## APPENDIX A

SCORBOT - ER VII
ESHED ROBOT

# THE CONTROL SYSTEM

## Degrees of Control

This section describes various types of motor control, ranging from lack of control (open loop) to state and velocity control.

### Open Loop Control (lack of control)

In open loop control, power is applied to the motor, and is disconnected after a predefined period of time. We can describe the path (x) and speed (v) as shown in Figure A-1. The actual path (and the speed) cannot be predicted since it is determined by the moment motion begins and by the weight of the load.

### State Control (constant speed)

In state control the system receives information from feedback devices (such as encoders) regarding the amount of motion performed. Once the target motion is achieved, the system shuts down the power to the motor. Speed is not defined and varies according to factors such as load, friction, and strength of feeding power supplies.

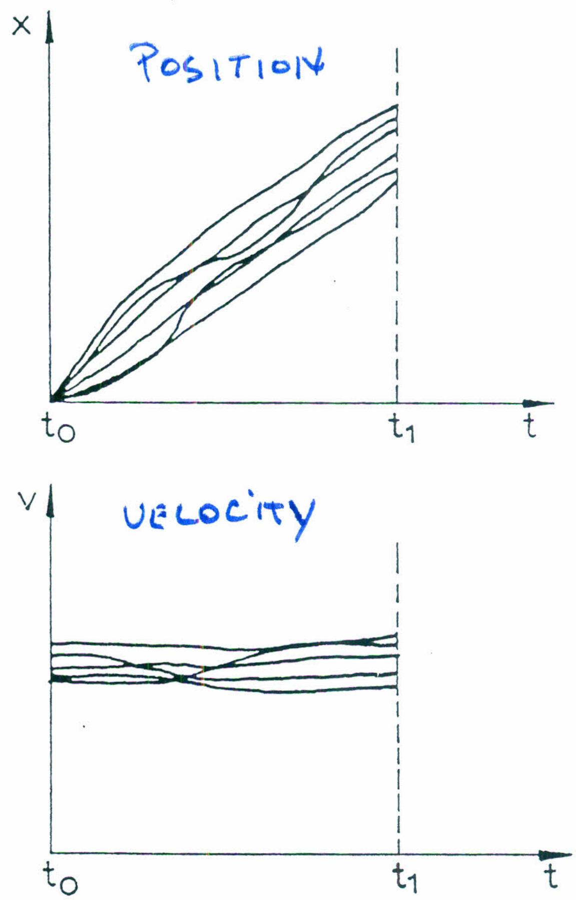


**Figure A-1: Open Loop Control**

Inertia will cause the motor to continue rotating for a while, until it comes to a complete stop. Most control systems can recognize this extra rotation and will apply voltage (power) in the opposite direction in order to cancel this **overshoot.** The process is described in Figure A-3.

In Figure A-3 the system has stabilized at the desired state with no state error; that is, the motor has stopped exactly where required. Systems can, however, stabilize with a **steady state error** or remain in a state of vibrations, as shown in Fig. A-4.

