AN INVESTIGATION OF MOTORCYCLE BRAKING CONTROL GAINS

by

R.G. Juniper

M.C. Good

Department of Mechanical
and Industrial Engineering
University of Melbourne

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Author(s)

R.G. JUNIPER

M.C. GOOD

Performing Organisation (Name and Address)

DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING,
UNIVERSITY OF MELBOURNE,
PARKVILLE, VIC, 3052.

Sponsor (Name and Address)

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Abstract

A pilot experimental investigation was made of the effect of motorcycle brake control gains on rider subjective opinion and objective performance in emergency stopping manoeuvres. A variable braking control gradient (VBCG) motorcycle was developed for the experiment, which allowed independent variation of the force and displacement control gains of the front and rear wheel brakes. Development of the VBCG system was preceeded by a comprehensive investigation of the braking performance characteristics of three production motorcycles.

KEYWORDS: Motorcycles, Braking Systems, Vehicle Dynamics Modelling, Pedal Force, Pedal Travel.

NOTES:

(1) ORS research reports are disseminated in the interests of information exchange.

(2) The views expressed are those of the author(s) and do not necessarily represent those of the Commonwealth Government.

(3) The Office of Road Safety publishes two series of research reports
  (a) reports generated as a result of research done within the ORS are published in the OR series;
  (b) reports of research conducted by other organisations on behalf of the ORS are published in the CR series.

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CONTENTS

0. EXECUTIVE SUMMARY

INTRODUCTION

This report documents work performed in the second phase of a two-phase research project concerned with braking, stability and handling of motorcycles. Phase I of the project, a literature and research review*, was directed at surveying the state of knowledge, isolating problem areas and recommending priorities for further research. As a result of this review, an investigation of some ergonomic aspects of motorcycle braking control was initiated as Phase II of the project.

The physical performance of motorcycle braking systems has been the subject of both scientific study and government regulation in recent years. The task of applying the brakes on a motorcycle during an emergency stop is quite demanding, requiring as it does the independent modulation of front and rear braking effort so as to avoid wheel lock-up and consequent loss of directional control. However, very little information is available in the literature as to how the difficulty, or otherwise, of the braking task is related to the braking system characteristics. The motorcycle accident literature shows that riders typically do not make full use of the braking capacity of their machines, the front brake being especially under-utilized. In view of this, and the relatively high frequency and severity of motorcycle accidents, it was concluded in Phase I of this study that the relationship between brake system "feel" properties and rider/cycle braking performance is a matter requiring investigation at a high priority. Accordingly, in

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* Juniper, R.G. and Good, M.C., Braking, Stability and Handling of Motorcycles. Australian Department of Transport, Office of Road Safety, Report CR 29 (1983).

Phase II, an experimental study was undertaken, aimed at identifying the most important vehicle parameters affecting the "braking quality" of motorcycles and quantifying the effect of these parameters on both objective measures of rider/cycle braking performance and riders' subjective ratings of braking quality.

To enable the experimentation to be performed efficiently, a variable brake control gradient (VBCG) motorcycle was developed. The investigations of the response characteristics of some production motorcycles, and the means by which the main features of these responses were made variable in the VBCG motorcycle, are described in this report. A simple mathematical model of the brake system which accounts for the main response characteristics is also developed. Finally, a pilot study, in which two experienced riders performed a number of braking tasks with the VBCG motorcycle is described.

INVESTIGATION OF BRAKE RESPONSE PROPERTIES

To allow the design of a VBCG motorcycle to proceed, information on the dynamic response properties of production motorcycle brake systems was required so that the important features of these responses could be reproduced and varied independently. Although useful data on braking system components have been reported previously, it was necessary to undertake an experimental and analytical investigation in order to gain an understanding of the complete system dynamic responses. It should be noted that, to reduce the scope and hazards of this study, braking under dry weather conditions only was considered. Although wet weather braking is considerably more difficult, it seems that comparitively little riding is in fact done in the wet.

Three motorcycles, of 250, 400 and 750 ml engine capacity, were selected for investigation. All the machines were equipped with hydraulically-operated, single, stainless steel disc brakes, except for the rear wheel of the 400 ml motorcycle, which was fitted with a single leading-shoe, lever-operated drum brake. The disc pads on the 250 ml machine were of the sintered metal "all weather" type; all the remaining pads were the conventional organic type. It was thought that the variations in machine size and brake type could yield some interesting contrasts in dynamic behaviour.

The motorcycles were instrumented to measure forward speed, hand and foot brake lever input force and displacement, main-frame deceleration and pitch rate, and suspension deflections. Signals from up to eight transducers could be simultaneously conditioned, encoded and recorded with a light-weight data acquisition system which replaced the normal fuel tank on the motorcycles.

The data acquisition system was developed for this and a companion DoT study*. In the system the eight channels of data were encoded into a serial stream of clock-synchronized pulses, using a time-division multiplexing scheme, for recording on a high-quality, portable audio cassette tape recorder. Decoding circuitry allowed subsequent reconstruction of the clock pulses and the eight parallel channels of data, with a bandwidth from d.c. to 20 Hz. These data were transferred to a laboratory computer system for processing and analysis.

The brake system on a motorcycle produces deceleration in response to the rider applying a force to, and the consequent displacement of, the brake control lever. Manual control research has shown that human operators are capable of controlling either limb position or force, the choice depending on the appropriateness to the dynamics of the system under

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* "Motorcycle Rider Skill Assessment", DoT Order No. H 40598.

control. Reliable feedback of one of these quantities can also enhance control of the other. It is thought that automobile drivers control their force output to the brake pedal in order to achieve desired decelerations. Motorcycle brakes, however, are subject to fairly large hysteretic effects in the deceleration response to forces applied to the control lever. It has been suggested that, because the hysteresis in the deceleration/lever-displacement relation is less marked, a viable strategy would be to use lever displacement to control force output.

Experience in automobile handling research has shown that a fruitful way of characterizing the vehicle's response properties is in terms of the steady-state control gains and measures of the rapidity and stability of the response to control inputs which are representative of driver inputs in typical manoeuvres. Accordingly, a series of tests was performed on the three production motorcycles which, it was hoped, would yield useful parameters for characterizing "steady-state" force and displacement gains (and their variation with forward speed), the hysteresis levels affecting modulated force and displacement inputs, and the response times and overshoots associated with rapid brake applications. The tests, performed separately for the front and rear brakes, were:

(a) Step lever-displacement input test.
A characteristic feature of the brake force response to a rapid step-like input of lever displacement for all the hydraulic brake systems was an initial peak, or "overshoot", followed by a gradual decline in the force level required to maintain a constant lever displacement. Thus the brake system presents a time-varying "stiffness" to the rider. For the motorcycles with organic disc pads, and for the drum brake, the "force gain" G_F (m/s^2 of deceleration per N of force applied to the brake lever) was essentially constant throughout the stop. With the sintered

metal pads on the 250 ml machine, however, both the front and rear gains usually increased as the speed decreased. The deceleration response of the motorcycles was quite rapid, the difference between the 63% rise times of deceleration and lever displacement being of the order of 25 ms.

(b) Sinusoidal lever input test.

With a little practice, the test rider was able to produce a reasonably smooth, constant amplitude sinusoidal input of brake lever displacement, with a frequency of about 2 Hz. This test input was chosen as representative of controlled braking situations in which the braking effort is modulated for fine control of deceleration. There was very little hysteresis in the relationship between deceleration and lever displacement for any of the brakes tested. The lever-force characteristics were however subject to substantial hysteresis, which would mitigate against fine adjustment of deceleration by force control. The sensitivity of the motorcycle deceleration (a) to lever control inputs of force (F) and displacement (δ) was characterized by the "force gradient" dF/da and the "displacement gradient" $d\delta/da$, measured as the slopes of the respective characteristic curves during the brake application phase of the sinusoidal lever input. Other brake "feel" parameters measured were the "brake stiffness" $dF/d\delta$ and the "force hysteresis". There was a roughly two-fold variation between machines in all the parameters, except for the front displacement gradient, which was remarkably consistent at about 2.6 mm per m/s^2 for all three machines.

(c) Swept-sine lever input test.

Although motorcycle brake systems clearly exhibit some nonlinear response characteristics, a linearized frequency-domain representation of the dynamics may provide some insights into rider control strategies in closed-loop, controlled braking tasks. Frequency response functions relating deceleration to lever force and displacement inputs, and lever force to displacement ("dynamic stiffness"), were obtained as follows: When travelling at 100 km/h the test rider applied a sinusoidal lever input which started slowly, but which increased in frequency up to the limit of his capability (about 7 Hz) during the test. The resulting deceleration, lever-force and lever-displacement traces were processed by digital Fourier Analysis techniques to yield the required frequency response functions. For all the hydraulic brake systems tested it was found that, whereas the force gain was relatively constant over the range of applied frequencies, the displacement gain and the brake dynamic stiffness were constant at low frequencies, but displayed a roughly three-fold increase over the frequency range 0.5 - 1.5 Hz. The higher gain levels were maintained for frequencies up to near the limit of the input bandwidth (7 Hz). The phase difference between the deceleration and the lever displacement was quite small at all frequencies. By contrast, the deceleration increasingly lagged the lever force as the frequency increased.

MATHEMATICAL MODEL OF BRAKE SYSTEM

A relatively simple mathematical model of a hydraulic brake system was developed, in which the main sources of elasticity, dry friction, viscous resistance and lost motion were identified. The model was successful in accounting for the main features of the experimental responses, including:

(a) the dynamic force magnification and long-term stiffness variation effects observed in the step lever-displacement tests;

(b) the hysteresis loops observed in the sinusoidal lever input tests;

(c) the forms of the frequency response functions measured in the swept-sine lever input tests.

VARIABLE BRAKE CONTROL GRADIENT MOTORCYCLE

The "steady-state" gradients of lever force and displacement with deceleration (as determined by the sinusoidal lever input test) were selected as the primary brake system parameters to be manipulated with the VBCG motorcycle. For the other possibly relevant feel properties, the design objective was to maintain very short response times, and representative levels of force hysteresis.

The means by which the force and displacement gradients of the VBCG motorcycle were made independently variable, using an air-assisted hydraulic brake system, are described in the report. Calibration tests showed that the control gradients of production motorcycles measured in the present study, and in a previous investigation, generally fell within the range achievable with the variable brake system. The level of force hysteresis was somewhat higher than measured on the production machines in the present study, but still within the range measured in the earlier study.

Experienced test riders reported that the VBCG motorcycle behaved and felt "normal". The only qualifications to this were that some riders commented on the relatively high level of force hysteresis for the rear brake, and the noise made by the discharge of air when the brakes were released. Riders rapidly became accustomed to the latter idiosyncracy of the VBCG system; the former could be corrected by reducing the friction in the brake lever fulcrum.

PILOT STUDY OF ERGONOMIC ASPECTS OF BRAKING CONTROL

An experiment was designed to determine the effect of the displacement and force control gradients on motorcycle braking quality. The relative importance to riders of these two gradients, and the interactions between their values for the hand and foot brakes, were of interest. It was intended that the experiment would be performed using a group of about thirty riders of varying levels of experience and skill. Before undertaking a full-scale study it was considered prudent to carry out a pilot study, with two skilled riders only, to evaluate the proposed experimental procedures and performance measures. It was also thought that the results of a pilot study involving a wide range of brake system characteristics might show that some combinations of characteristics were clearly unacceptable. These could then be eliminated from the full-scale study, thereby reducing both the magnitude and the hazards of that task. In the event, there was insufficient time available in this project to do more than carry out the pilot study.

