered from the 12V rail. One alternative is to use a high-performance rail-to-rail op amp and/or a higher-performance transistor with lower $V_{CE(sat)}$. This approach increases performance somewhat but requires more expensive components. A virtually "free" alternative may exist in many applications. The same results can be achieved by connecting the op amp's positive supply input and the drive transistor's collector

to a voltage higher than the 12V rail. The LM358 op amp shown has a maximum power supply voltage of 30V, Q2 can withstand up to 30V as well, whereas Q1, a TIP31 NPN transistor, can withstand up to 40V. A popular application of the MIC502 is within switching power supplies, such as those for desktop PCs. In this case, the 12V rail may be the highest output voltage provided. However, the 12V rail is often provided by a linear postregulator powered by a loosely regulated secondary output. In this case, the op amp and transistor can be powered from the *input* side of the 12V regulator. This will generally provide at least 1.5V to 2.0V additional drive without having to invest in a rail-to-rail op amp and/or a higher performance transistor. This scheme is illustrated in Figure 11. When using this technique, the gain of U1a may be increased to provide higher fan drive. Many "12V" fans are, in fact, rated for inputs up to 13.8V. Increasing the gain of U1a to 3.65 will provide up to 13.8V of fan drive, provided it is available from V_{UNREG}. In all cases, the MIC502 and its associated circuitry remains powered from the regulated 12V rail.

Schematic

The basic linear drive circuit is shown in Figure 9. The addition of locked-rotor detection results in the circuit of Figure 10. Figure 11 demonstrates a modification of the previous circuits that achieves higher fan drive in applications where more than 12V is available. (See "Maximizing Fan Drive" above.)

Parts List

Table 2 lists the components used in the circuits of Figure 9, Figure 10, and Figure 11.

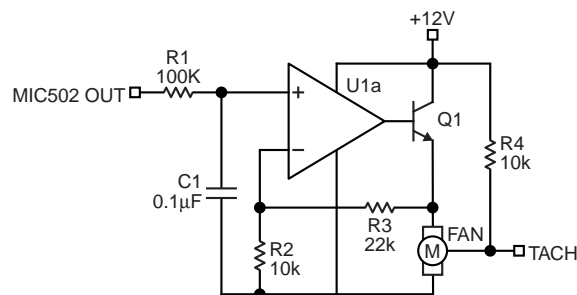**Bold** items are optional depending on overall circuit configuration. See text.

Figure 9: Linear Fan Drive Circuit for Preserving Tachometer Signal

Designation	Description
U1	LM358 Dual Op-Amp
Q1	TIP31 Bipolar Transistor
Q2	2N2222 Bipolar transistor
R1, R5, R8	100k 5% 1/8W resistor
R2, R4, R7, **R9**	10k 5% 1/8W resistor
R6	3.3M 5% 1/8W resistor
R7	10k 5% 1/8W resistor
C1, C3	0.1µF capacitor
C2	0.01µF capacitor

Table 2: Parts List For Linear Fan Drive Circuit With Locked-Rotor Detection

Component Selection

Most of the components used are noncritical low-cost devices. Substitutions can generally be made without adverse effects. All the resistors are standard 5% tolerance. Additional comments should be made regarding some of the components:
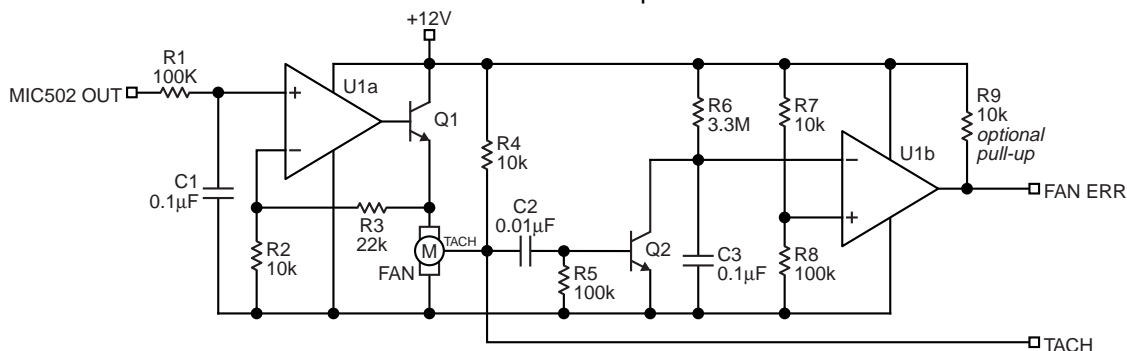