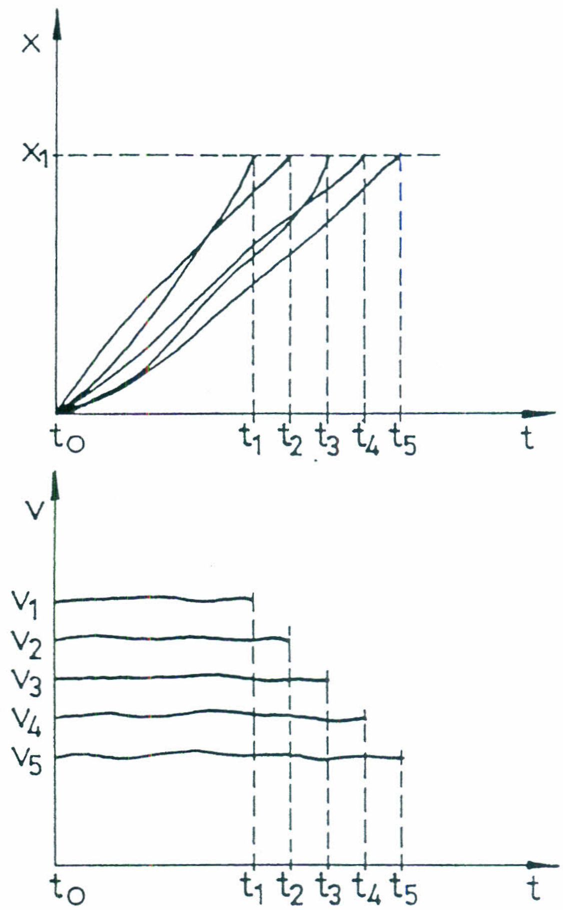


**Figure A-2: State Control System**

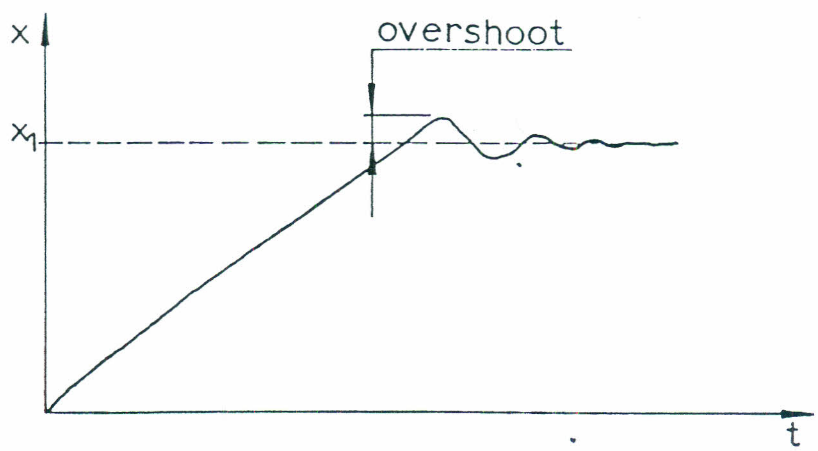


**Figure A-3: Overshoots in State Control System**

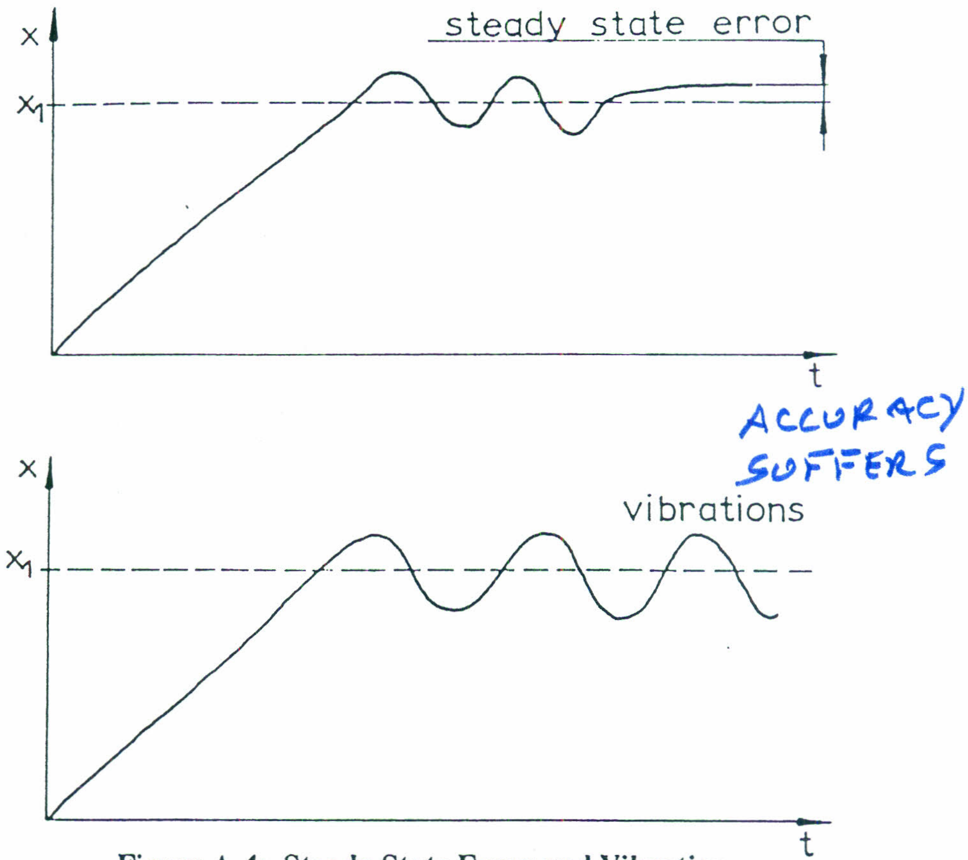


Figure A-4: Steady State Error and Vibration

## State and Speed Control

In addition to the state information described above, the system receives feedback regarding the motion rate. The state and speed curves are described in Figure A-5.

For better path performance (that is, to avoid overshoots), acceleration and deceleration should be implemented at the begining and end of the motion. Various profiles of control, such as trapezoid and paraboloid, may be used, as described in Figure A-6. Unbalanced control may, however, cause vibrations, overshoots and errors.

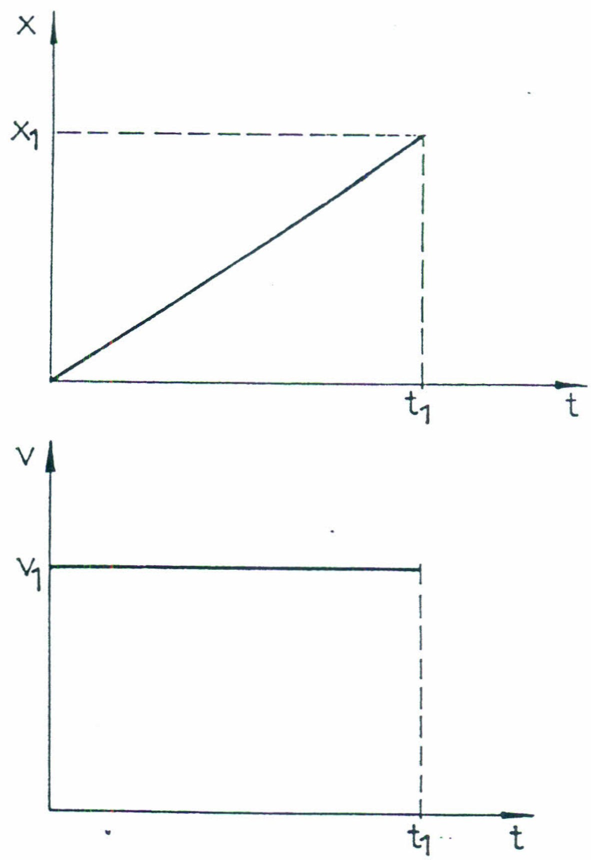


Figure A-5: State and Speed Curves

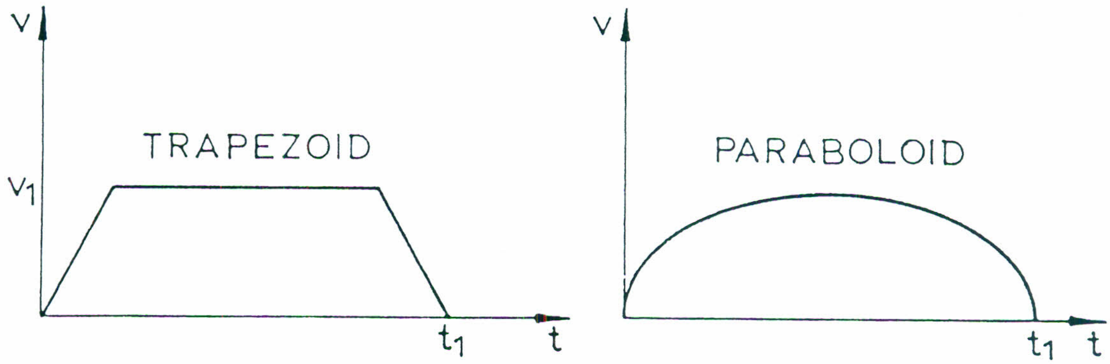


**Figure A-6: Profiles of Control**

### Position Measuring Devices

The location position of a motor is commonly measured by an electro- optical encoder. It transmits electrical pulses proportional in number and rate, respectively, to the amount of the motor's rotation and rate of motion.

The rate of motor rotation is commonly measured by a tachometer. It converts (in real time) the rate of rotation into a proportional electrical voltage value. Since the cost of mounting a tachometer on each motor makes it impractical, many machines and robots instead use a fast processor for real time calculation of the rate transmitted by encoder signals.

## SCORBOT-ER VII Control System

1. SCORBOT-ER VII controls both the path (position) and the speed, and enables you to choose the control profile: trapezoid or paraboloid (default is paraboloid). The SCORBOT-ER VII control system is PID: proportional, integral, differential.

2. The control system block diagram is shown in Figure A-7.

   **Stage A:**

   The processor calculates the required position and speed every 10ms. It outputs a value (digital) in the range of ±5000 millivolts (the entire range is linear).

