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FORCE ANALYSIS OF MAGNETIC BEARINGS WITH POWER-SAVING CONTROLS

Dexter Johnson and Gerald V. Brown
NASA Lewis Research Center

Daniel J. Inman
State University of New York at Buffalo

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ABSTRACT

Most magnetic bearing control schemes use a bias current with a superimposed control current to linearize the relationship between the control current and the force it delivers. For most operating conditions the existence of the bias current requires more power than alternative methods that do not use conventional bias. This paper examines two such methods which diminish or eliminate bias current.

In the typical bias control scheme it is found that for a harmonic control force command into a voltage-limited transconductance amplifier, the desired force output is obtained only up to certain combinations of force amplitude and frequency. Above these values the force amplitude is reduced and a phase lag occurs. The power-saving alternative control schemes typically exhibit such deficiencies at even lower command frequencies and amplitudes. To assess the severity of these effects, a time history analysis of the force output is performed for the bias method and the alternative methods. The frequency content of the actual force is compared to that of the commanded force. A Fourier series representation is used with a concentration on the fundamental frequency component, which is necessary to evaluate the stability of the resulting closed loop system. Results of the above analysis show that the alternative approaches may be viable.

The various control methods examined here were mathematically modeled using nondimensionalized variables to facilitate comparison of the various methods. For example, values of critical frequency, which is the lowest frequency at which a force deficiency occurs, can be compared.

INTRODUCTION

The present operation of magnetic bearings involves the standard usage of bias current in addition to a superimposed control current. This linearizes the relationship between the control current input and the force output of the magnetic bearing. With the existence of the bias current, even in no load conditions, there is always some power consumption. In earthbound applications of magnetic bearings this constant power loss may not be of critical importance but in aerospace applications it becomes an important concern.

In this paper two alternative control methods will be examined and compared with the bias method. Primarily, we will be looking at the nonlinear aspects of the magnetic bearing and its controls (see [1-2]). The controls that are proposed are designed to reduce the power loss effect of bias while continuing to provide satisfactory control performance. Research into the limitations of the performance of conventional magnetic bearings, due to their nonlinear nature, has been reported in [3]. Peak force capacity and force slew rate limitation are examples of the phenomena that are encountered when the performance of magnetic bearings is pushed to extreme conditions. Peak force capacity is primarily due to the limitation of the current of the magnetic bearing power supply and the force slew rate limitation is mostly due to the limiting rate at which current to the magnetic bearing can be changed because of power supply voltage limits.

The nonlinear nature of the magnetic bearing due to operational limitations such as a saturated voltage supply, as opposed to the inherent nonlinear relationship between force output and current, can be observed by examining the force response or output for a given amplitude and frequency of control current input. Specifically, for a given frequency, if the output amplitude is not proportional to the input amplitude then the system has some type of nonlinearity present. Here we examine the frequency content of the force output obtained (as opposed to desired force output) for a current command input with varying frequency and amplitude. By doing so we obtain the degree of force output distortion, if any, and its implications on stability. We also show that in comparison to the conventional bias method the alternative methods perform satisfactorily with a saving in power consumption.

Conventional Bias Operation

In Fig. 1 there is shown a general diagram of a magnetic bearing. It involves two electromagnets situated on opposite sides of the levitated or attracted object (usually a rotor). Each electromagnet has a magnetic core which is wound with electrically conducting wire. When current flows through the coils a magnetic force of attraction is produced. Two opposing magnets constitute a force actuator for that axis (in the figure it is shown as the x axis) and allow one dimensional positioning of the attracted object.

The magnetic bearing system is an inherently unstable one. This is because the attractive force generated by the magnetic bearing increases as the distance between it and the attracted object decreases; thus the system behaves like a nonlinear spring-mass system with negative spring constants. Therefore, an electronic control system must be used with the bearing to provide stability. Typically, proportional-derivative control is used.

The basic force relation for a single coil is given by

$$F = K(I/g)^2 \quad (1)$$

where F is the attractive force, K is a constant (for nominal operational conditions) that depends on the magnetic flux, number of coil turns, magnetic reluctance, and other parameters related to magnetic properties (see [3]), I is the current in the coils, and g is the air gap distance between the magnet poles and the attracted object.

For the bearing shown in Fig. 1 with two electromagnets, the net force on the attracted object is

$$F_{net} = K[(I_1/g_1)^2 - (I_2/g_2)^2] \quad (2)$$

where the subscripts denote a particular magnet and its variables. It should be noted that typically there is another set of electromagnets situated along the vertical axis allowing two-dimensional positioning of the object. Our focus here is on the one-dimensional operation; the analysis applies to both axes if examined independently.

The relationship between the current in the coils and the resulting force by the bearing is clearly nonlinear. It is preferred, when implementing control systems, to have a linear system such that classical linear control methods may be used. This is desired due to the difficulty in controlling nonlinear systems. To convert the net force-current relationship into a linear one it is very common to introduce a bias current control mode of operation. This mode of operation involves having the current that flows in the coils of the opposing magnets consist of two parts. This is accomplished by the following method.

$$I_1 = I_b + I_c \quad (3)$$

and

$$I_2 = I_b - I_c \quad (4)$$

where I_b is the bias current, which has a constant value, and I_c is the control current which can be fluctuated as desired. The result is a net force from the two opposing magnets which is directly proportional to the control current, i.e.

$$F_{net} = K_1 I_c \quad (5)$$

where K_1 is a constant which is dependent on K and I_b.

This mode of operation is acceptable for earthbound application but for space applications the concern for power savings becomes increasingly important. The ever present bias current produces a constant power loss. It is one of the objectives of this research to investigate other possible operational modes which will minimize or eliminate excessive power loss due to the bias effect. Presented here will be an analysis of the effect on the force output of the magnetic bearing for some proposed power-saving controls.