The experimental design was based on Response Surface Methodology (RSM), which provides an experimentally efficient means for investigating the effects of a large number of independent variables, and their interactions. Second-order response surfaces were to be fitted to the data to allow optimum brake configurations to be defined. The RSM design required five levels for each of the independent variables and the VBCG system was set up and calibrated accordingly. The ranges of control gradients explored in this study were:

Front displacement gradient	(FBD):	1.0 - 5.7 mm per m/s^2
Front force gradient	(FBF):	17.5 - 76.7 N per m/s^2
Rear displacement gradient	(RBD):	1.6 - 12.9 mm per m/s^2
Rear force gradient	(FBF):	25.8 - 84.6 N per m/s^2

The experimental braking task involved the rider travelling in a straight line at 30 km/h (chosen low for safety reasons) and monitoring a traffic signal light ahead. On receipt of a red signal, the rider's task was to bring the motorcycle to a stop before reaching a line marked across the roadway. The timing of the signal light was adjusted to require either a "slow" stop (0.2g nominal deceleration), a "medium" stop (0.3g) or a "quick" stop (0.5g). Because of the rider's reaction time, the actual deceleration required exceeded these nominal values. To prevent anticipation of a quick stop, "no stop" runs were randomly interspersed through the test sequence.

Two expert riders were used as subjects in the pilot study, in the hope that they would exhibit more consistent braking behaviour and provide more meaningful subjective ratings of various aspects of the braking quality than would less-skilled riders. Ratings of the brake force and displacement requirements and overall impressions of the braking quality were obtained from the riders; objective measures of the deceleration performance, the contributions to this from the front and rear brakes, the overall stopping distance and the rider's reaction time were derived from the recorded data. SPSS Multiple regression was used to obtain the coefficients defining the response surfaces and statistical measures of the strength and significance of the observed relationships.

The main findings from the data analysis were:

(a) The two expert riders were able to modify their control inputs so as to (on average) achieve roughly the same braking performance over the whole range of brake configurations.

(b) On average, both riders distributed the braking effort between the front and rear wheels in an optimal manner, again despite the wide ranges and combinations of front and rear brake sensitivities with which they were presented.

(c) All the data, however, exhibited a large error variance which generally precluded the definition of significant relationships between response measures and the brake configuration variables.

(d) Performance in the quick stop task was primarily affected by the front brake displacement gradient. However, only small and contradictory trends were obtained from the two riders: for one, average deceleration increased marginally with a more displacement sensitive front brake; for the other it decreased slightly.

(e) Subjective ratings of the brake system were primarily influenced by the rear brake displacement gradient. Again, however, quite contradictory results were obtained from the two riders.

CONCLUSIONS

Useful information has been obtained about the performance characteristics of conventional motorcycle braking systems. The major features of the experimental responses have been accounted for with a relatively simple mathematical model. A variable braking control gain motorcycle, and a light-weight data acquisition system have been developed and have proved themselves as reliable tools for carrying out motorcycle braking experiments. The results of a pilot study of the effect of braking control gains on braking quality attest to the adaptability of expert riders to changes in vehicle characteristics and to the individual differences between human subjects. The variability in the pilot study data was disappointing and suggests that modifications in experimental technique are required. Future studies should allow the riders a longer time in which to become familiar with each new braking configuration and braking from higher speed should be attempted. A paired-comparison experimental design should lead to more consistent subjective ratings than were obtained in the present study. Experiments with less skilled riders would also probably yield performance measures that were more strongly affected by the brake system variables.

1. INTRODUCTION

1.1 BACKGROUND TO THIS STUDY

In its report on motorcycle and bicycle safety, the House of Representatives Standing Committee on Road Safety (HoR, 1978, Para. 81) recommended that:

> "A literature and research review of existing and potential problems relating to motorcycle stability and handling be undertaken by the Advisory Committee on Safety in Vehicle Design."

Furthermore, the committee recommended experimental appraisal of antilock and linked brake systems. They expressed concern about possible motorcycle instabilities arising through the fitment of fairings and the carrying of luggage. In addition, they said that the safety aspects of the matching of tyres to machines should be investigated.

On the basis of these recommendations the Office of Road Safety of the Australian Department of Transport commissioned a two-phase research project entitled "Braking, Stability and Handling of Motorcycles". Phase I, a literature and research review, has been reported separately (Juniper and Good, 1983). This report documents the Phase II investigation of a high-priority problem area revealed by the review, namely the effect of motorcycle brake control gains on braking performance.

1.2 OUTLINE OF STUDY

The topics covered in the literature review (Juniper and Good, 1983) included braking problems, and stability and handling aspects of motorcycles. The accident studies reviewed highlighted many problem areas with motorcycles. In particular, in-depth accident studies suggested that many riders do not utilize the full deceleration capability of their motorcycle when braking to avoid a collision. Hence many accidents were more severe than they would have been if the riders had used both front and rear brakes up to the available limits of friction between the tyres and the road surface. This suggests a possible mis-match between the characteristics of motorcycle brakes and the rider control capabilities.

Important aspects of the design of any dynamic system incorporating a human controller are the sensitivity of the system response to control inputs and the control 'feel' available from the manipulator used to exercise control. The literature review revealed no accounts of scientific studies of the effect of motorcycle brake control gains or feel properties on braking performance, although the need for such studies was noted (Ervin, McAdam and Watanabe, 1977; Irving, 1978; Zellner, 1980; Taguchi and Sunayama, 1973).

After consultation with the Office of Road Safety, Phase II was initiated as an experimental study of the ergonomic aspects of motorcycle braking control. The study comprised three main parts.

First, the dynamic response to braking inputs of three motorcycles was to be investigated in some detail. The information gained here was hitherto unavailable and was necessary to allow characterisation of the response properties, so that these could be manipulated in experiments with riders. This part of the study is described in Chapter 2.

Having determined that the primary response parameters of the brake system are the force and displacement control gradients (respectively, the brake lever force and displacement increments required to increase the deceleration by $1 m/s^2$), a variable brake control gradient (VBCG) motorcycle was designed and constructed to allow rapid and independent experimental control over these parameters. The development of the VBCG system is detailed in Chapter 3.

The third part comprises a pilot study of the effects of brake control gradients on motorcycle/rider braking performance using the VBCG motorcycle. This experiment is reported in Chapter 4.

It should be noted that this work is concerned with dry weather braking only. Although considerable problems exist in braking of motorcycles with wet brakes and on wet surfaces, the restriction to dry braking was made because:

(a) the great majority of riding is done in dry weather; Hurt, Ouellet, and Thom, (1981) put the figure at more than 97% for California, USA;

(b) the resources of the study were not sufficient to encompass the additional experimental variables and methodological problems introduced with wet weather braking.

2. CHARACTERIZATION OF MOTORCYCLE BRAKE RESPONSE PROPERTIES

2.1 INTRODUCTION

The review by Juniper and Good (1983) found no published study of the effects on motorcycle/rider braking performance of the response properties of the motorcycle braking system. Even for automobiles there are few studies available. Mortimer et al. (1970) characterized automobile brakes in terms of the steady-state deceleration/pedal force gain and studied the effect of various levels of this gain on braking performance. The weak optima found for the force gain depended somewhat on the skid number of the pavement, but performance was independent of the amount of pedal displacement required to achieve a given force level. It was concluded that the brake is modulated largely by force feedback rather than by displacement.

Motorcycle brakes, however, are subject to fairly large hysteretic effects in the deceleration response to forces applied to the brake lever. It has been suggested (Zellner, 1980; Zellner and Klaber, 1981) that, because the hysteresis in the deceleration/lever displacement relation is less marked, 'a viable strategy would be to use lever displacement to control force output'.

Manual control research has shown that human operators are capable of controlling either limb position or force, the choice depending on the appropriateness to the dynamics of the system under control (see, for example, Good, 1979). Reliable feedback of one of these quantities can also enhance control of the other. Experience in automobile handling research (Good, 1977; 1979) has shown that a fruitful way of characterizing the vehicle's response properties is in terms of steady-state control gains or gradients and measures of the rapidity and stability of the response to control inputs which are representative of driver inputs in typical manoeuvres.

Before appropriate parameters could be selected for experimental investigation of their effects on motorcycle braking performance, it was necessary to investigate in some detail the question: 'What actually happens when the brakes of a motorcycle are applied?'

Three motorcycles were selected for the purposes of investigating brake dynamic behaviour. One of the machines was of 250 ml engine capacity, and had single disc brakes on both wheels. It was fitted with 'all weather' disc pads of sintered metal construction. The manufacturer claimed these brakes give good response characteristics in wet conditions. The second motorcycle was of 400 ml capacity and configured with a stainless steel disc brake on the front wheel, and a single leading-shoe, lever-operated drum brake on the rear wheel. The third motorcycle, of 750 ml engine capacity, had stainless steel single disc brakes on the front and rear wheels, with conventional organic material brake pads. It was expected that this variation in brake configurations and machine size could yield interesting contrasts in dynamic behaviour.

2.2 ON-BOARD DATA ACQUISITION

A light-weight data acquisition system was developed in order to measure rider inputs and motorcycle responses whilst the machine was being ridden in a normal manner. An important criterion was that it should not significantly alter the motorcycle mass distribution, so as not to influence the dynamic behaviour of the machine. The major part of the hardware was arranged to replace the fuel tank on any of the machines. A small one litre vessel was used for fuel supply during testing.

The system provided for eight analogue input channels which could be recorded for up to 45 minutes continuously. It employed a high quality portable cassette tape recorder. The data for the 8 channels was encoded into a single channel of information using

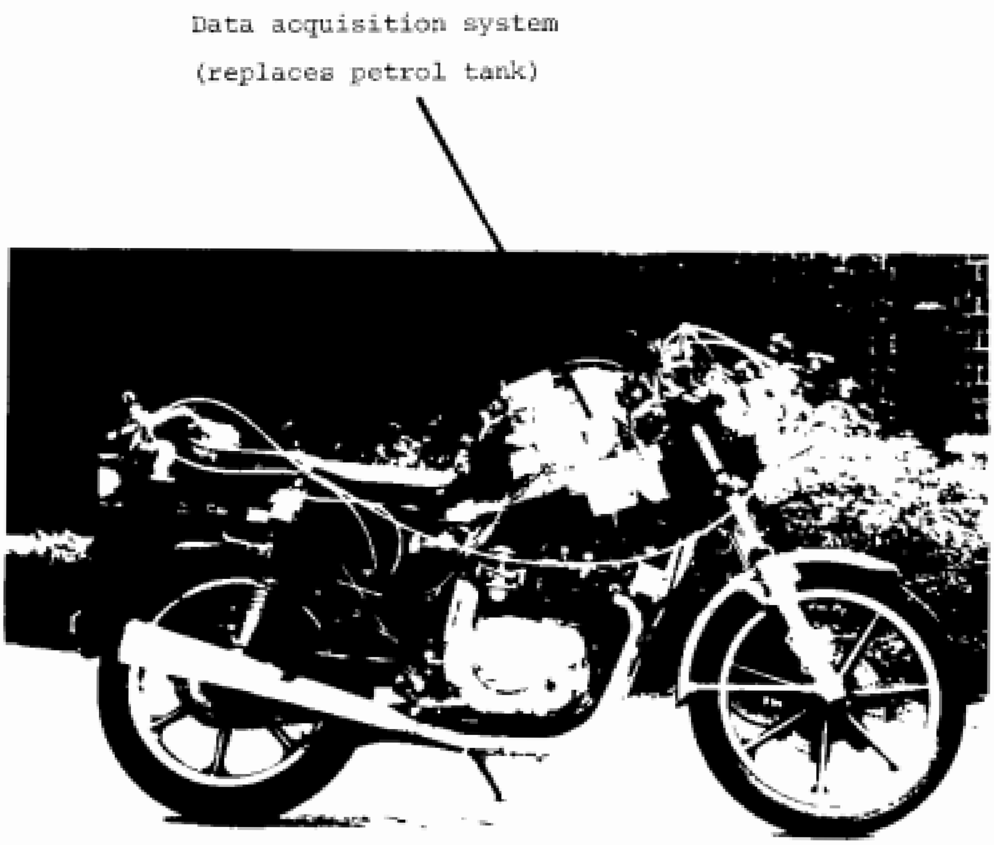


Figure 2.1 Data acquisition system mounted on 250 ml motorcycle

a time division multiplexing scheme, which resulted in a square wave of frequency varying between 3.75 kHz and 7.5 kHz. Decoding circuitry, back in the laboratory, reconstructed the analogue input signals from the cassette tape. The level of the analogue input signals was required to be between 0 and 10 volts. The system bandwidth was found to be from d.c. to 20Hz per channel. This was considered adequate for the motorcycle experiments, as rider inputs and motorcycle dynamics are generally of frequency less than 10Hz.