   **Stage B:**

   The DAC (Digital to Analog Converter) unit outputs an analog voltage proportional to the digital input. The analog output from the DAC is $-2.5 \leq V \leq +2.5$. It is then multiplied by 2 (that is, $-5 \leq V \leq +5$) to comply with TTL logic. In Figure A-8 we refer to the 5V level of analog voltage stage.

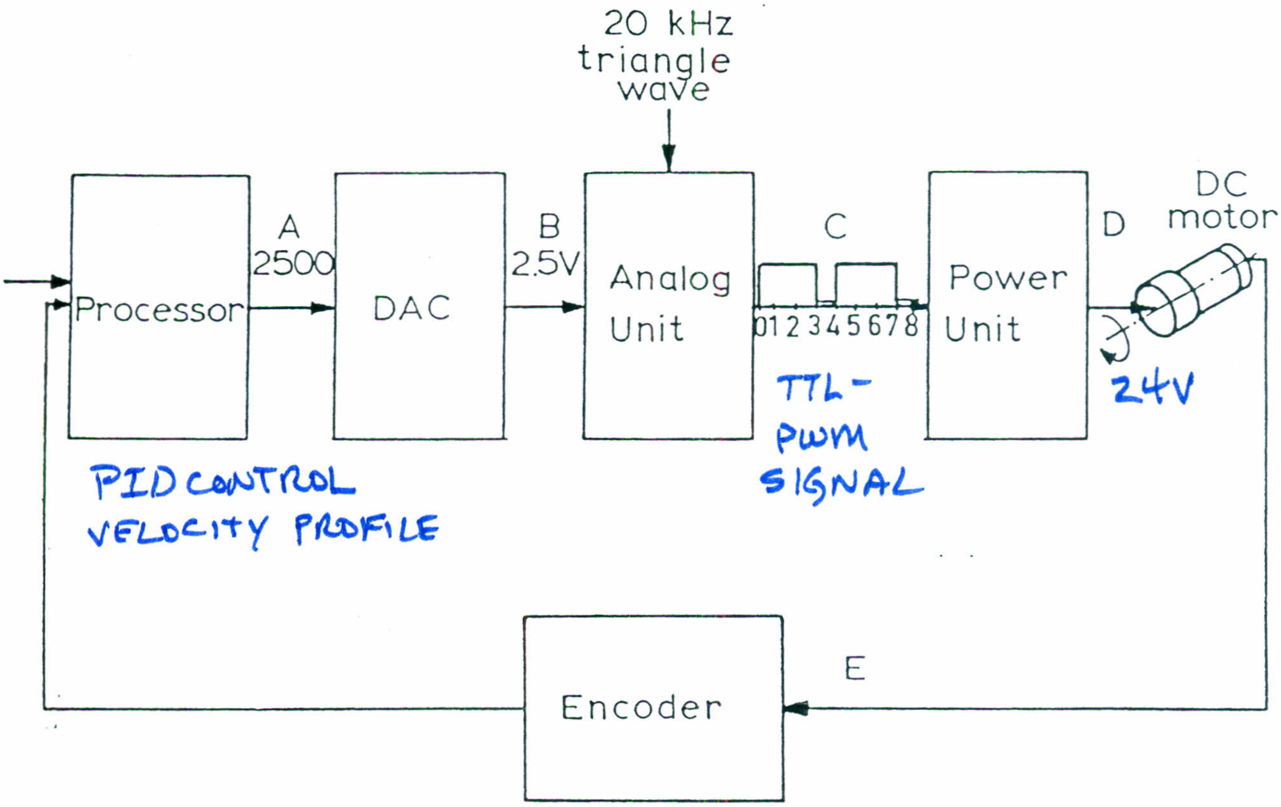


Figure A-7: SCORBOT-ER VII Control System

### Stage C:

The analog unit creates a continuous signal at 20 KHz. The duty cycle ranges proportionally as follows:

| | | |
|---|---|---|
| 100% | = | Full Speed - clockwise (CW) |
| 50% | = | Stop |
| 0% | = | Full Speed - counterclockwise (CCW) |

### Stage D:

The power unit drives the motor by switching ± 24VDC to it, at 20KHz, in accordance with the duty cycle produced by the analog unit. The motor cannot react to this high frequency of switching and is then affected by the average value of the power flow.

3. The entire process is described in Figure A-8 and is known as PWM (Pulse Width Modulation) control.

4. During motor rotation, the encoder attached to it produces pulses proportional to the amount of rotation.

5. Every 10 ms the processor reads the encoder and calculates the motor's position and rate. The rate is calculated as dx/dt (first deriative of the path).

The processor then compares the actual values of x (position) and v (speed) with the desired ones, determines the **error** values and takes the necessary action to cancel them.