NONDIMENSIONAL VARIABLES

The operation of magnetic bearings involves additional hardware which affects its performance, such as power supplies, transconductance amplifiers, sensors, and the rotor (i.e. the plant). Here we consider only the magnetic bearing with a transconductance amplifier and a voltage limited power supply. The following simple circuit relationship is obtained:

$$L\frac{dI}{dt} + IR = V \qquad (6)$$

where L is the coil inductance of the magnetic bearing, R is the lumped resistance of the circuit, dI/dt is the time derivative of I, which is the current, and V is the voltage applied to the circuit by the transconductance amplifier. If the output voltage does not reach its limits, this equation can be used to find the voltage required to produce a commanded current. On the other hand the commanded current and its derivative may require more voltage than is available. The equation can then be integrated with respect to time to find the actual current, which will differ from the commanded current as long as the voltage is at its limit. This equation was nondimensionalized by using the parameters L, R, a nominal bias current equal to half the maximum allowable current, I_b, and the limiting voltage value of the power supply, V_{max}. Specifically, we define the nondimensional variables, $v \equiv V/V_{max}$, $i \equiv I/I_b$, $\beta \equiv R/(V_{max}/I_b)$, and $\tau \equiv [V_{max}/I_b L]t$.
The final result is

$$\frac{di}{d\tau} + \beta i = v \qquad (7)$$

which is the nondimensional equation used for simulation.

SIMULATION

In a typical biased operation for a given v, Eqn. (7) can be solved to yield the current, i. If the current is known the force output can be determined from Eqn. (2). We have used a computer solution method in which v is a feedback function related to the difference between the desired force and the actual force. The method of solution is analogous to a control loop that uses force feedback. A computer simulation was performed where the desired force is a cosine function with an amplitude of I_{max}^2 (the maximum allowable current in the coils, squared) equal to four and zero phase. Throughout this paper we consider only commanded force of a single frequency. The actual force is determined by the currents produced via Eqn. (7). The voltage demanded is proportional to the difference of these two forces. The result of this simulation is shown in Fig. 2 for a frequency ratio (as will be defined below) of 0.6 which does not cause the voltage to reach its limits (the time variable has been normalized by using the cycle period of the commanded force for the abscissa in all force, current and voltage simulations). It shows the time history of the currents in each opposing magnet along with the net force and the voltage supplied (demanded). Current in magnet 2 is plotted as negative as a convenience in all similar figures. If the voltage demanded is greater than that which the power supply can deliver then the desired force output will not be achieved. The occurrence of this phenomenon appears at a particular value of desired cosine force frequency for a fixed amplitude. This frequency will be defined as the critical frequency and it must be specified with an accompanying force or current amplitude level. Additionally, the frequency ratio will be defined as the ratio between the force command frequency and the critical frequency. A simulation for a frequency ratio of 1.2 and which causes voltage limited operation, is shown in Fig. 3.

ALTERNATIVE CONTROL SCHEMES

As discussed previously, the level of current used in the operation of the magnetic bearing gives an indication of the power loss that would be observed. With current flowing in the two opposing magnets at all times there will always be a power loss. If we can operate one magnet at a time or decrease the period of time that they operate together, a power saving can be realized, the coils will run cooler and rotor heating from eddy currents and hysteresis will be reduced.

In method A below we simulate a strategy in which (for a cosine commanded force) magnet 1 is requested to produce all the force f for f greater than zero and magnet 2 for f less than zero. Lagging response will be seen to occur near f equal to zero because of voltage railing (saturation). The lag is reduced in method B, which anticipates the zero crossing of force, by initiating current in the opposing magnet when the voltage applied to the operating magnet reaches its limit.

Method A

In this method, for one cycle of desired (commanded) force, we command enough current (according to Eqn. (1)) in magnet 1 to produce the desired force when that force is positive and current in magnet 2 when that force is negative. Thus magnets 1 and 2 are not intended to operate concurrently. Unfortunately due to the inductive effects in the coils, there will be some current flowing in both magnet coils for a small duration of time. The simulation of this mode of operation, for a frequency ratio of 0.5, is shown in Fig. 4. The current in magnet 1 produces the commanded force until the amplifier voltage reaches its negative limit. Thereafter the force does not decrease as rapidly as desired. Furthermore the buildup of negative force (i.e. force directed towards magnet 2) is not as rapid as requested because the voltage for magnet 2 rails immediately upon start-up.

This method has actually been used to suspend a very flexible rotor through two critical speeds.

Method B

In this method, for one cycle of current demanded, the current in the coils of magnet 2 begins to flow when the voltage required by magnet 1 reaches its maximum negative value equal to the voltage limit of the power supply. The operation of magnet 1 ceases when the current through its coils becomes zero. When magnet 2 demands the maximum positive voltage the current in magnet 1 again begins to flow. The simulation of this method, with a frequency ratio of 0.5, is shown in Fig. 5.

FORCE ANALYSIS

It is desired of the magnetic bearing to produce a force in accordance with a given control criterion. When there is a voltage limitation due to frequency and amplitude modulation the desired force output may not be obtainable and some distorted response is obtained instead. Therefore, our main focus here is to examine the effects of the resulting force deficiency.