Figure 2.1 shows the data acquisition system mounted on the 250 ml machine. Although it is seen to be some centimetres higher than the original fuel tank, this proved to be not noticeable to the rider, as his vision is generally concentrated ahead of the motorcycle.

2.3 QUANTITIES MEASURED TO DETERMINE BRAKING BEHAVIOUR

In order to reduce the speed of a motorcycle, the rider provides a force and displacement at the front brake hand lever and/or the rear brake foot pedal. In response to these inputs, the motorcycle decelerates and the main frame of the machine pitches forward.

The quantities measured to investigate brake dynamics were front brake lever force and displacement, rear brake lever force and displacement, motorcycle forward speed, main frame deceleration and pitch rate, and suspension deflections.

The details of the design and calibration of the various transducers may be found in Appendix A. Table 2.1 shows the sensitivities of the transducers as used on three motorcycles.

TABLE 2.1

TRANSDUCER SENSITIVITIES

Motorcycle	Front Brake(1) Force N/v	Rear Brake Force N/v	Front Brake(2) Displacement mm/v	Rear Brake Displacement mm/v	Speed (m/s)/v	Front Suspension Deflection mm/v	Rear Suspension Deflection mm/v
250 ml	25.7	25.5	4.47	9.8	4.71	15.0	10.1
400 ml	62.6	27.8(3) 30.18(4)	4.47	7.2	5.15	15.0	10.1
750 ml	38.1	36.7	4.47	7.43	5.00	15.0	10.1

Notes: (1) Measured when force applied 115 mm from lever fulcrum

(2) Lever displacement measured 115 mm from fulcrum

(3) Applies to gauges adhered to brake actuating arm

(4) Applies to gauges adhered to rear brake lever

2.4 TEST SITE

The experimental work in this phase of the program was performed at the Australian Department of Defence Trials and Proving Wing, located at Monegeetta, 55 km NNW of Melbourne.

Two areas were used, these being the straightaway and the bitumen pads. The straightaway is a smooth, straight and very nearly level stretch of concrete roadway of 620 m length, with distance markers placed at 200 m intervals. The bitumen pads measure 60 m by 60 m each and are interconnected at their corners, thereby providing approximately 170 m of clear roadway. The pad surfaces are very smooth, first-quality hot-mix bitumen, and were found to be of sufficient length for most test procedures. Smooth road surfaces were necessary to minimise data dropouts due to tape recorder vibration.

2.5 PILOT STUDY OF MOTORCYCLE BRAKE DYNAMICS

One of the three motorcycles was fully instrumented. Many exploratory experiments were then performed so as to identify the minimum requirements for characterization of the dynamic response of a motorcycle brake system. Experiments were then performed with the other two machines to obtain the required parameters which would allow comparison of their braking behaviour. The 400 ml machine was chosen for the first series of experiments, with the major effort being devoted to its front brake, as the rear wheel was fitted with a mechanically operated drum brake.

2.5.1 Response Characteristics Methodology

The brake system on a motorcycle produces deceleration in reponse to the rider applying force and displacement at the brake control lever. To investigate the behaviour of a dynamic system, it is common to observe its response to certain standardized inputs, which may be of step, ramp, impulse or sine wave form.

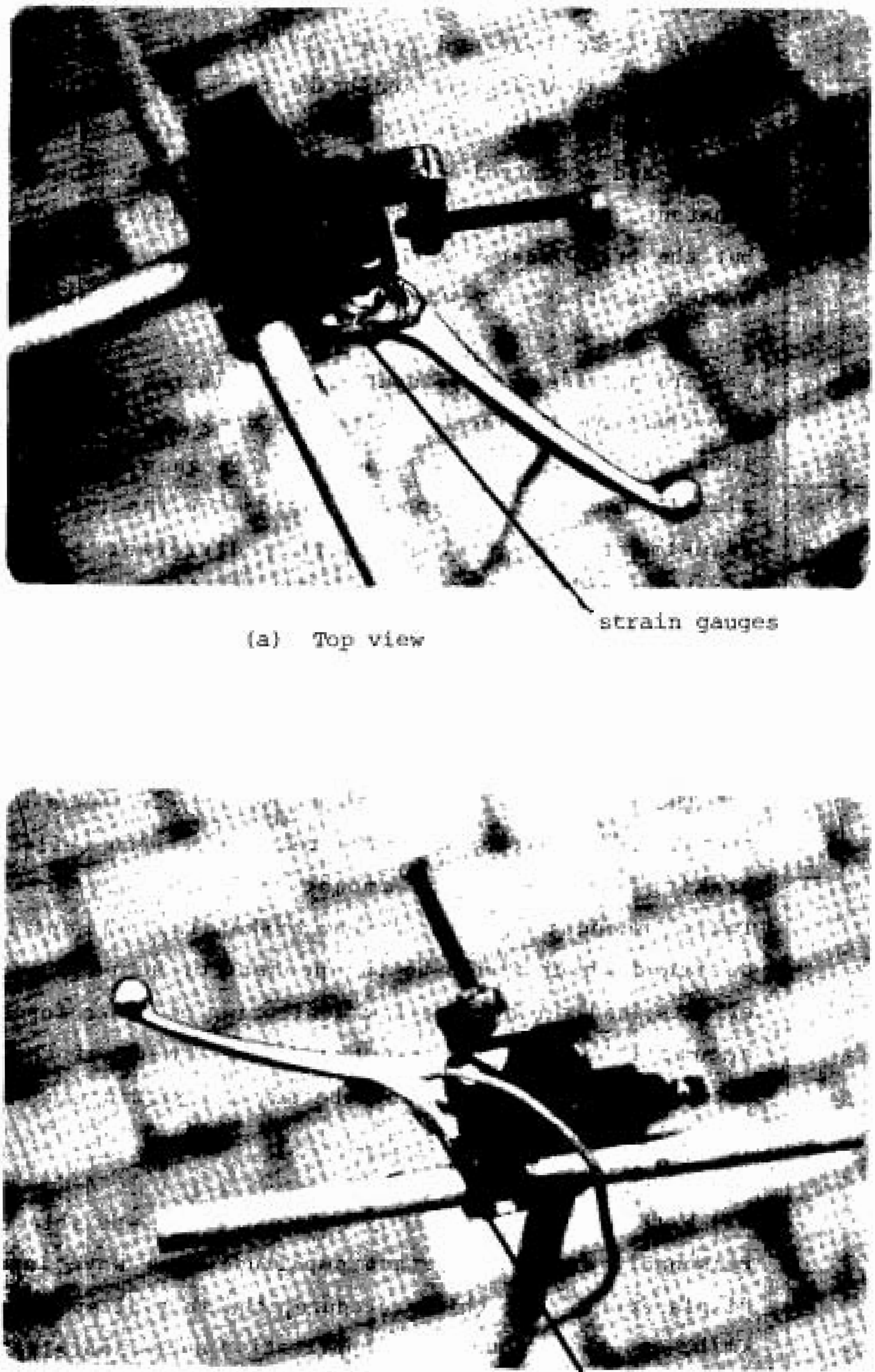
Weir, Zellner and Teper (1978) used a brakeline pressure limiter to regulate applied brake force during cornering/braking experiments. The test rider applied a large pedal or hand grip force, and a control system limited the brakeline pressure to a constant, preset value. This, then, provided a step force input, but the brake master cylinder dynamics were eliminated from the system, so that only wheel cylinder dynamics would be observable.

To provide a step input response in the present experiments, a mechanical displacement limiter was fitted to the front brake lever on the 400 ml machine. This is shown in Figure 2.2, and allowed the rider to apply a rapid step input of displacement. Adjustment was provided so that different levels of input displacement could be applied. The strain gauges used to measure force input were 'downstream' of the displacement limiter. Thus they continued to measure force behaviour after the displacement limit had been reached.

The rear brake on the 400 ml motorcycle was a mechanically-operated drum type. When the rear suspension deflects during a braking manoeuvre, the amount of braking effort is altered. Taking account of this, a rear brake displacement limiter was designed which would be independent of suspension deflection effects, and yet still allow monitoring of brake force. This was accomplished by limiting the displacement of the rear brake actuating arm, and adhering the sensing strain gauges along this arm (see Appendix A).

With a little practice, the test rider was able to provide a reasonably smooth, constant amplitude sine wave input of brake displacement. For this procedure, the initial speed was about 60 km/h, and the frequency of application approximately 2.0 Hz.

As a further attempt to investigate the frequency response of the system, a 'swept sine wave' technique was employed. This



(a) Top view

(b) Underside view

Figure 2.2 Front brake displacement limiter.

test commenced at about 100 km/h. The rider applied a sine wave displacement input which started very slowly but the frequency of which increased up to the limit of the rider's capabilities (about 7 Hz) during the test.

2.5.2 Interpretation Of Step Displacement Data

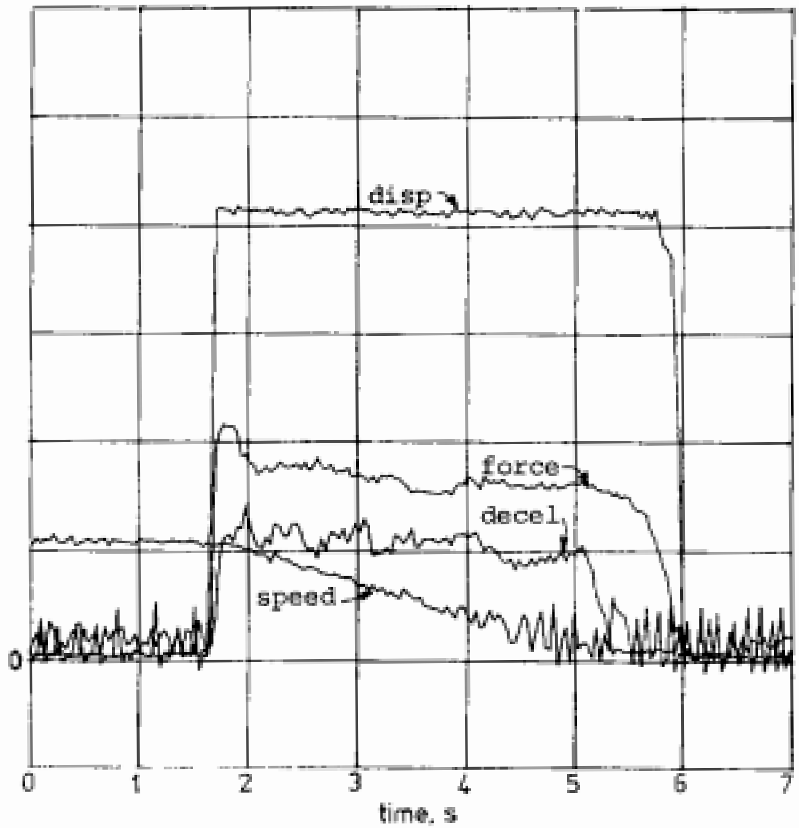
Figure 2.3 shows traces of front brake force and displacement, and speed following a step input of brake displacement from 20 km/h. These data allow the variation of the deceleration/force gain, G_F (m/s^2 per N), with speed, V, to be observed.

Appendix B shows that the rate of change of G_F with V can be interpreted as the Recovery Rate Gradient (RRG) investigated by Zellner and Klaber (1981). Figure 2.4 shows that for the 400 ml machine there was essentially no variation of force gain G_F with speed, so that the front brake for this motorcycle has a zero RRG.

Referring again to Figure 2.3, it can be seen that while the brake lever displacement was held constant, the required brake force varied with time, reaching a peak early in the test and slowly declining afterwards. This 'dynamic force magnification effect' means that the force gain and 'stiffness' the brake system presents to the rider will vary.

2.5.3 Displacement Modulated Data

Figures 2.5 and 2.6 show the deceleration-displacement and deceleration-force characteristics for a 2 Hz sinusoidal input of brake lever displacement. Figure 2.5 demonstrates that deceleration follows the modulated displacement input quite closely, with little hysteresis. However in Figure 2.6 there is a substantial hysteresis in response to force inputs. The magnitude of the force hysteresis is about 70 N.