6. The entire control cycle takes 10 ms.

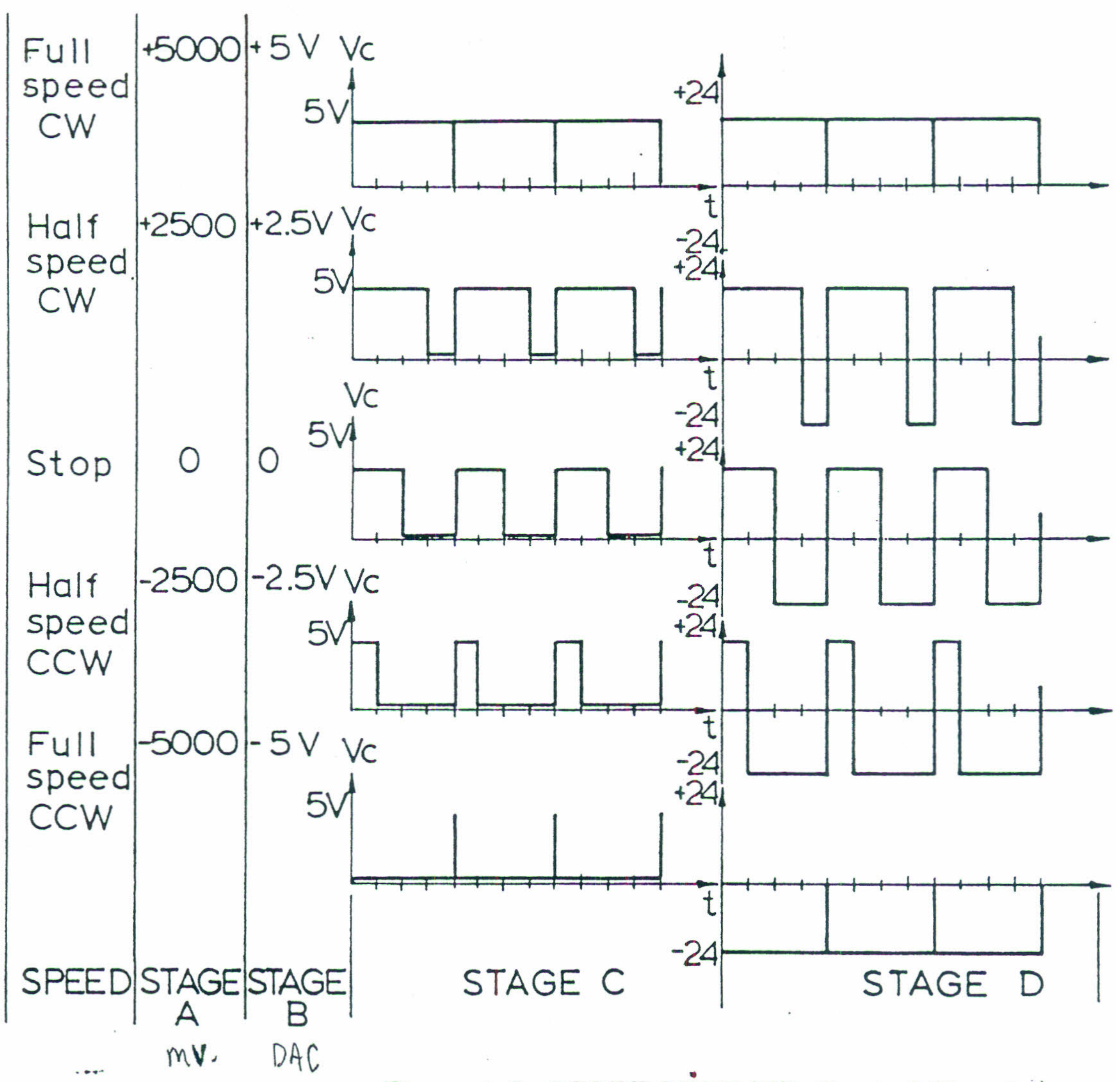


**Figure A-8: SCORBOT-ER VII Control Signals**

FROM PROCESSOR AND DAC

KLAFTER



LINEAR AMPLIFIER

short circuit, which, as explained previously, can cause a runaway condition—an especially dangerous occurrence in robotic applications.

There are other factors that must be considered when working with linear servo amplifiers: for example, the power dissipation capability of both the power transistors and the associated heat sinks, the need to provide some type of *active* cooling (e.g., by using a fan), and the need to protect both the power transistors and the motor from current overloads by using current limiting. The last of these factors is particularly important in robotic applications since it is not at all uncommon for a stall to occur in the middle of a move due to the manipulator coming into contact with a foreign object that has accidentally found its way into the workspace. Clearly, one or more motors will stall in this case and some type of protection is absolutely essential in order to prevent amplifier and/or motor damage or destruction. Current limiting is one such technique, although fusing of motors and software methods (i.e., implementation of "timeout" criteria; see Section 4.4.4) are also often employed.

### 4.11.2 Pulse-Width-Modulated Amplifiers

One of the major difficulties with the linear amplifiers described in the preceding section is that, very often, the output is only a fraction of the total supply voltage, for example, during the initial or final portions of a move or when the move is deliberately performed at low speeds. This is accomplished by operating the power transistors in their active (i.e., linear) regions, which means that the collector-to-emitter voltage drop $V_{CE}$ of the transistor(s) that is (are) conducting is significant. Consequently, the power dissipated in the collector (i.e., the product of collector current and the collector-to-emitter voltage) can be large (on the order of tens of watts and sometimes as high as 100 W), so the transistors and heat sinks must be sized accordingly. Although it is certainly possible to obtain these large transistors with the technology currently available, the added cost incurred is not always warranted. Fortunately, it is now possible to use a different approach that is generally more cost-effective (i.e., pulse-width modulation, PWM).

With the advent of power transistors that can be switched at megahertz rates, the use of PWM amplifiers to drive servomotors in robotic applications, as well as other incremental motion applications, has become quite practical and attractive. The major advantage of a switched device over a linear device is that in the former, the power transistor is either "off" or in (or close to) saturation. In either case, the power dissipated in the collector is considerably less than in an equivalent linear amplifier. This is easily understood by recognizing that since little or no collector current flows when the transistor is turned off, the power dissipation is quite small. When current does flow, however, the transistor is in saturation, which means that the drop across its collector is only 1 or 2 V. Thus the dissipation is still quite small (i.e., under 12 W for a continuous armature current of 6 A). An equivalent linear device might dissipate 72 W (assuming a 12-V drop across the collector).

Just as with linear servo amplifiers, PWM devices can be of the H or T type and the same comments concerning the advantages and disadvantages of both are pertinent (see Figures 4.11.1 and 4.11.2). However, unlike the linear case, the output voltage of the T or H circuit will be almost equal to the *full value* of either the positive or negative dc supply voltage (see Figure 4.11.3).

How can these types of signals provide the required variation in armature voltage and hence rotor speed? The answer to this question is found by recognizing that the servomotor is a low-pass filter [e.g., see the transfer function in Eq. (4.3.5)]. With $T_S$ defined as the period of the switching signal waveform, then if the radian switching frequency $\omega_S = 2\pi/T_S >> \omega_E$, the electrical pole of the motor (i.e., $\omega_S > 100\ \omega_E$), the filtering action of the motor will cause the effective armature voltage to be the "average value" of the waveforms in Figure 4.11.3.* Mathematically, this means that

$T(s) \propto \frac{1}{s^n}$ P212

$\omega_S > 100\omega_E$ AVERAGE

$$(V_{\text{arm}})_{\text{ave}} = \frac{1}{T_S}\int_0^{T_S} V_{\text{arm}}(t)\, dt \tag{4.11.1}$$

Thus applying Eq. (4.11.1) to the waveforms in Figure 4.11.3, it is seen by inspection that the motor will not move for the square wave in part (a) because $(V_{\text{arm}})_{\text{ave}} = 0$, whereas the nonzero average value of this quantity for the waveforms in (b) and (c) will produce rotor motion. It is important to understand that Eq. (4.11.1) will not be strictly correct if the switching frequency is too low. For example, if it is only about 10 times higher than the electrical pole of the motor, the effective armature voltage will be somewhat less than the average value and the armature current may exhibit significant ripple (see Problem 4.33).