The method of examination involves looking at the describing function (see [4,5]) representation of the force output. This method is an extended version of the frequency response method for linear systems and is designed to approximately analyze and predict nonlinear behavior. The concept which underlies this method is that a steady-state sinusoidal input into a nonlinear element will produce an output that has components of the same frequency as well as its harmonics. Describing function analysis focuses on only the fundamental component. It relates the amplitude and phase of the fundamental component of the nonlinear element's output to the amplitude and phase of the sinusoidal input. Using this method involves acquiring the Fourier series representation of the nonlinear element output response. The Fourier series analysis assumes for an input of

$$x(t) = A\sin(\omega t) \tag{8}$$

that the output y(t) can be expressed as follows

$$y(t) = A_0 + \sum_{n=1}^{\infty} A_n\cos(n\omega t) + B_n\sin(n\omega t) \qquad (9)$$

which can be written as

$$y(t) = A_0 + \sum_{n=1}^{\infty} Y_n\sin(n\omega t + \phi_n) \qquad (10)$$

where

$$A_n = \frac{1}{\pi}\int_0^{2\pi} y(t)\cos(n\omega t)\,d(n\omega t) \qquad (11)$$

$$B_n = \frac{1}{\pi}\int_0^{2\pi} y(t)\sin(n\omega t)\,d(n\omega t) \qquad (12)$$

$$Y_n = \sqrt{A_n^2 + B_n^2} \qquad (13)$$

$$\phi_n = \arctan\frac{A_n}{B_n} \qquad (14)$$

For the describing function analysis only the first terms are of interest. Consequently, this results in revealing output magnitude and phase versus command input frequency. There is an interest as to whether higher harmonics due to the deficiency in force can affect the control properties of the magnetic bearing as a force actuator, but for now we investigate only the fundamental effects. This analysis helps in comparing the different methods and thus yields information as to whether the power saving methods are viable in comparison to the bias case.

In Fig. 6 the magnitudes and phases of the describing functions are shown. For the bias method there is no decrease in output magnitude for low frequency ratio. As the frequency ratio increases and surpasses the critical frequency, a decrease in output magnitude is observed. As the frequency ratio approaches the high end of the frequency spectrum the slope of the response appears to become constant. There is no phase lag below the critical frequency ratio (numerical inaccuracy causes the small value shown in the figure). As the frequency ratio increases beyond the critical frequency ratio the phase lag increases. As the frequency ratio progresses even further the slope of the phase lag tends to level off at some constant value.

For method A the magnitude is approximately constant at the low end of the frequency spectrum as in the bias method but there is an earlier initiation of magnitude fall-off which is prior to the bias critical frequency. (For comparison sake, all references to the critical frequency in the analysis to follow will be to the bias critical frequency, which is defined for the maximum allowable current amplitude. It is shown below that the other two methods always have force distortion; thus a critical frequency of zero.) As the frequency increases the magnitude continues to decrease until it begins to level off for high frequency ratios. The phase increases in a smooth and continuous fashion for low frequency ratios.

The magnitude and phase for Method B behave like those of Method A but the magnitude fall-off and phase lag are less than those for method A for all frequencies.

COMPARISON OF RESULTS

The operation of the magnetic bearings under the various methods examined here is similar. The differences are primarily the magnitudes of the effects and not the qualitative characteristics. All of the methods introduce phase lag and magnitude fall-off. The range of their occurrence is for all operation frequencies for Methods A and B and beyond the critical frequency for the bias method. Deviations from ideal behavior of the bias method phase and magnitude begin abruptly at the critical frequency ratio while for the other methods, the magnitudes and phases vary in a smooth and continuous manner. The bias method shows no variation of magnitude or phase below the critical frequency. This indicates that no force deficiency is present in this operation range. The other methods always distort the force output but for low frequencies this effect is small. The bias method yields the lowest distortion throughout the spectrum whereas Method A shows the most.

More specifically, on the low end of the frequency ratio spectrum (less than 0.4) the magnitudes of all the methods vary very little from each other, but there is a slight separation in value of phase lag between Method A and the other methods with all methods having less than 5 degrees of phase lag introduced. For the region of critical frequency between 0.4 and 1.0 the differences between the methods become very pronounced. The magnitude ranges from a value of 4.0 for bias down to 2.7 with Method A obtaining the lowest value. The introduction of phase lag for this range varies from 0 to 26 degrees. After the critical frequency the rates at which the magnitude fall-off and phase lag occur appear to be similar for all methods although the values are different due to the differences which occur at lower frequency ratios.

Command Amplitude Variation

The describing functions obtained from reducing the amplitude of the current flowing in the magnets coils to half the maximum allowable amplitude is shown in Fig. 7 for the various methods. It shows that there is no force distortion for the bias method for the given range of frequency ratios. This is because the voltage supplied is never above its limiting value. Therefore, the bandwidth of the bias method is increased and force distortion is delayed to a higher frequency ratio (not shown in the figure).

For method A and B the describing functions show much less magnitude fall-off and phase lag than for the higher command force amplitude. As for the effect in the bias case, it results in increasing the bandwidth of operation, and broadens the range where no force distortion occurs. Once again, method A has the greatest force distortion over the given frequency ratio range of all the methods and bias, the least.

The magnitudes at the critical frequency ratio range from about 1.0 to 0.95 and for a frequency ratio of 2.0 from about 1.0 to 0.7. For phase lag the range is 0 to 5 degrees at the critical frequency ratio and 0 to 27 degrees for a frequency ratio of 2.0.

DISCUSSION OF RESULTS

The results show that the methods proposed as power-saving controls operate using less current than the commonly used bias method but have qualitatively similar effects on force output. The bias has the definite advantage over the other methods from a linear controls viewpoint in that it has a particular operating range where the force output is not distorted. The force distortion produced in methods A and B possibly can be tolerated and may be of little consequence for some range of operation frequencies.

The most viable method of the two proposed methods is clearly method B. At frequency ratios below 1.0 for the maximum current amplitude case the magnitude decreases no more than seven percent and even more importantly the phase lag is no more than 10 degrees. These deficiencies are not of great magnitude. Method A is not as viable as method B but for smaller ranges of operation frequencies it too can be used without appreciable decline in performance while still saving power.

The power saving that is realized is qualitatively evident by examining the amount of current flowing in the coils of the magnets. In the bias case, control current is flowing in both magnets almost all the time, in addition to the ever-present bias current. In method A current is commanded in only one magnet at time, but inductive effects cause some overlap. In method B simultaneous currents are actually commanded during a portion of a cycle. Since power loss is related to current, method A would have the least power loss, method B would be next and the bias method would have the greatest.