Scales:	disp	4.47 mm/div
	force	62.6 N/div
	decel	1.96 ms^{-2}/div
	speed	5.15 ms^{-1}/div

Figure 2.3 Force and deceleration response to a rapidly applied displacement limited ramp, front brake 400 ml motorcycle.

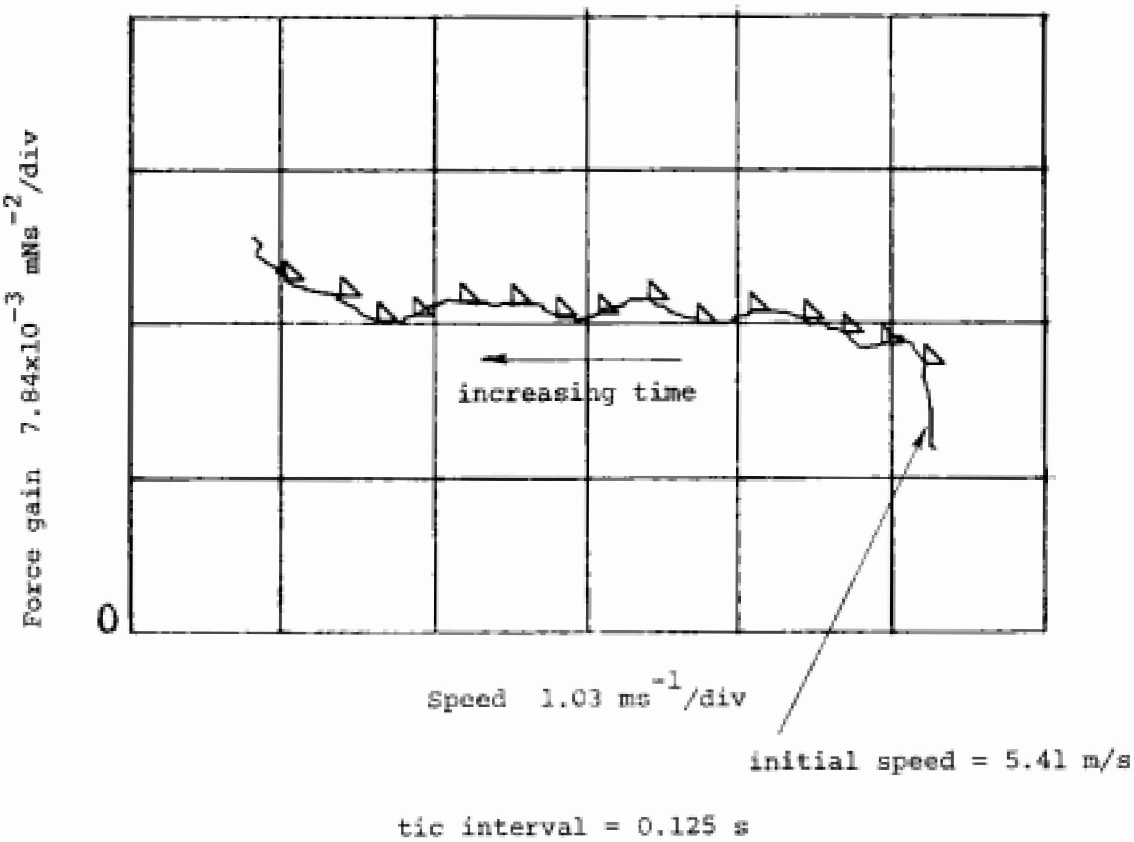


Figure 2.4   Force gain versus speed, 400 ml motorcycle.

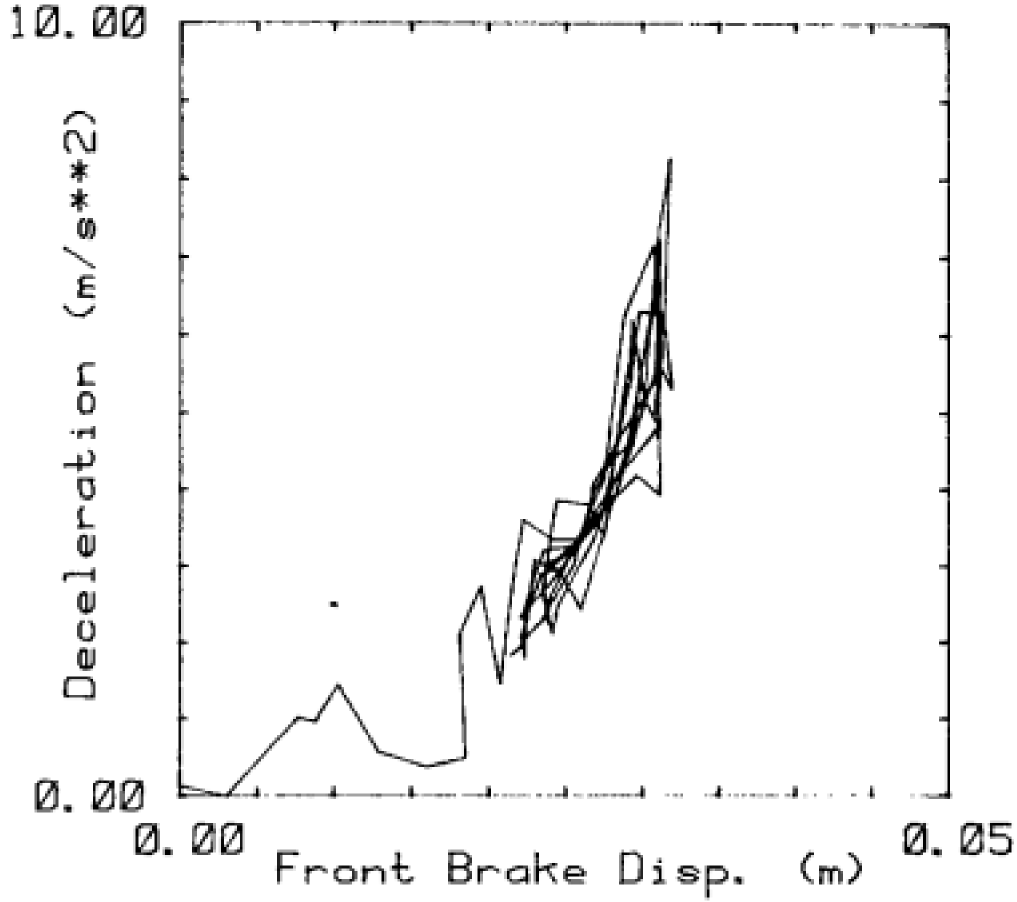


Figure 2.5 Deceleration vs. displacement, 400 ml motorcycle

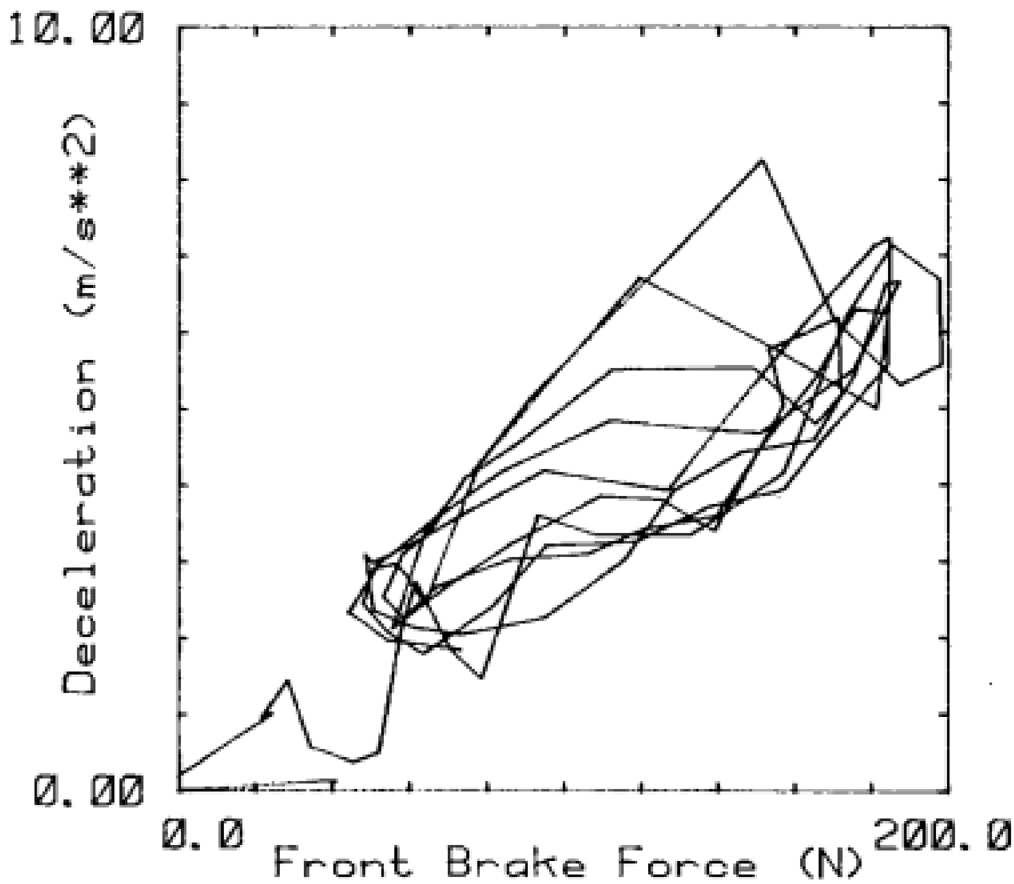


Figure 2.6 Deceleration vs. force, 400 ml motorcycle.

As pointed out by Zellner and Klaber (1981), the presence of hysteresis results in the loss of fine control and increases the phase lag between small amplitude control inputs and machine reponses. Hysteresis therefore degrades the quality of the braking system, especially for force inputs.

These data can also be used to extract the force gain G_F and the displacement gain G_δ parameters. The slopes of the deceleration-displacement and the deceleration-force graphs during the brake application phase of the modulated input represent G_δ and G_F, respectively. A computer program was written to extract the data for the application phase and then to fit a 'least-squares' straight line to the points. This yielded an average displacement gain G_δ and force gain G_F for the usable range of the brake control.

2.5.4 Swept Sine Wave Data

These data were used to determine deceleration/force, deceleration/displacement and force/displacement frequency response functions, which are shown in Figures 2.7 and 2.8 and 2.9 for the 400 ml machine. For the 400 ml motorcycle, the force gain is approximately constant over the range of rider control frequencies, whereas the displacement gain is frequency dependent, increasing by a factor of 3 between 0.5 and 1.5 Hz. The magnitude of the 'dynamic stiffness' F/δ is similarly frequency dependent; however, there is a high frequency phase lead for this frequency response function.