In actual use, a PWM servomotor drive can be made to produce practically any type of acceleration, velocity, or position profile that might be required in a given application. For example, if it is desired to cause a servomotor to turn with a trapezoidal velocity profile (see Figure 4.6.7), this can be achieved by making the pulse width, $T_p$ in Figure 4.11.3, vary trapezoidally with time (see Problem 4.34). In a robotic application the joint processor converts the velocity error samples into equivalent values of $T_p$. This is accomplished by causing the associated control logic to command the appropriate power transistor(s) in the PWM amplifier to turn on for $T_p$ milliseconds. In view of the discussion of the preceding paragraph, faithful reproduction of the desired profile will occur only provided that the switching frequency is "high enough." This statement, in effect, implies that the frequency must be chosen so that the *sampling theorem* is satisfied.

Unlike the linear servo amplifier, there is another cause of power dissipation in a PWM device, and this places a practical upper limit on the switching frequency.

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*Recall that a periodic waveform such as a square wave can be represented by a Fourier series:

$$V_{\text{arm}}(t) = V_{\text{dc}} + \sum_{n=1}^{\infty} [A_n \cos(n\omega_S t) + B_n \sin(n\omega_S t)]$$

If this signal is passed through a *low-pass* filter network with a cutoff frequency below $\omega_S$ (and hence $n\omega_S$), only the dc term will be transmitted, and the output will be $V_{\text{dc}}$.

NO MOTION

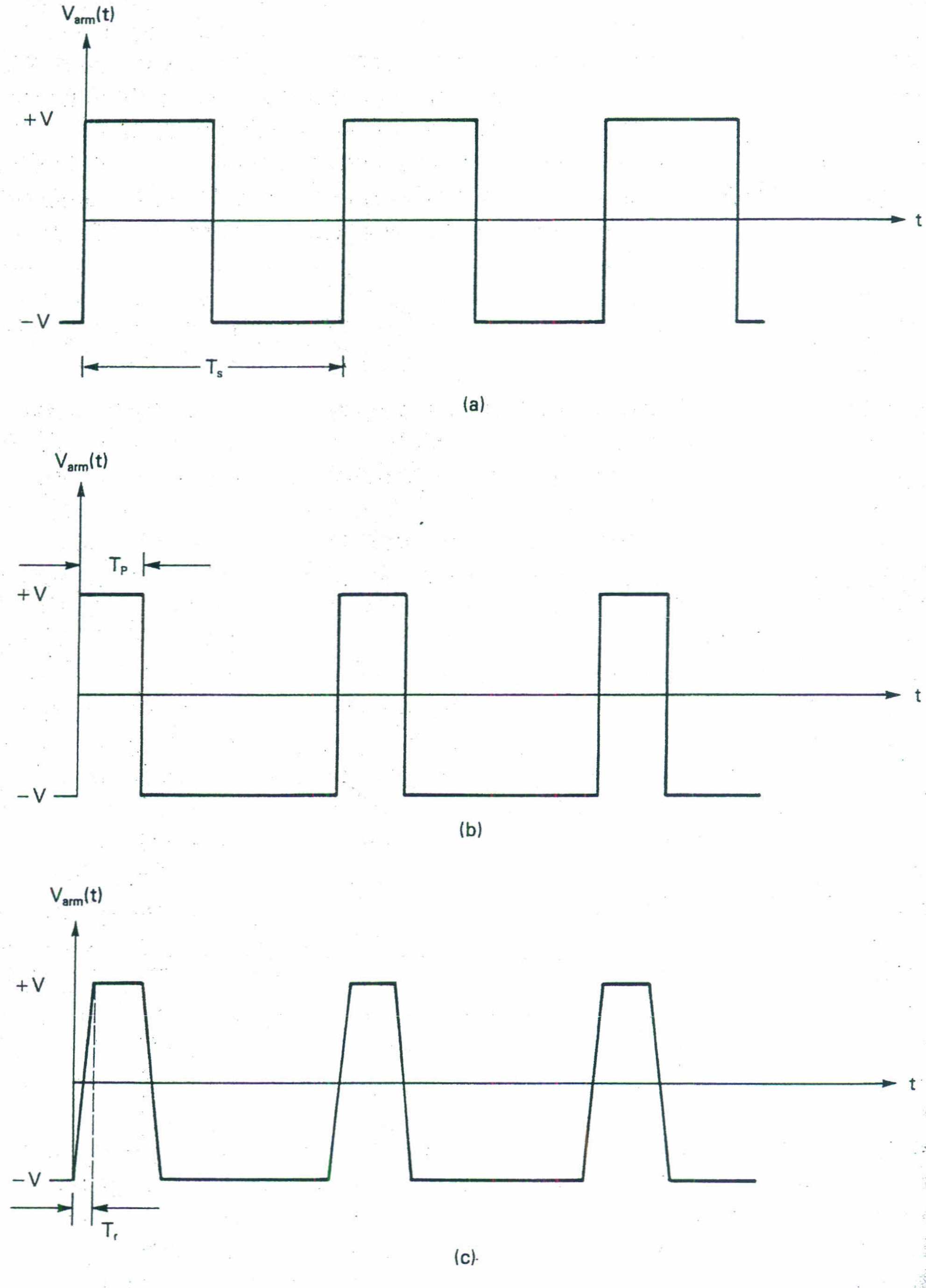



**Figure 4.11.3.** Typical PWM waveforms: (a) no load PWM output, ideal switch, $(V_{arm})_{ave} = 0$, motor does not turn; (b) loaded PWM output, ideal switch, $(V_{arm})_{ave} = -V/2$, motor turns CCW; (c) same as part (b), except nonideal switch and power transistors in active region during $T_r$.

# The Control Parameters

The PID (proportional, integral, differential) control parameters allow the controller to adapt to various conditions of operation, such as overcoming nonlinear functions in the system. The parameters are user definable, using ACL commands, in the SCORBOT-ER VII controller.

## Proportional

The proportional parameter is the gain of the control system. its value determines the reaction time to state (position) errors. When a state error exists, as measured in encoder pulses (that is, the actual motor position is off by a certain amount of encoder pulses), the processor multiplies the error by the proportional parameter and adds the product to the DAC value, thereby reducing the error. The greater the proportional parameter, the faster the sytem responds and reduces the error. But, using too great a value for the proportional parameter will cause the axis to vibrate.

The proportional parameter is the parameter in the PID control system which acts most quickly in reducing the position error, especially during motion. It is also the first parameter to respond to position errors when the robot has stopped at a target position. However, the proportional parameter cannot completely cancel the error because once it has reduced the error to a small value, it cannot generate enough power to overcome friction in the system and propel the axis to its target position.

## Integral

This parameter is the connection of the control system to the history of the control along the path. All the state errors which have been recorded every 10 ms are totalled and their value is multiplied by the integral value.