Implications as to the effects on stability primarily lie within the amount of phase lag produced. With increased phase lag, stability may deteriorate. The extent of its effect can only be determined from the analysis of the closed loop system with the magnetic bearing and the proposed controls considered here as elements of the system. The relative comparison of the amount of phase lag for each method has been shown.

In conclusion, the specified methods show some ability to provide alternative power-saving modes of operation in comparison to the widely used bias method. Other limitations not considered here, such as harmonic production, may need to be included in future analysis. Future work will involve proposing and evaluating other alternative methods with more quantitative analysis, e.g. calculated power loss, effect of force harmonics, and response to nonsinusoidal force commands.

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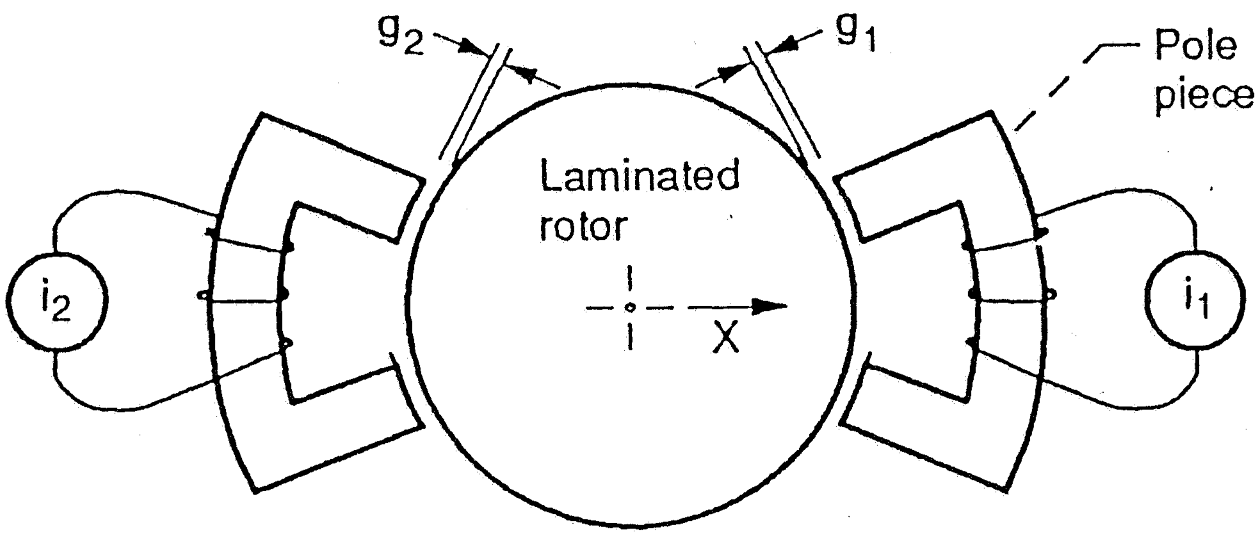
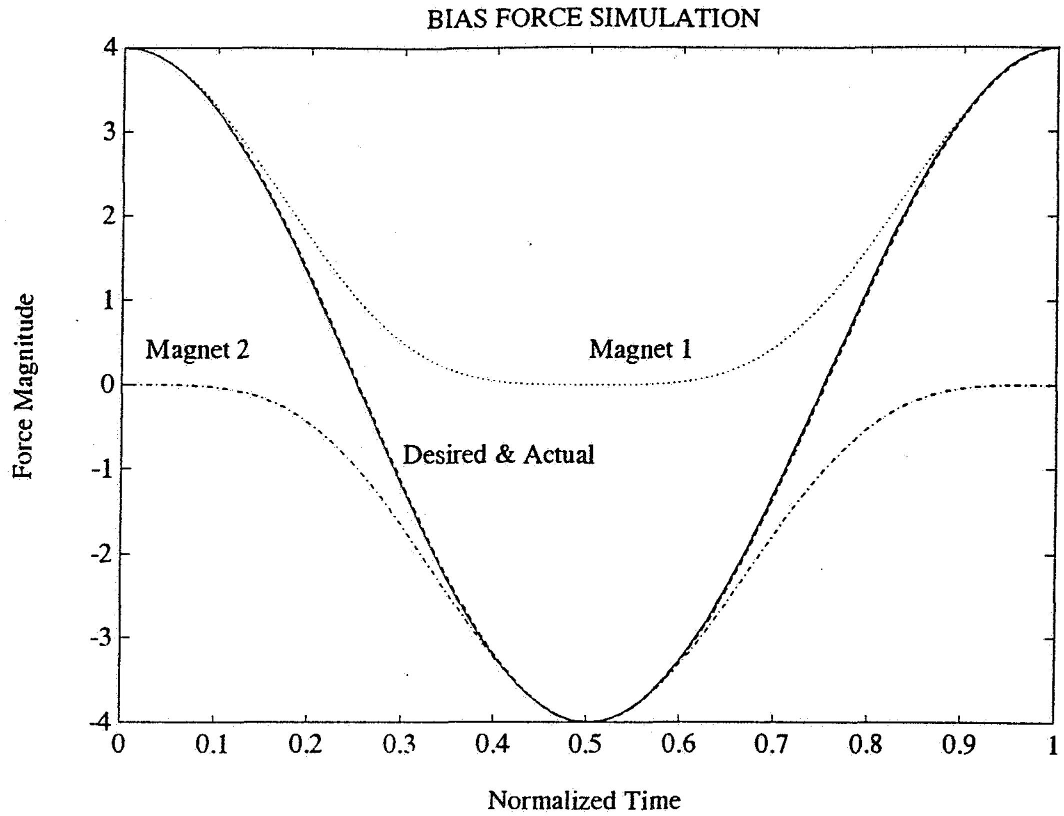
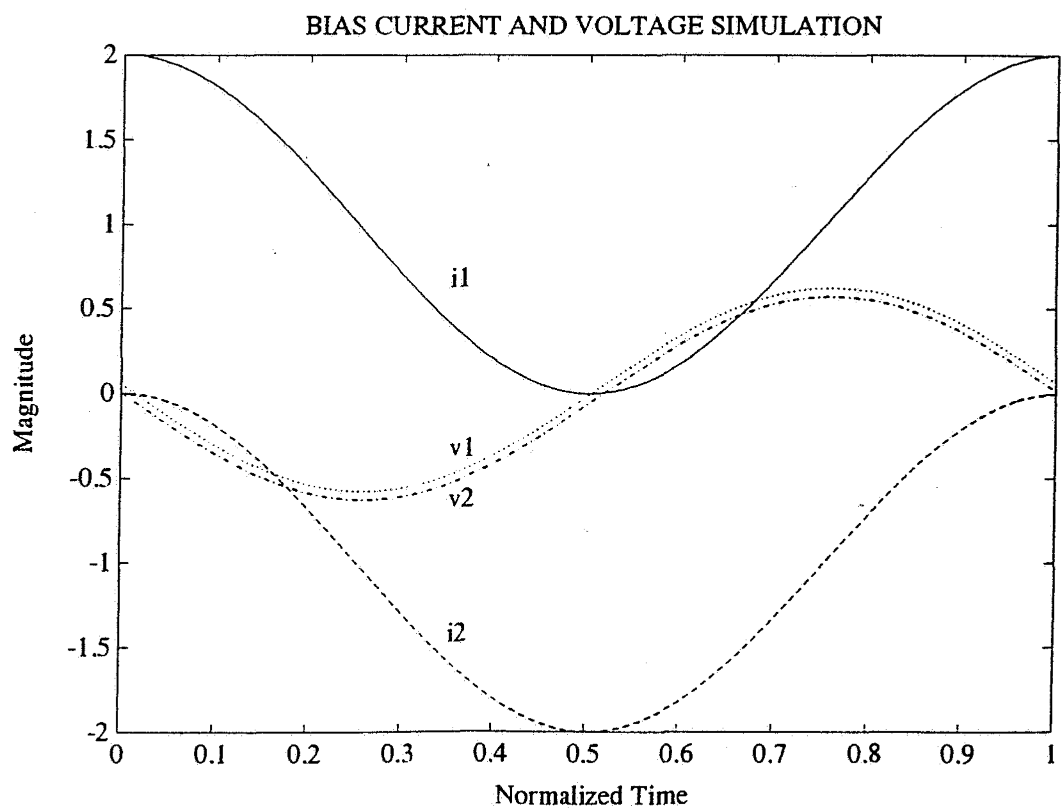
MAGNETIC BEARING