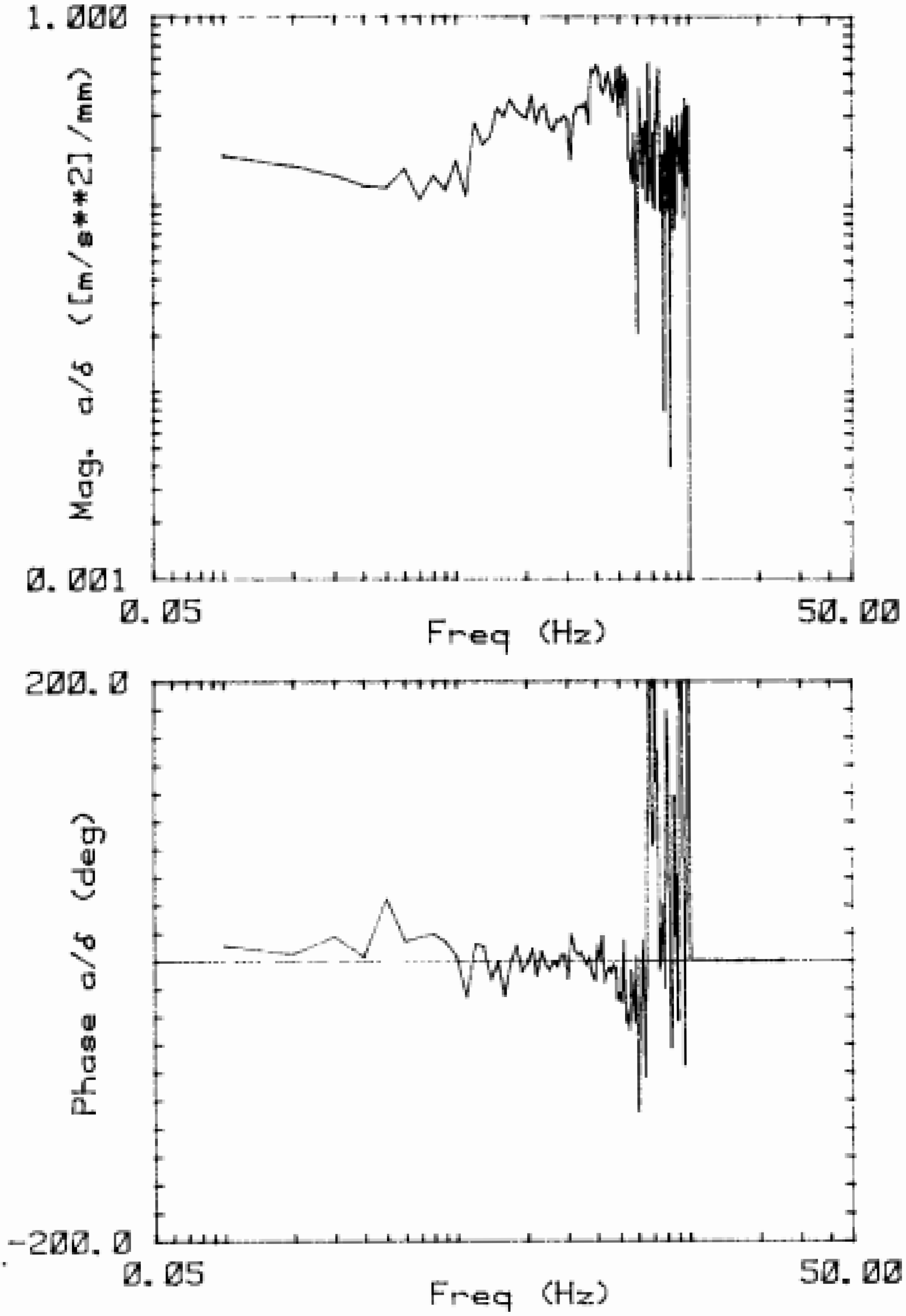


Figure 2.7 Deceleration-displacement transfer function, 400 ml motorcycle.

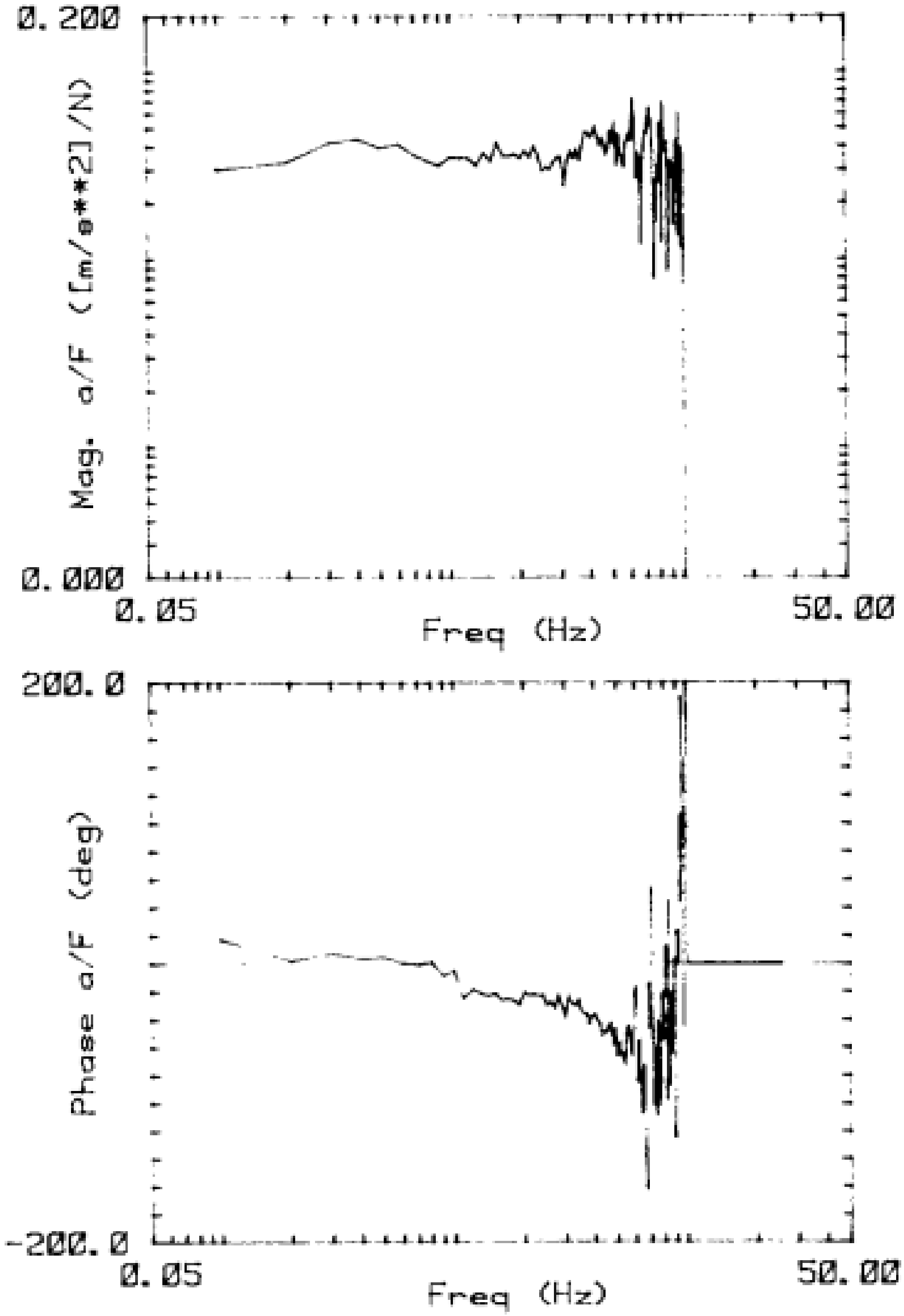


Figure 2.8 Deceleration-force transfer function, 400 ml motorcycle.

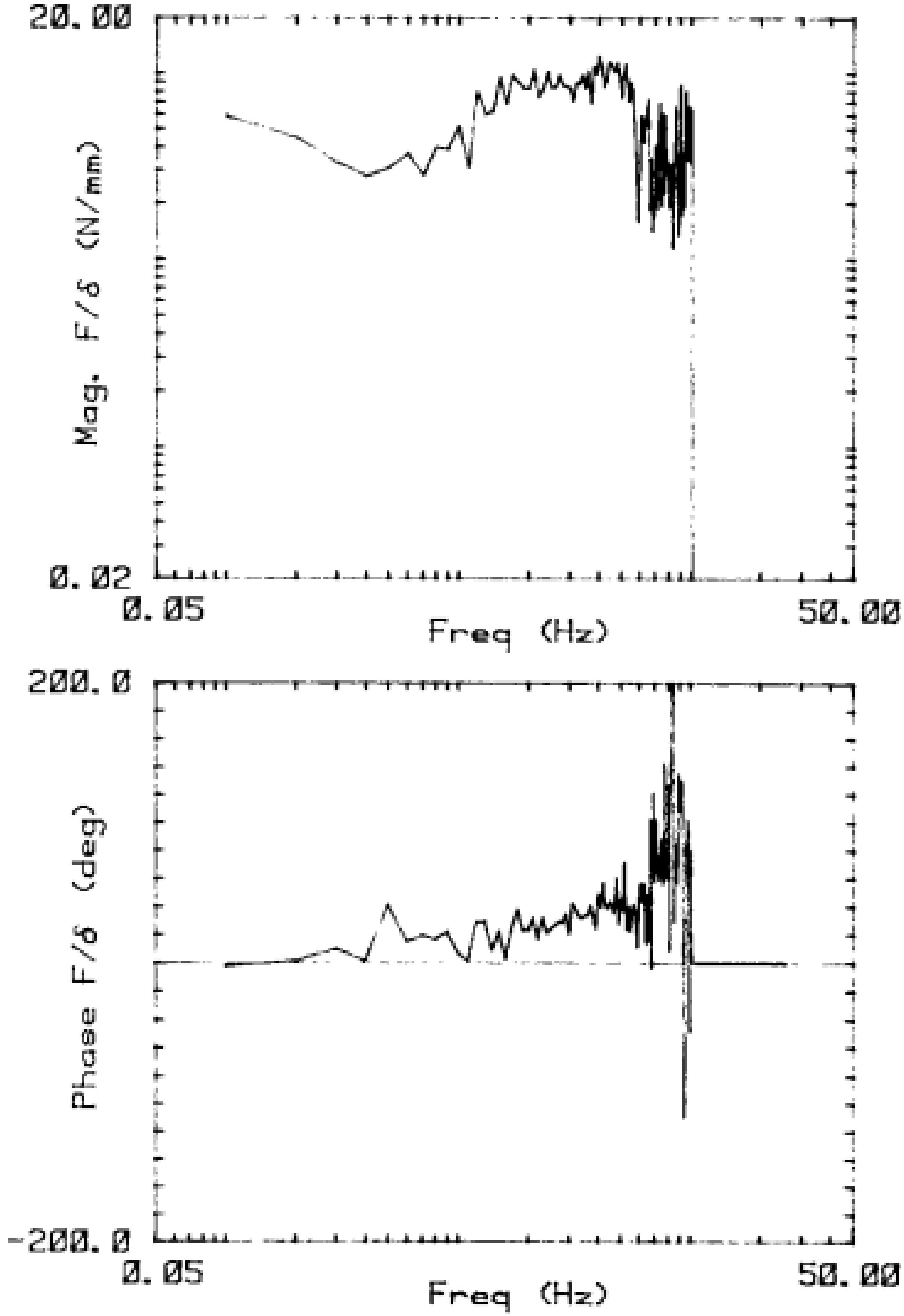
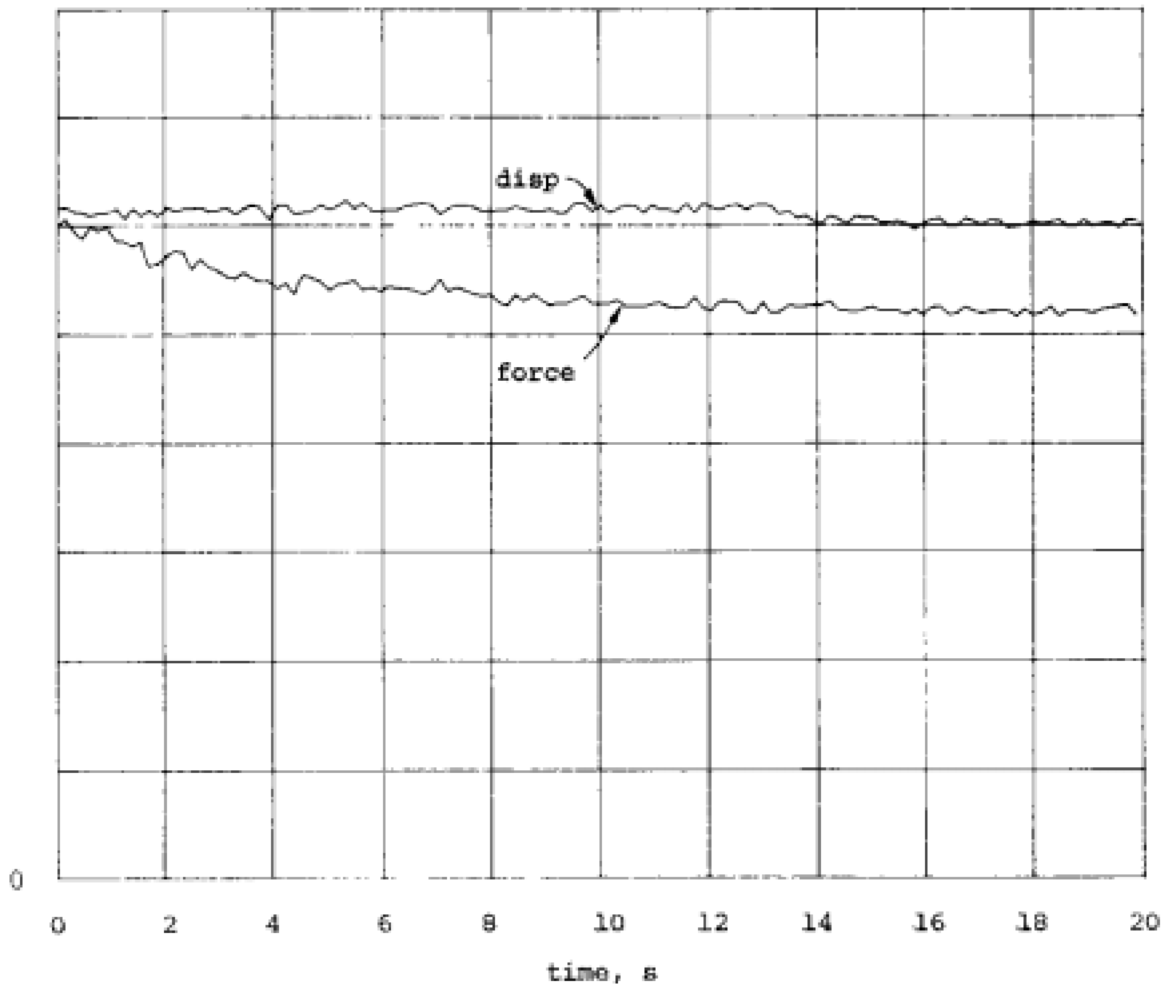


Figure 2.9 Force-displacement transfer function, 400 ml motorcycle.