Unlike the proportional parameter, the integral parameter takes effect more slowly and is less noticeable during motion. However, when the axis comes to a complete stop and the proportional parameter can no longer reduce the steady state error, the integral parameter takes over and can cancel the error completely.

The integral parameter is able to reduce the steady state error to zero since its value increases every 10 ms, thus strengthening the control system's ability to react and reduce the error. However, using too great a value for the integral parameter may cause overshoots, while too small a value may prevent the cancellation of a steady state error.

## Example

Let's assume an ERROR of 2 encoder pulses, which the proportional parameter cannot cancel. The values of the proportional and integral parameters will develop as follows:

| | | | | |
|---|---|---|---|---|
| Time (ms) | 10 | 20 | 30 | 40 |
| Proportional | 2 | 2 | 2 | 2 |
| Integral | 2 | 4 | 6 | 8 |

The integral parameter will begin cancelling the error.

## Offset

Control theories may assume complete linearity (speed vs. power supplied to the motor).

However, at low levels of power, the motor will not move at all, mainly due to friction (that is, the static friction is higher than the dynamic friction – a non-linearity). Figure A-9 shows complete linearity and non-linearity situations.

The offset is a threshold level of the DAC. Above this DAC value the control system will act as a linear system. Below this value, the control system will act as an ON/OFF system. Figure A-10 demonstrates the offset influence.

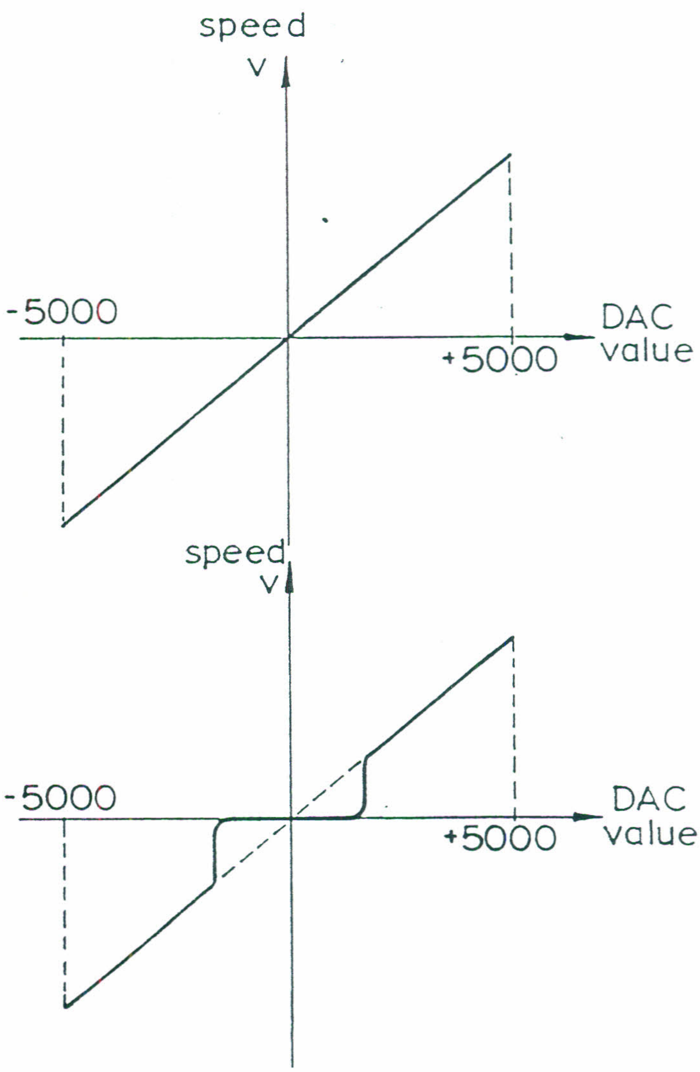



**Figure A-9: Complete Linearity in Theory: Speed vs Power**

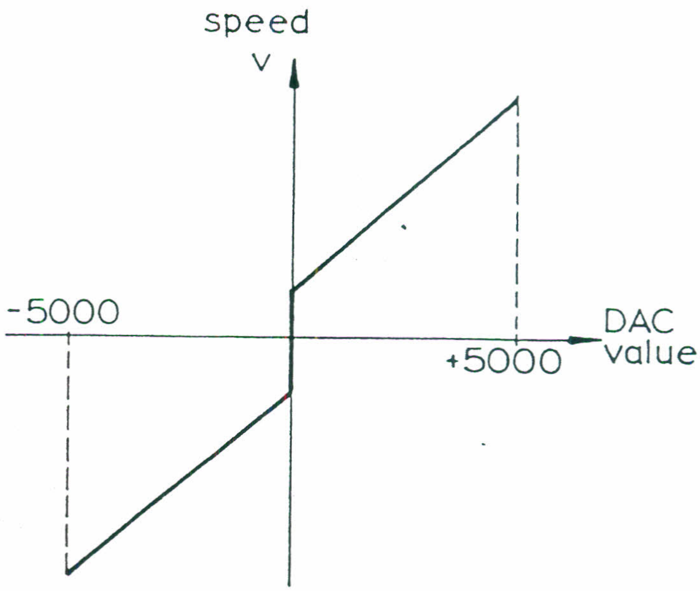



**Figure A-10: Offset in the Control System**

## Differential

The differential (or derivative) parameter is responsible for reducing the speed error along the path. The control system calculates the actual speed every 10ms and compares it to the desired value. While the robot is accelerating (during the first part of path) the differential acts as a driving factor. While the robot is decelerating (during the second, and last, part of path), the differential acts as a braking factor. A good differential setting will result in a clean and smooth motion along the entire path. Lack of the differential will cause braking motions towards the end of path. High differential values will cause small vibrations along the path and extra stiffness of the arm.

## Summary

1. Proportional Parameter

   Enables fast and powerful reactions of the arm to movement commands. Cannot eliminate small value steady state errors. Responsible for the repeatability of the motion.

2. Integral Parameter

   Assists the proportional parameter in eliminating steady state errors. Affects the time needed to stabilize in a position within the required repeatability.