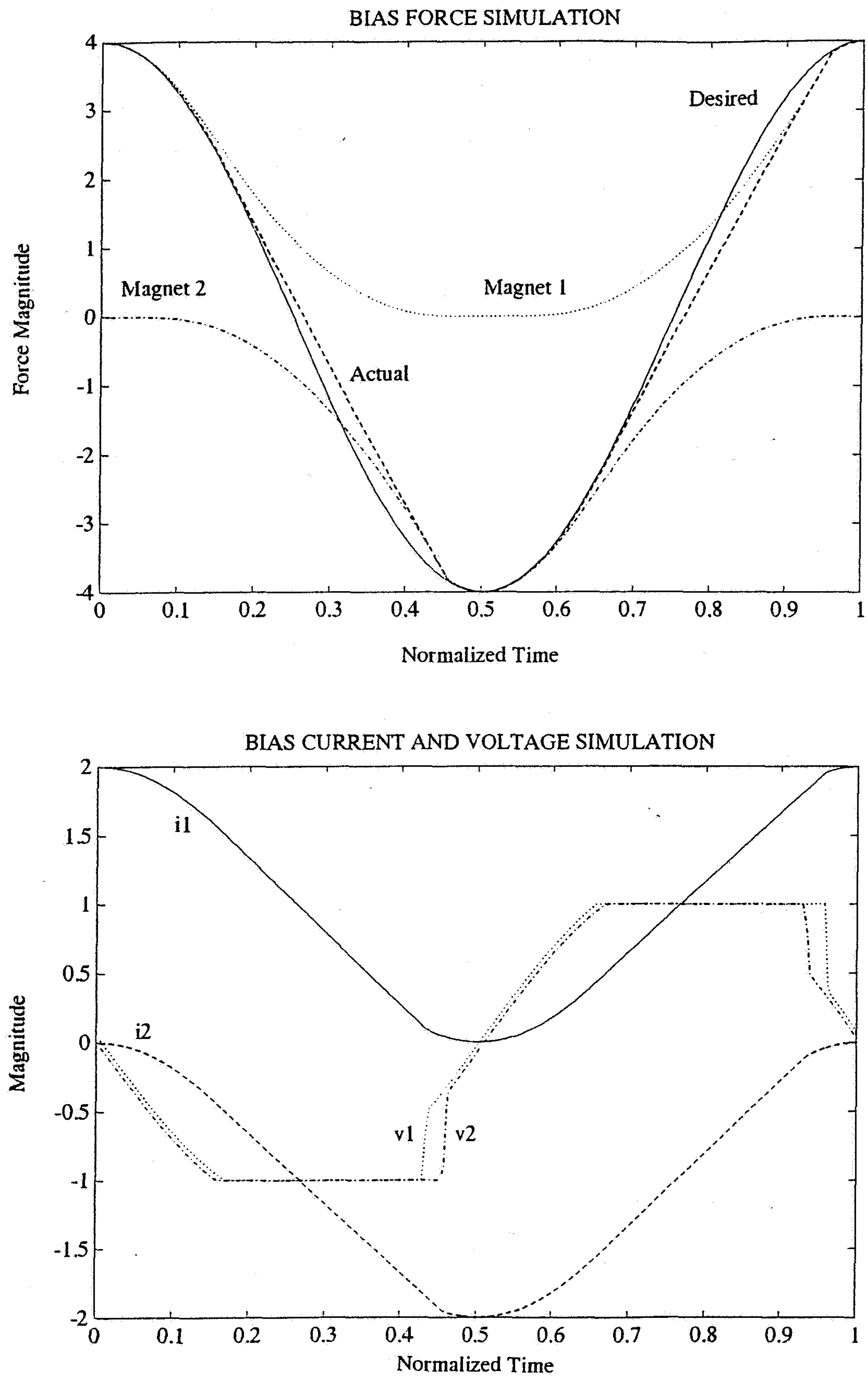


1. Diagram of magnetic bearing components operating along a single axis.

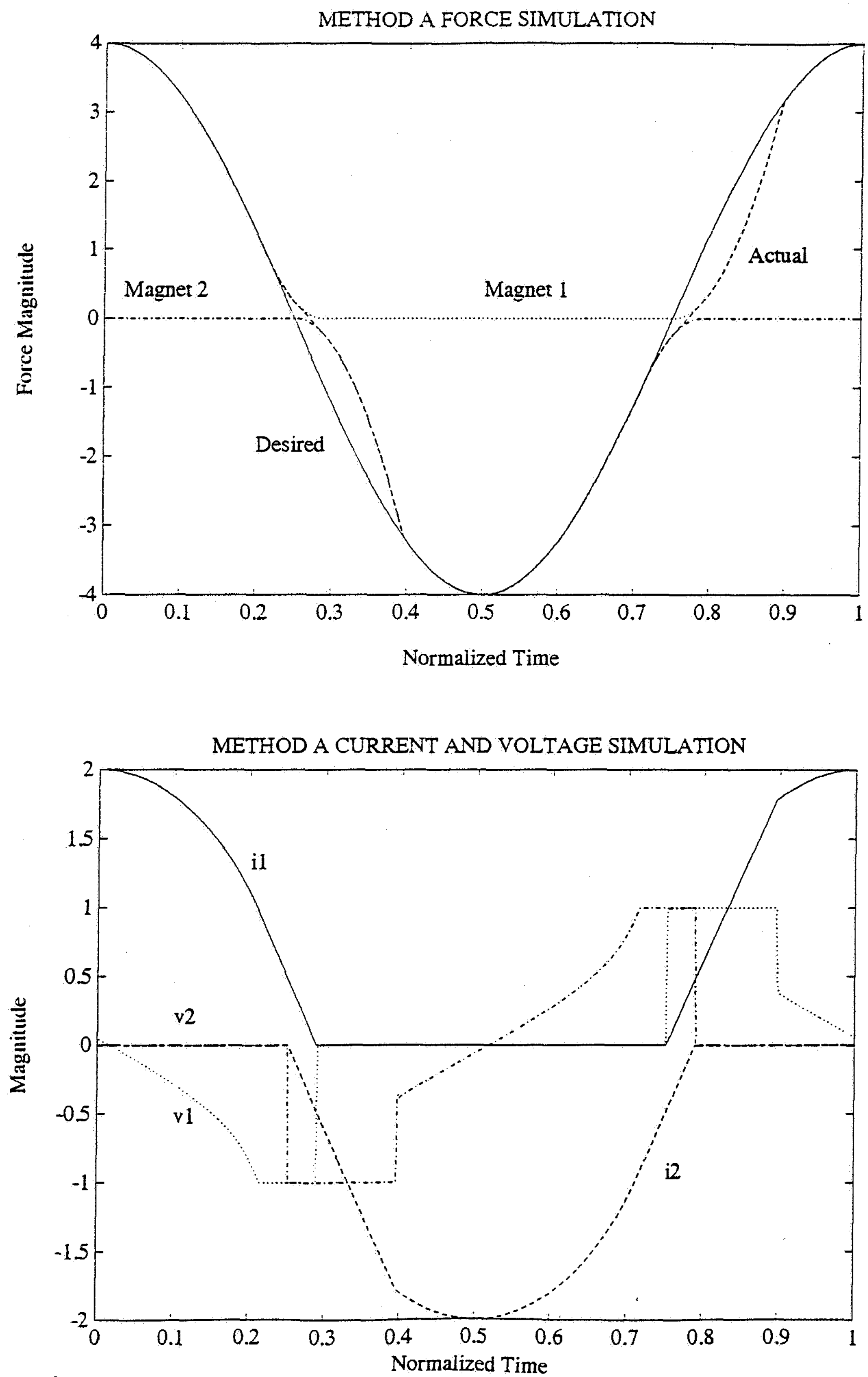