Scales: disp 4.47 mm/div

force 31.3 N/div

Figure 2.10 Dynamic force magnification effect, front brake 400 ml motorcycle.



Scales: disp 4.47 mm/div

force 62.6 N/div

Figure 2.11 Long term front brake force behaviour after a step input of displacement, 400 ml motorcycle.

2.5.5 Static Tests

Laboratory tests with the instrumented brake system on the 400 ml machine supplied further information. For example, Figure 2.10 clearly demonstrates the dynamic force magnification effect (discussed in section 2.5.2) in response to a rapid application of brake lever displacement. Figure 2.11 shows front brake force and displacement again, but over a much longer time period. Here it can be seen that the force required to maintain a constant displacement reduces considerably over the first five seconds. This is thought to be due to internal leakage within the hydraulic master cylinder. The brake system thus presents a time varying stiffness to the rider.

2.6 MATHEMATICAL MODEL OF AN HYDRAULIC DISC BRAKE SYSTEM

A mathematical model of a typical motorcycle disc brake system was developed to account for the main features of the behaviour observed in Section 2.5. The details of the model derivation can be found in Appendix C.

Figure 2.12 shows schematically the physical arrangement of a motorcycle hydraulic disc brake system, and Figure 2.13 is a symbolic representation of the identifiable stiffness, damping and coulomb friction effects.

2.6.1 Force-displacement Behaviour

Figure 2.14 is a sketch of the expected force response for a very slow displacement input. This predicted relationship compares favourably with the form obtained in a laboratory test of the 400 ml motorcycle front brake, as shown in Figure 2.15.

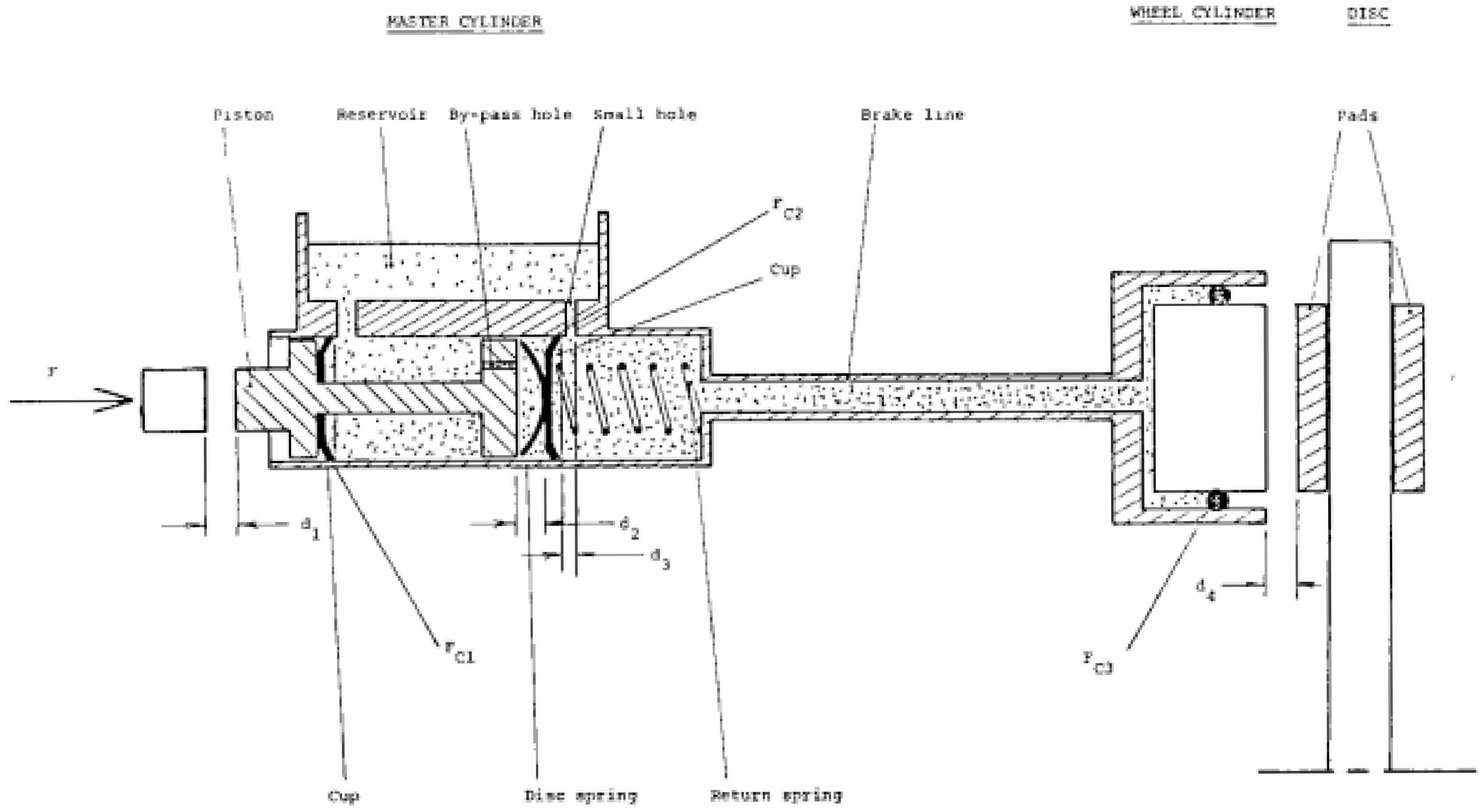


Figure 2.12 Schematic physical arrangement of a motorcycle hydraulic brake system.

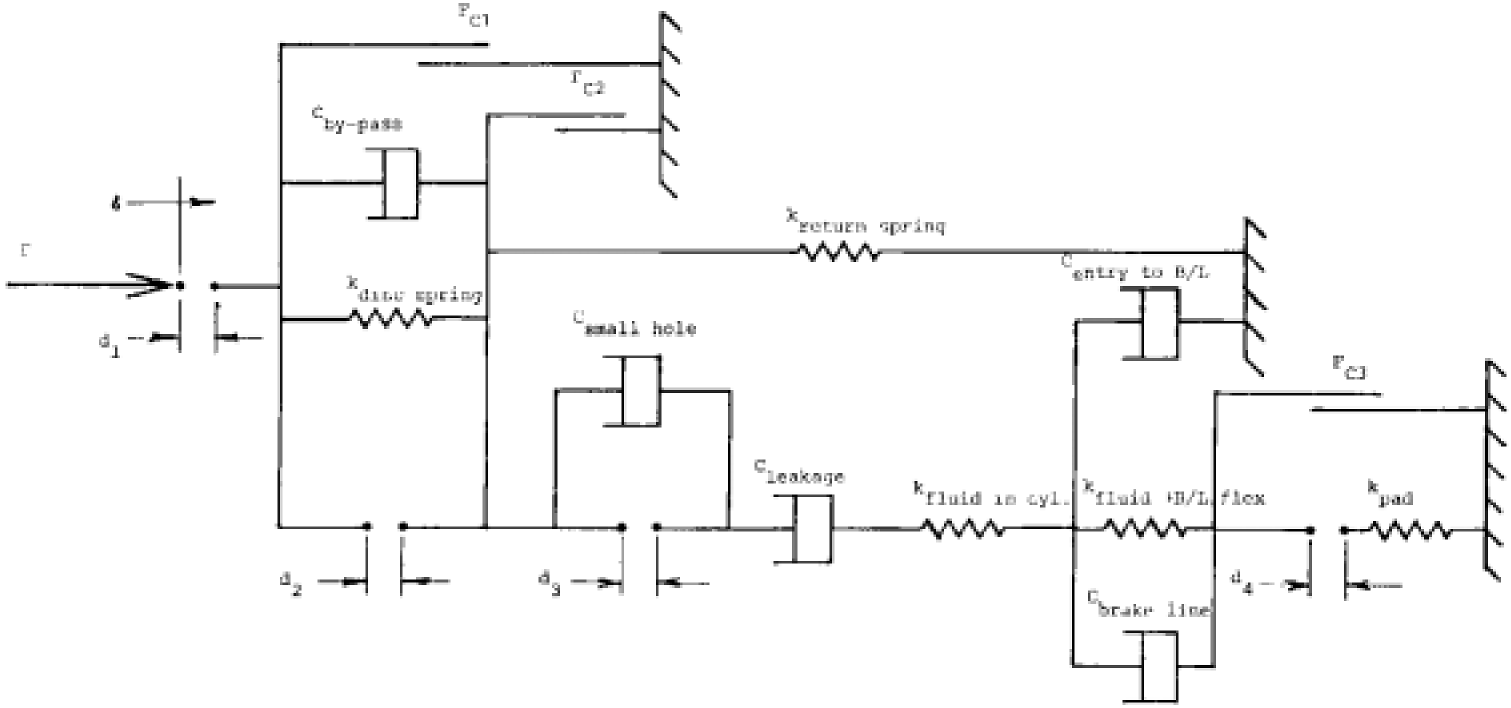


Figure 2.13 Symbolic representation of motorcycle hydraulic brake system.