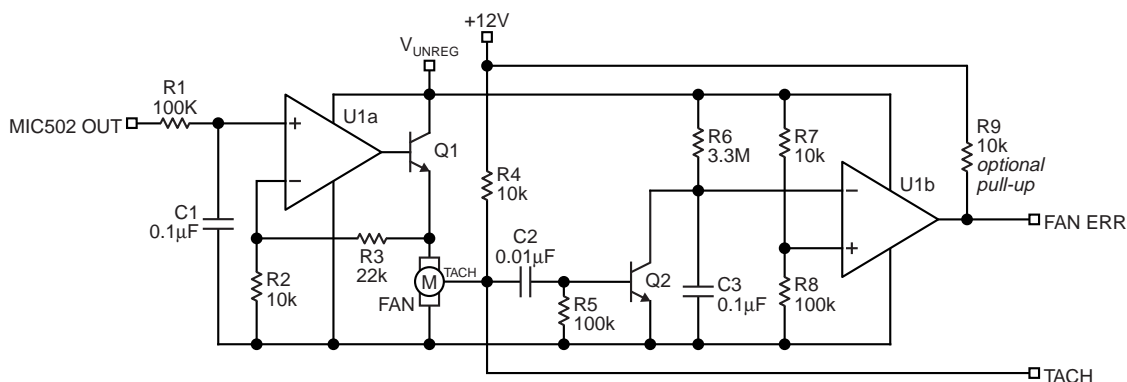**Figure 10: Linear Fan Drive Circuit With Locked-Rotor Detection**

Figure 11: Circuit for increasing fan drive

U1: The LM358 dual op amp was chosen because: it is commonly available from multiple suppliers, thus low cost; it has adequately low input bias current; it includes the required number of amplifiers; its input range includes ground; and it has a wide power supply operating range. Other op amps with the same or better performance can be used. Circuit performance can be increased by utilizing an op amp with higher output voltage swing. See "Maximizing Fan Drive" above.

Q1: The characteristics of Q1, an NPN bipolar power transistor, are not particularly critical. The TIP31 used here has a breakdown voltage, $V_{(BR)CEO}$, of 40V; a minimum gain of 25; comes in a TO-220 package; and can dissipate 40W. Any comparable device having adequate power handling capability should be usable. Circuit performance can be increased by utilizing a transistor with lower $V_{CE(sat)}$ and/or higher gain. Note that the LM358 is capable of driving 20mA minimum into the base of Q1. The maximum expected fan current should be no higher than Q1's minimum gain times the base current delivered by U1, or $I_{FAN} < \beta \times 20mA$.

Q2: The characteristics of Q2, a small-signal NPN bipolar transistor, are not particularly critical. The 2N2222 used here has a breakdown voltage, $V_{(BR)CEO}$, of 30V, a minimum gain of 35, comes in a TO-92 or SOT-23 package, and can dissipate 625mW. Any comparable device should be adequate.

Layout Guidelines

Noise on the power supply rails can adversely affect the circuit's operation. Some fans generate objectionable power supply noise when they commutate or otherwise switch on and off. If needed, bulk capacitance should be placed across the fan's power supply to remove switching noise. Enough bulk capacitance should already exist in the case where these circuits are used inside power supplies. For the most part, standard circuit layout rules apply. The following items are recommended:

- Add bulk capacitance as needed to insure that fan switching noise is not present on the circuit's power supply rails.
- All ICs have their supply pins bypassed to ground by 0.01µF capacitors placed as close to the IC as possible.

- In noisy environments, the MIC502's VT1, VT2, and VSLP pins should be bypassed to ground by 0.01µF capacitors placed as close to the IC as possible. The reference nodes for comparator U1b, i.e. the noninverting input, should be similarly bypassed. Noise on any of these nodes can cause erratic operation.
- The fan is provided with low-impedance connections, i.e., wide PCB traces, directly to the power supply.
- Power and ground connections are as short as possible.
- The circuit layout is as compact as possible and as far away from noise sources as possible.
- The power and ground connections for the fan are separate from that of the other circuitry. To minimize ground loops and/or ground bounce, these connections should be made as far upstream as possible, preferably directly to the bulk capacitance.

If erratic operation is encountered after all of the above guidelines have been followed, the cause may be due to one of the following items:

1. A test probe or lead wire is attached to one of the circuit's high impedance nodes such as the junction of R6 and C3. These sensitive nodes are marked in the schematics above. Remove all test probes, lead wires, etc. while testing.

2. Contaminants on the circuit board are creating conductive paths that upset one or more of the high impedance nodes. These sensitive nodes are marked in Figures 5 and 6. A thorough cleaning of the PCB should eliminate the problem.

3. The circuit is picking up noise from adjacent circuitry. Deactivate the suspect circuitry during testing to positively identify this as the cause. If this is found to be a problem, locate the circuit as far from the noise source as possible or add shielding.

4. One or more of the components is defective, the wrong value, or wired incorrectly.

If noise is found to be a problem, one option for reducing the circuit's sensitivity is to reduce the value of R6. This will require a proportional increase in the size of the associated capacitor C3. For example, if the value of R6 is reduced by half, the capacitance of C3 should be doubled. This will maintain approximately the same time constant. The values of these components were originally chosen to minimize capacitor size and cost.