KLAFTER

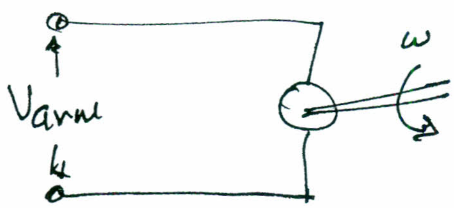
REVIEW FOR PWM

PWM P292 - LESS POWER VS. LINEAR

DC MOTOR P211 - 212

Torque $\propto$ $I_{arm}$ (armature)

SPEED $\propto$ $V_{arm}$ Eq 4.3.5 and Fig 4.3.3




$V_{ab} = +V$ CW

$V_{ab} = -V$ CCW

$V_{arm}$ IS CREATED BY A POWER AMPLIFIER (H or T type - p291)

To DETERMINE THE PWM FREQUENCY

$f_{pwm} = \frac{1}{T_s}$ Hertz fig 4.11.3 p294

Let $\omega_{pwm} = 2\pi/T_s >> \omega_E$ say $\omega_s > 100\,\omega_E = 100\,\omega_m$

BODE PLOT FOR MOTOR EQ 4.4.1 p225
FROM FIG 4.3.5 p215

MOTOR $\sim \frac{\alpha}{1 + s/44.14}$ $\omega_M = 44.14$ BW

$f_M = \frac{\omega_m}{2\pi} = 7.03\ Hz$ (p230)

So $f_{pwm} > 100 \times 7.03\ Hz$ > 1 kHz in PRACTICE

PWM

PULSES IN $\Rightarrow$ $\boxed{\text{MOTOR}}$ $\Rightarrow$ $(V_{arm})_{avg} = \frac{1}{T_s}\int_0^{T_s} V_{arm}(t)\,dt$

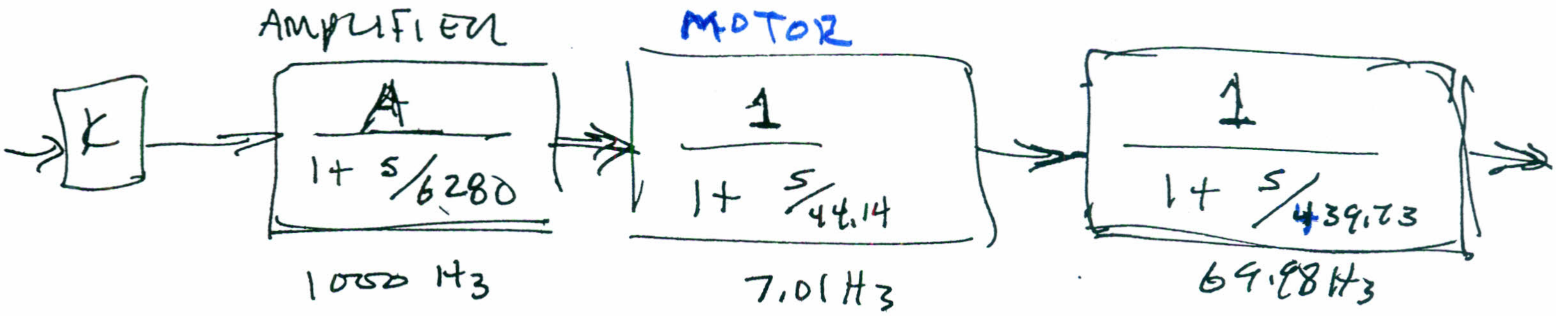
p293-K

DUTY CYCLE = $\frac{\text{TIME ON}}{T_s}$

50% $V_{arm} = 0$.
(P294-K)

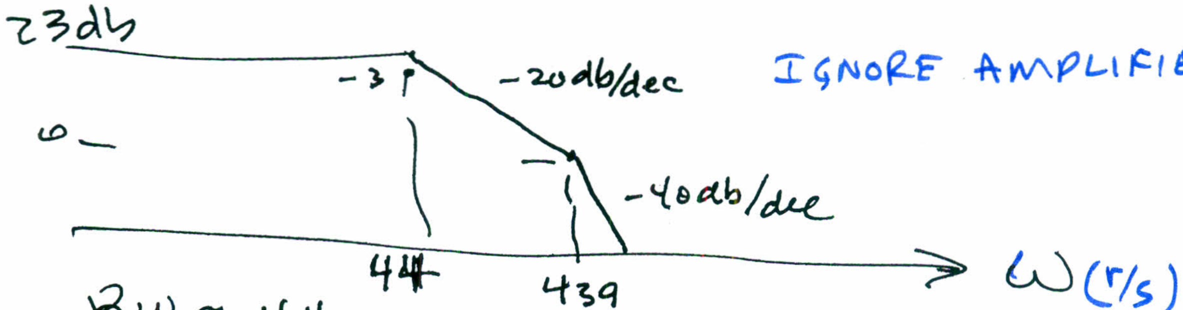
P225 – BODE PLOTS

EQ 4.4.3 FROM 4.4.1; MOTOR WITH VELOCITY FEEDBACK




BASICALLY IGNORE THE AMPLIFIER – IT IS HIGH FREQUENCY

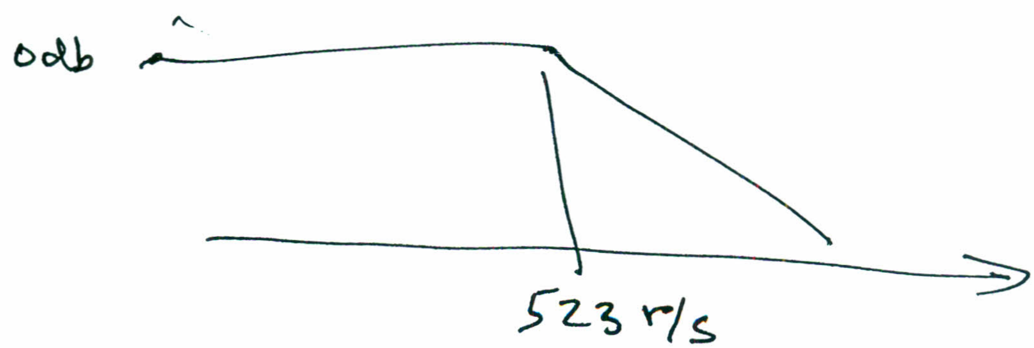
$$db = \underbrace{20\log(K_{bode})}_{23db} - \sum_{i=1}^{m} 10\log\left[1+\left(\frac{\omega}{\omega_{pk}}\right)^2\right]$$




IGNORE AMPLIFIER BW

BW ≈ 44 r/s

IN CLOSED LOOP P229 – EXTEND BANDWIDTH



plots of the magnitude and phase of the frequency transfer function versus frequency will usually reveal where the problem lies and compensation can then be added to correct it (these graphs are referred to as *Bode plots*).