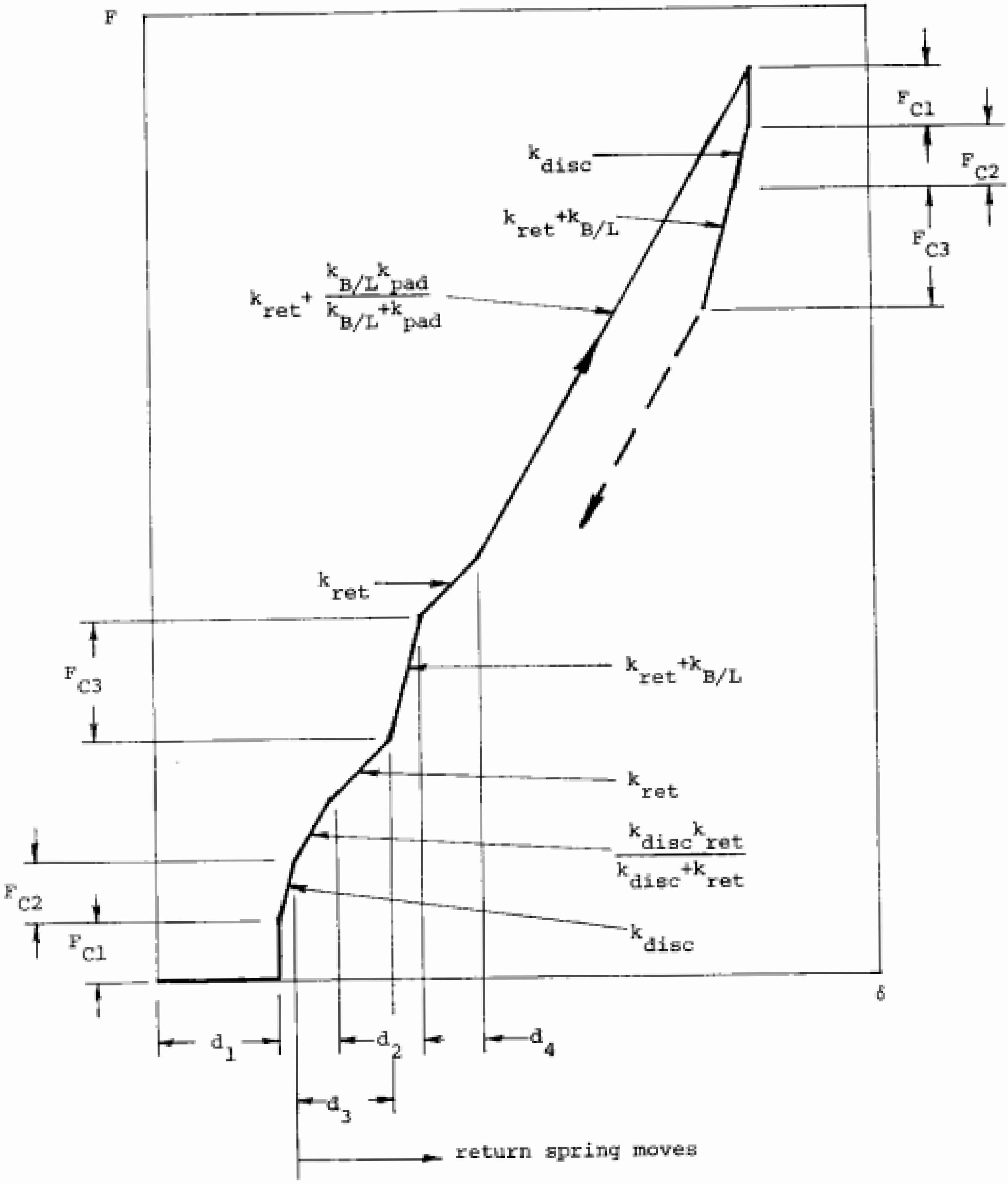


Figure 2.14 Expected force-displacement response of brake model.

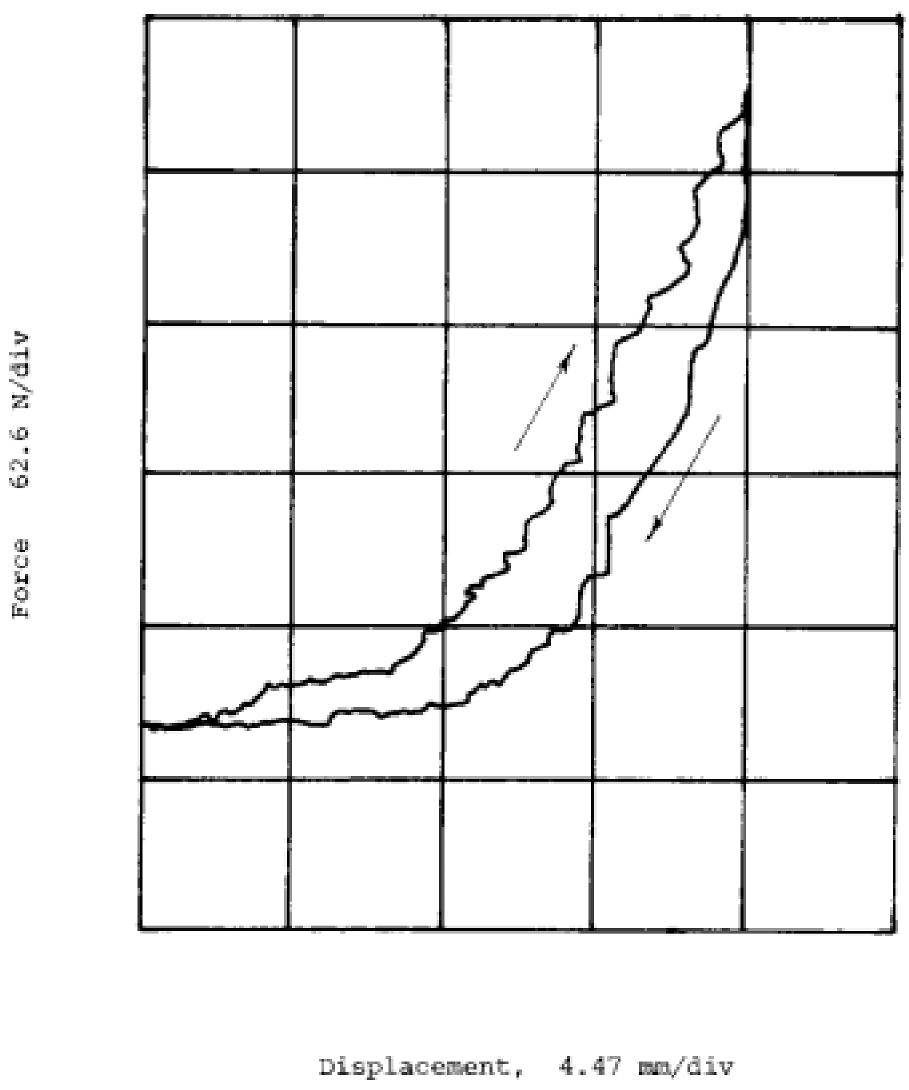


Figure 2.15 Front brake force-displacement behaviour when brake is slowly applied, 400 ml motorcycle.

2.6.2 Transfer Functions

The system represented in Figure 2.13 is non-linear due to coulomb friction effects F_{C1}, F_{C2} and F_{C3}, and due to displacement steps d_1, d_2, d_3 and d_4. For the purposes of accounting for the main features of the swept sine wave and step displacement results, a linear dynamic model is sufficient. Ignoring the coulomb forces and assuming the displacement steps to be 'taken up', results in the simplified spring-damper model shown in Figure 2.16.

In Appendix C it is shown that, for the model of Figure 2.16, the transfer function relating brake lever force F and displacement δ is of the general form

$$\frac{F}{\delta} = \left[k_1 + \frac{1}{1/k_2 + 1/k_3 + 1/k_4} \right] \frac{(1 + s/a_1)(1 + s/a_2)}{(1 + s/b_1)(1 + s/b_2)}. \qquad (2.1)$$

The disk clamping force F_c in response to brake lever displacement and force inputs is determined by the transfer functions

$$\frac{F_c}{\delta} = \left[\frac{1}{1/k_2 + 1/k_3 + 1/k_4} \right] \frac{(1 + s/a_3)}{(1 + s/b_1)(1 + s/b_2)}, \qquad (2.2)$$

$$\frac{F_c}{F} = \left[\frac{1}{1 + k_1/k_2 + k_1/k_3 + k_1/k_4} \right] \frac{(1 + s/a_3)}{(1 + s/a_1)(1 + s/a_2)}. \qquad (2.3)$$

If it is assumed that the motorcycle deceleration is proportional to the disk clamping force, equations (2.2) and (2.3) can be used to predict the form of the deceleration/displacement and deceleration/force frequency response functions measured in the swept sine wave tests.

By comparing the transfer function forms in equations (2.1) to (2.3) with the corresponding data for the 400 ml motorcycle

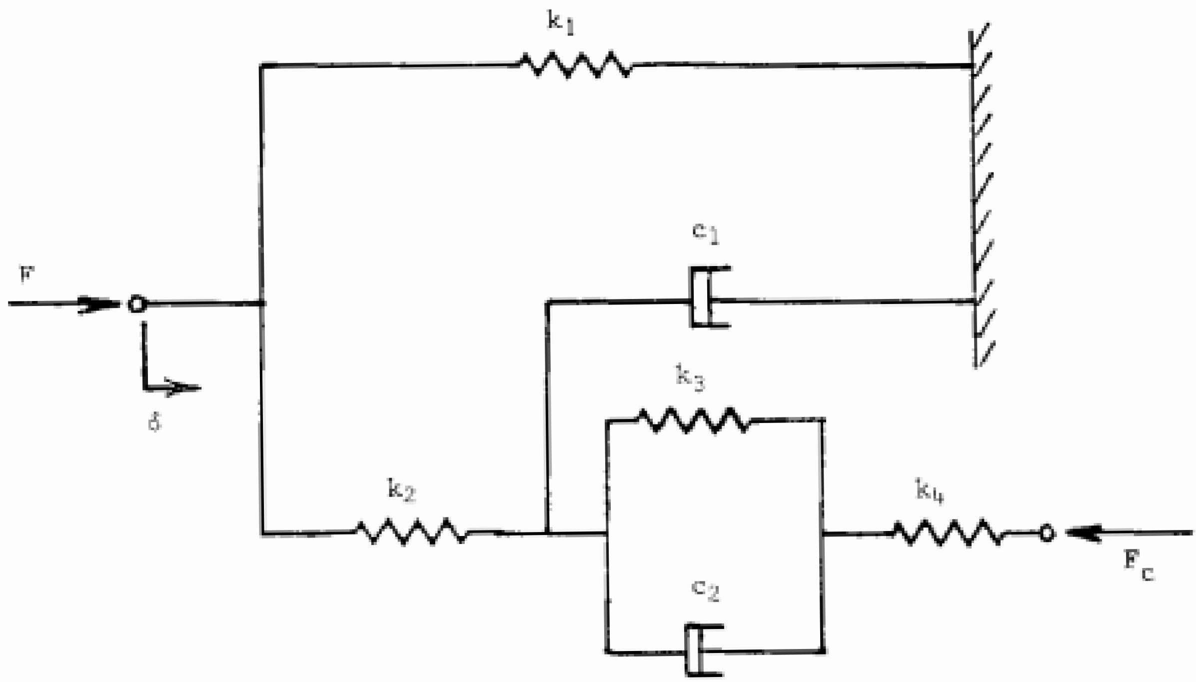


Figure 2.16 Simplified spring-damper model of brake system.