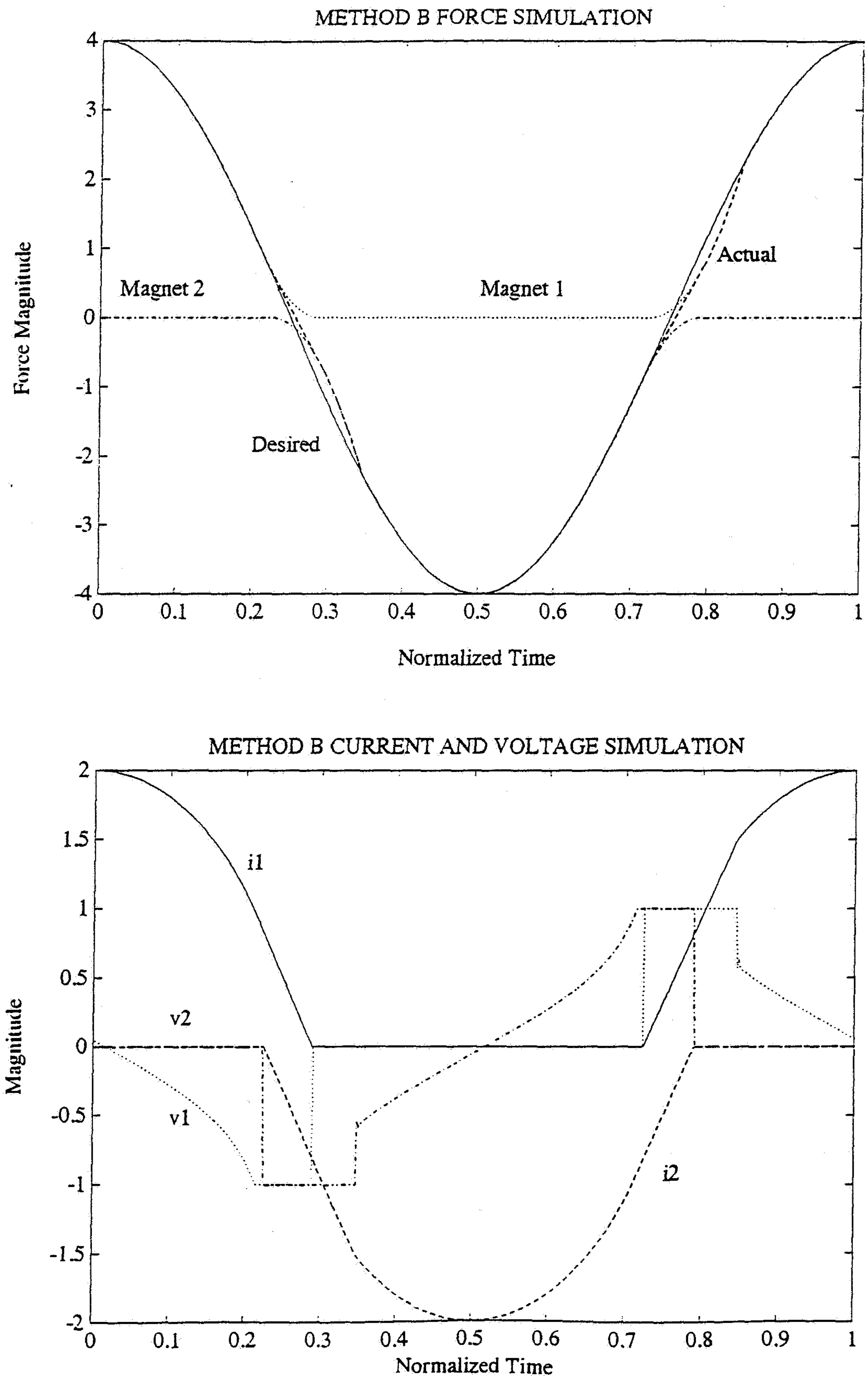
2. Simulation of Bias method for a frequency ratio of 0.6 showing a.) force magnitude and b.) current and voltage magnitude.