### 4.4.1 Bode Plots

Let us illustrate the frequency-domain approach through the use of an example. We begin by considering the tach or velocity portion of the position servo shown
P215 in Figure 4.3.5, consisting of an amplifier and servomotor. Assuming that the amplifier bandwidth is 1000 Hz (i.e., $\tau_A = 1/6280$) and that the motor in Example 4.3.1 is used with an inertial load of 0.007 oz-in.-s² [i.e., $J_T$ in Eq. (4.3.5) is 0.0108 oz-in.-s²], the tach open-loop transfer function is given by

$$\frac{K}{\alpha s^3 + \cdots + 1}$$

$\tau_A = 1\,\mathrm{ms}$

$T_m \approx 0.14\,\mathrm{sec}$

$$GH(s) = \frac{14.1AK_g}{(1 + s/6280)(1 + s/44.14)(1 + s/439.73)} \tag{4.4.1}$$

The frequency transfer function (FTF) is obtained from this equation by substituting $j\omega$ for $s$, where $\omega$, the radian frequency (having the units rad/s) is equal to $2\pi f$ ($f$ in hertz). The magnitude of the FTF, expressed in decibels [i.e., $20 \log_{10}(|\mathrm{FTF}|)$] and its corresponding phase angle both drawn versus $\log_{10}\omega$ are called Bode plots. This is shown in Figure 4.4.1 for the tach open-loop FTF.

In Figure 4.4.1a both the straight-line approximation and the continuous plots are given for $AK_g = 1$. The former is obtained by following a set of simple rules:

1. The FTF is placed in Bode form as shown in Eq. (4.4.2):

$$GH(j\omega) = K_{\mathrm{Bode}} \frac{\prod_{i=1}^{M} (1 + j\omega/\omega_{z_i})}{\prod_{k=1}^{N} (1 + j\omega/\omega_{p_k})} \tag{4.4.2}$$

   where $\omega_{z_i}$ and $\omega_{p_k}$ are called the "break" frequencies corresponding to each of the $M$ zeros and $N$ poles of $GH(s)$, respectively. Note that the transfer function in Eq. (4.4.1) is already in Bode form.

2. The magnitude of $GH(j\omega)$ expressed in dB is then

$$\mathrm{dB} = 20 \log (K_{\mathrm{Bode}}) + \sum_{i=1}^{M} 10 \log \left[1 + \left(\frac{\omega}{\omega_{z_i}}\right)^2\right] - \sum_{k=1}^{N} 10 \log \times \left[1 + \left(\frac{\omega}{\omega_{p_k}}\right)^2\right] \tag{4.4.3}$$

Where "log" implies "log to the base 10." Note that multiple poles and zeros are permitted so that all of the $\omega_{p_k}$'s and/or $\omega_{z_i}$'s need not be distinct.

$$H(j\omega) = H(s)\big|_{s=j\omega}$$

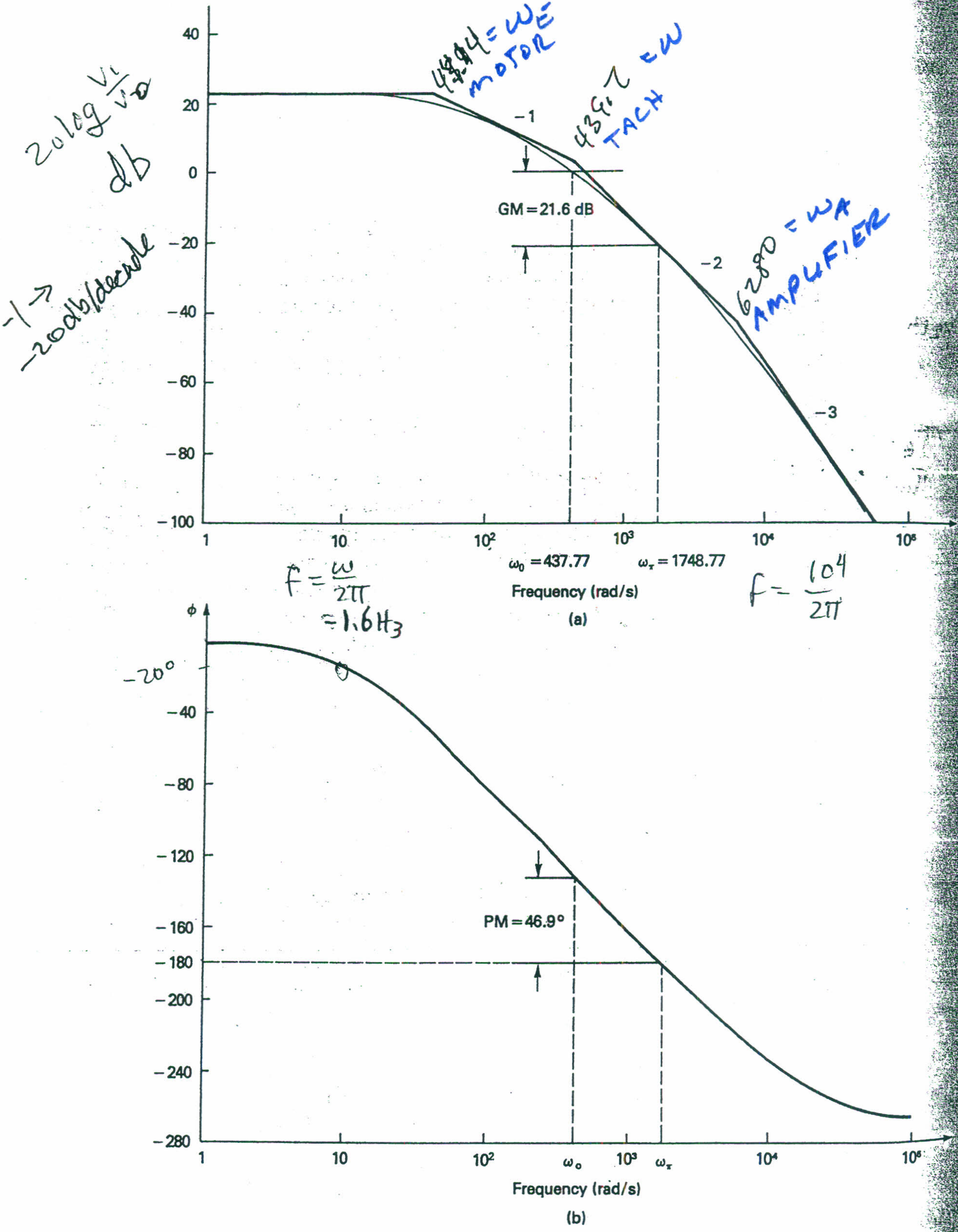



**Figure 4.4.1.** Bode plots for the open-loop tach described by Eq. (4.4.1) with $AK_g = 1$ and $K_g = 1$. The gain and phase margins are also shown: (a) magnitude (in dB) vs. $\log_{10} \omega$; (b) phase angle $\phi$ (in degrees) vs. $\log_{10}\omega$.