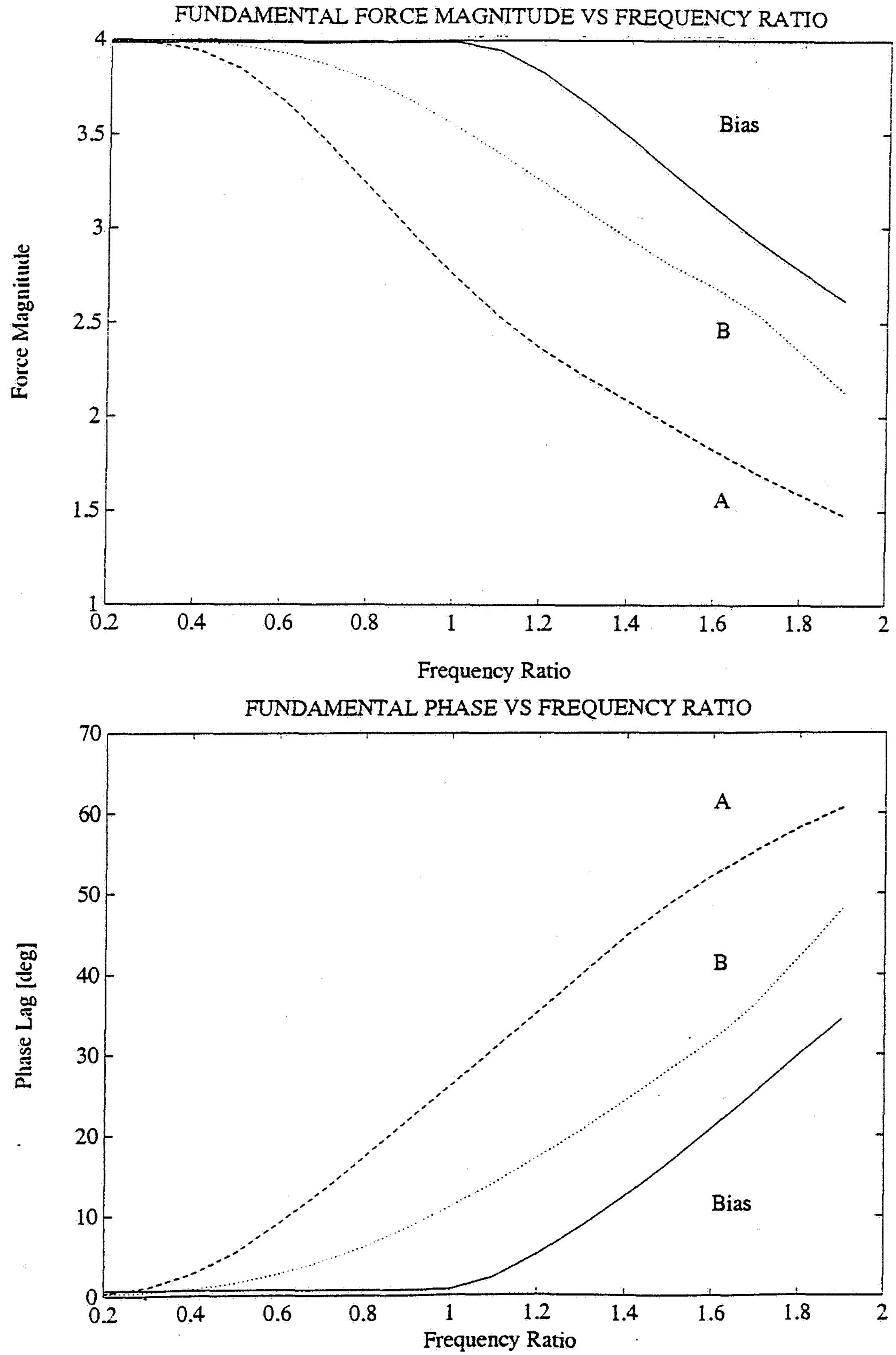
3. Simulation of Bias method for a frequency ratio of 1.2 showing a.) force magnitude and b.) current and voltage magnitude.



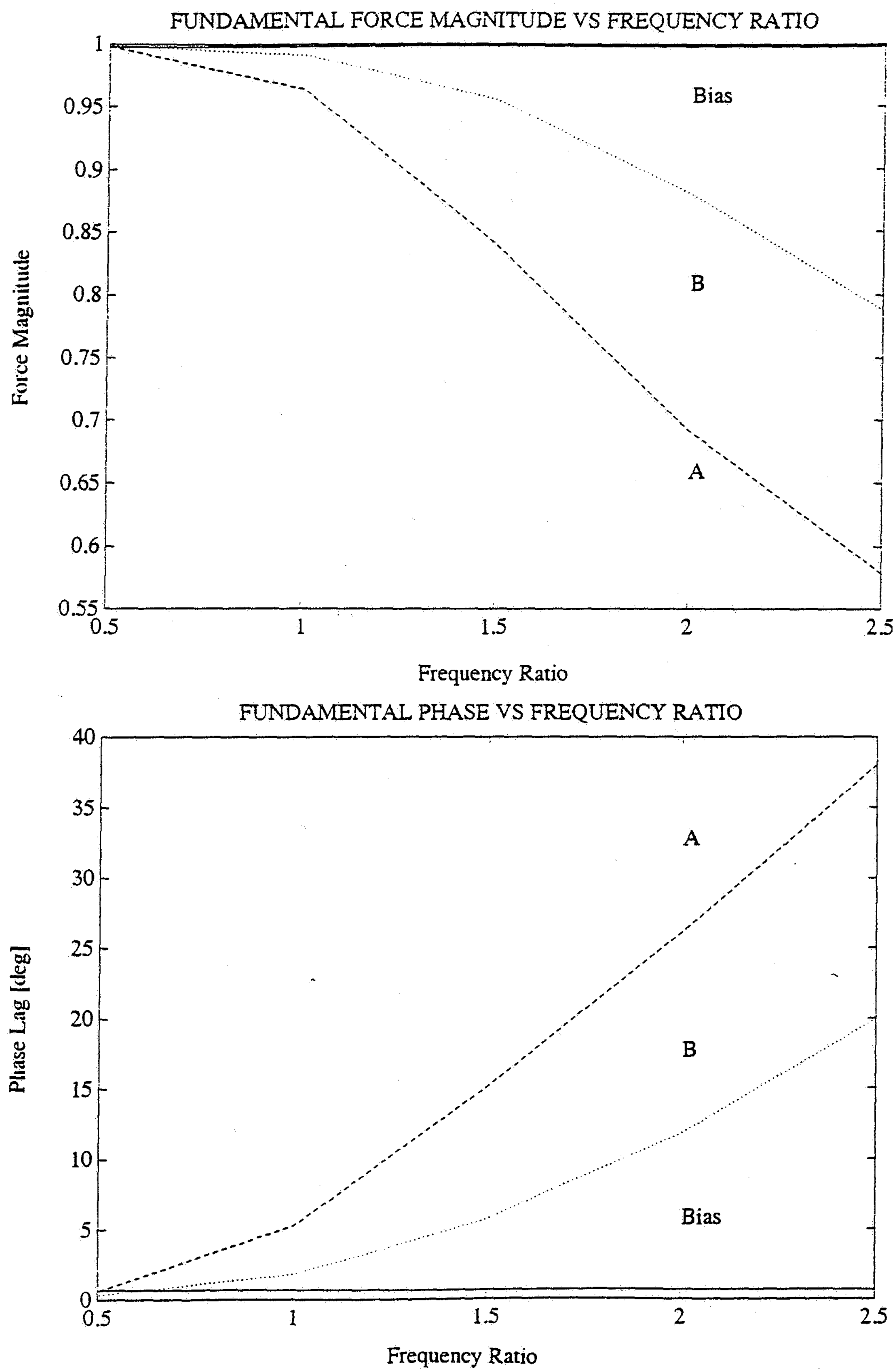
4. Simulation of method A for a frequency ratio of 0.5 show ing a.) force magnitude and b.) current and voltage magnitude.



5. Simulation of method B for a frequency ratio of 0.5 showing a.) force magnitude and b.) current and voltage magnitude.



6. Describing function for method A, B, and the Bias method for a maximum desired force amplitude of 4., showing a.) the fundamental Fourier series component magnitude and b.) the fundamental Fourier series component phase.



7. Describing function for method A, B, and the Bias method for a desired force amplitude of 1., showing a.) the fundamental Fourier series component magnitude and b.) the fundamental Fourier series component phase.

Session 11

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