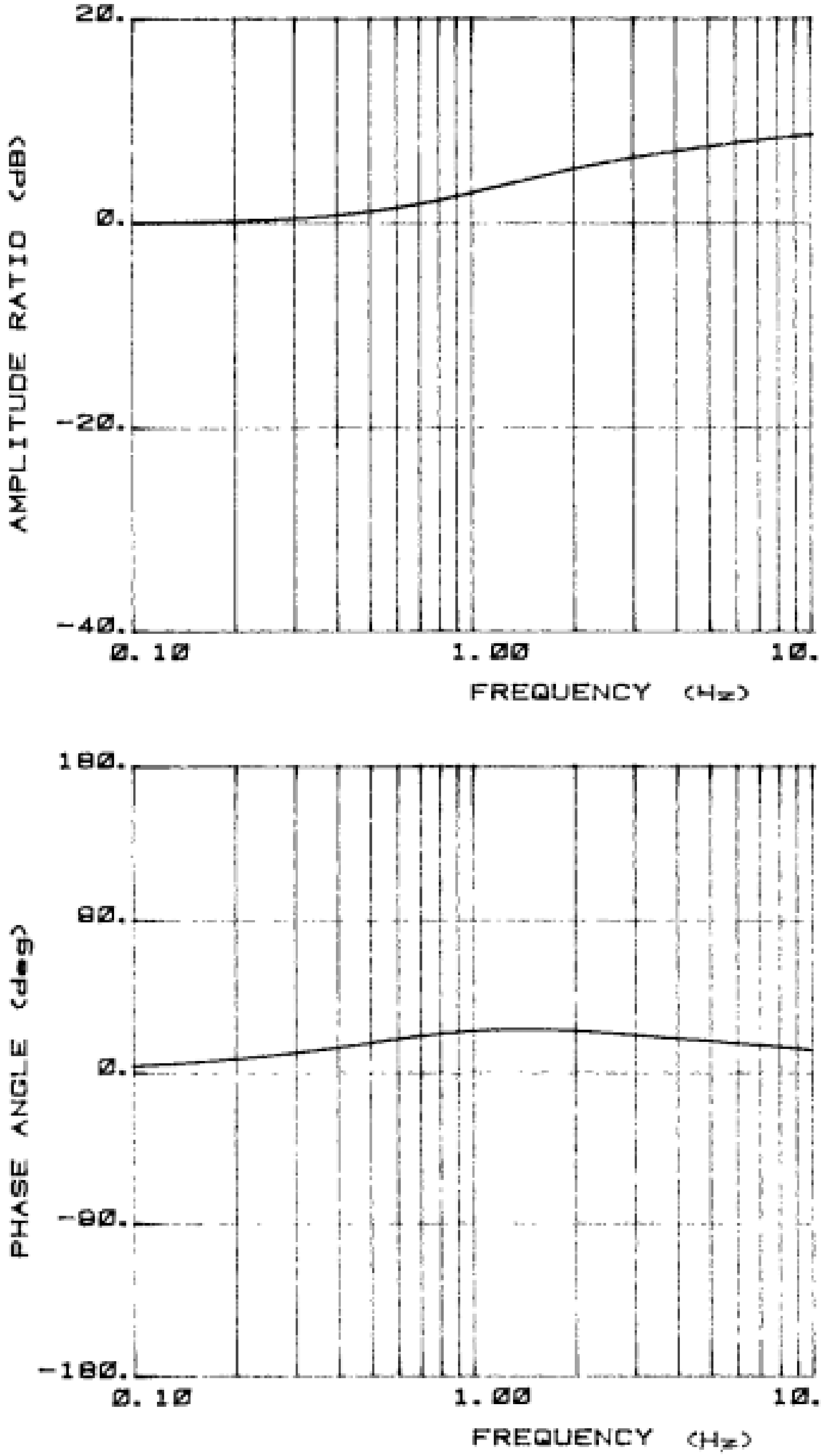


Figure 2.17 Predicted force-displacement frequency response function.

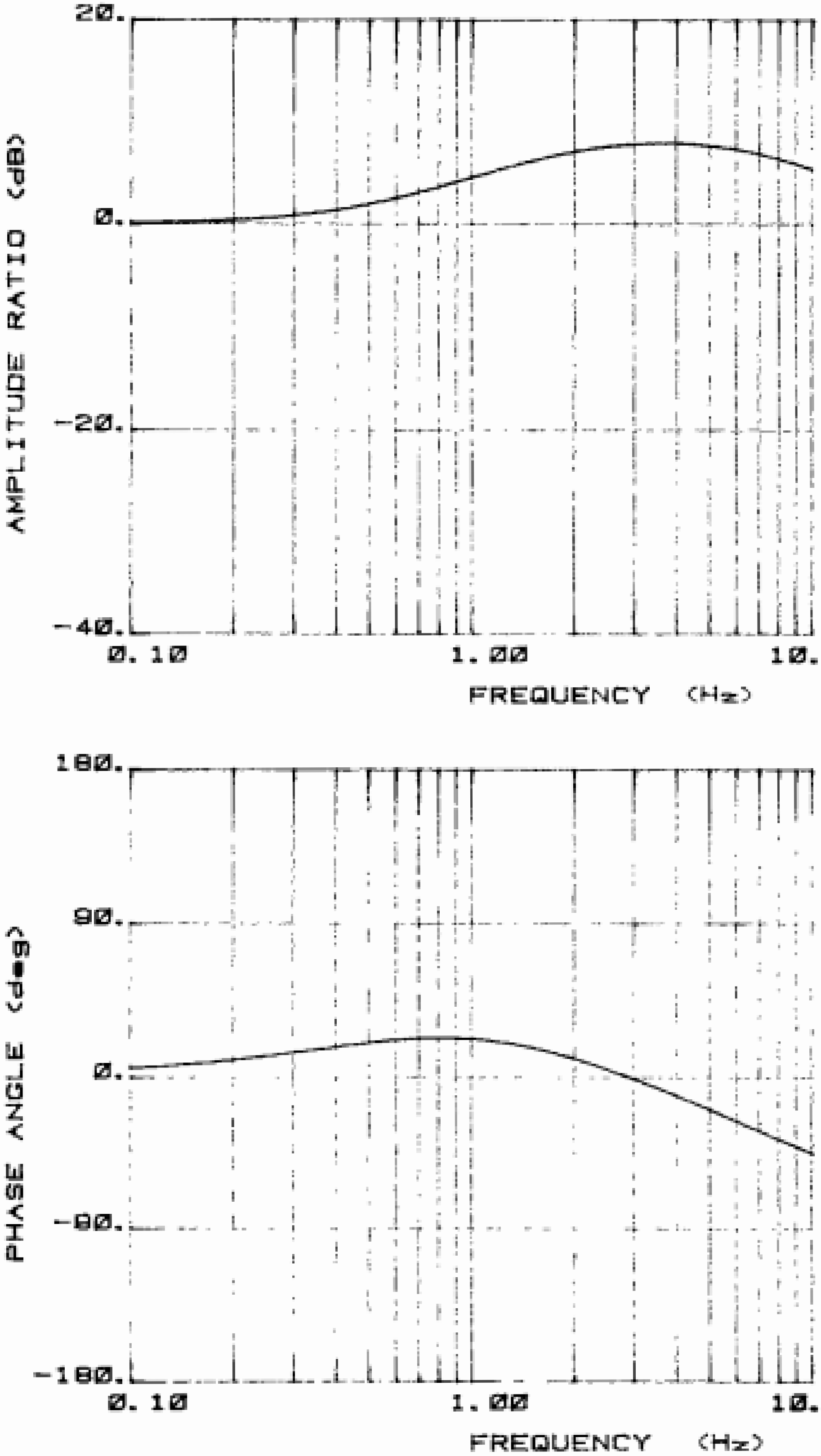


Figure 2.18 Predicted deceleration-displacement frequency response function.

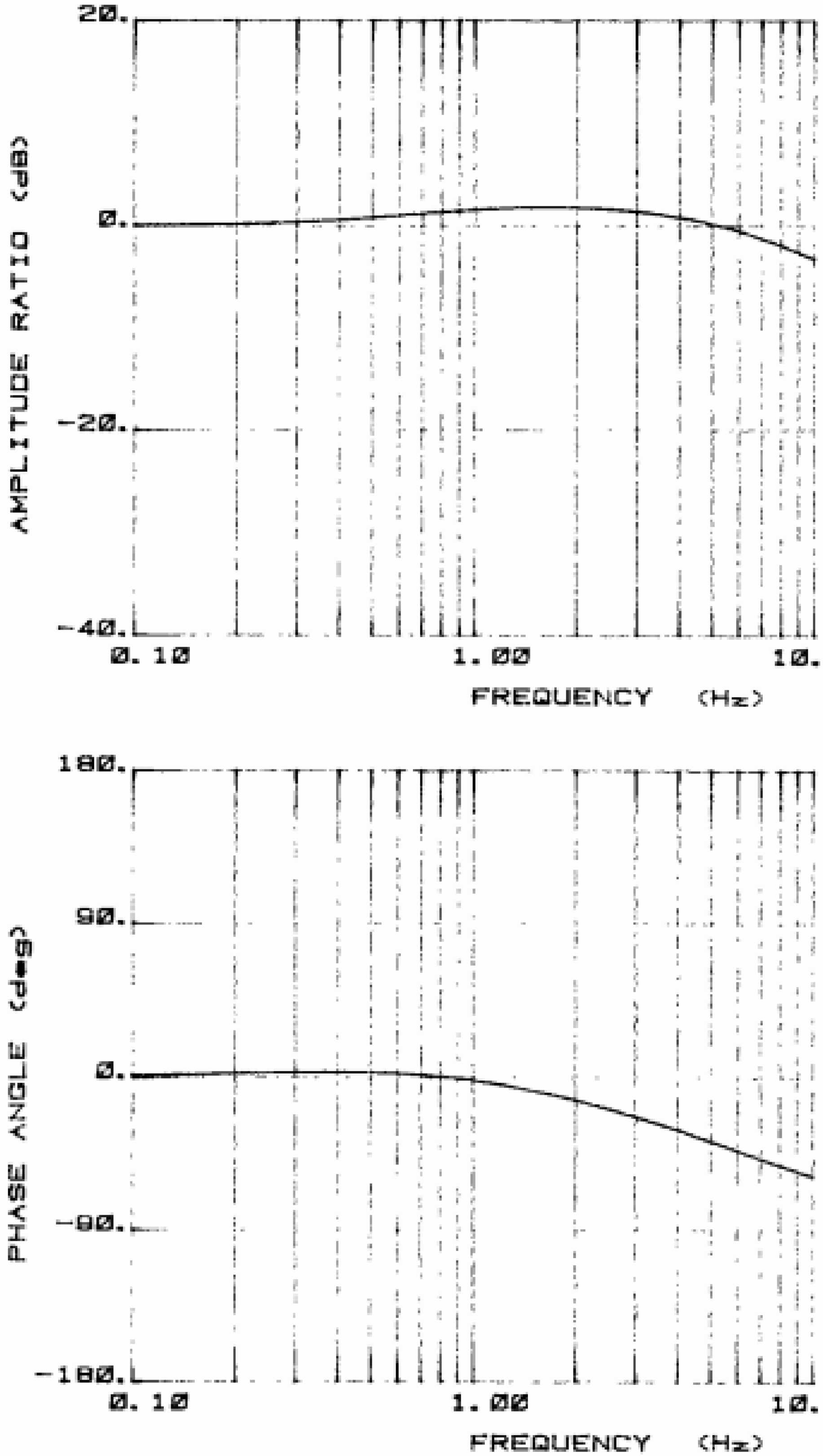


Figure 2.19 Predicted deceleration-force frequency response function.

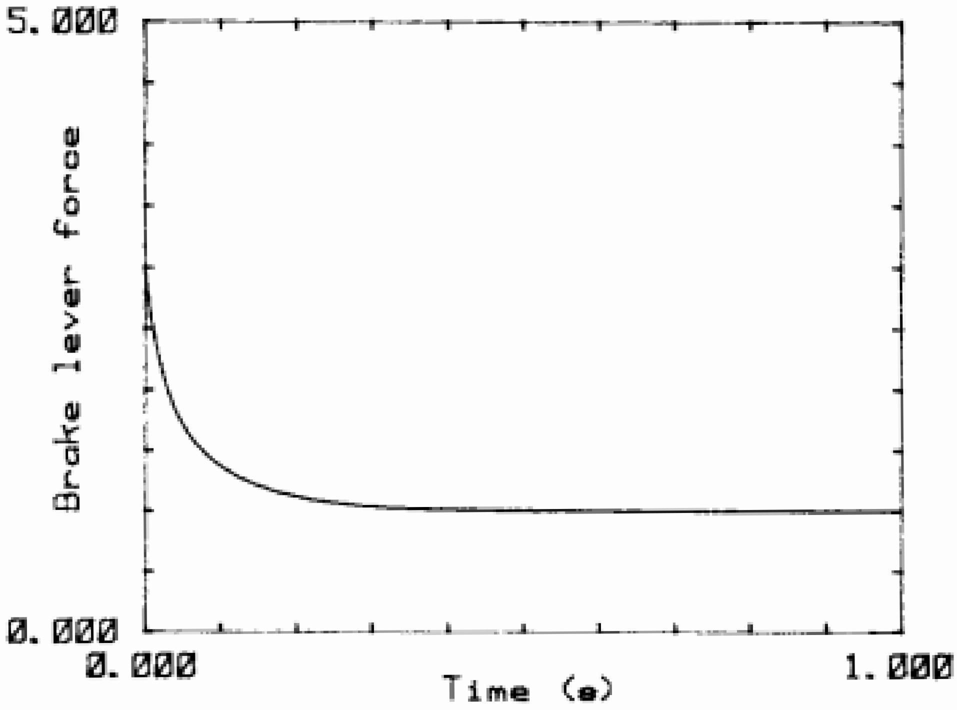


Figure 2.20 Predicted brake lever force response after a step of lever displacement.

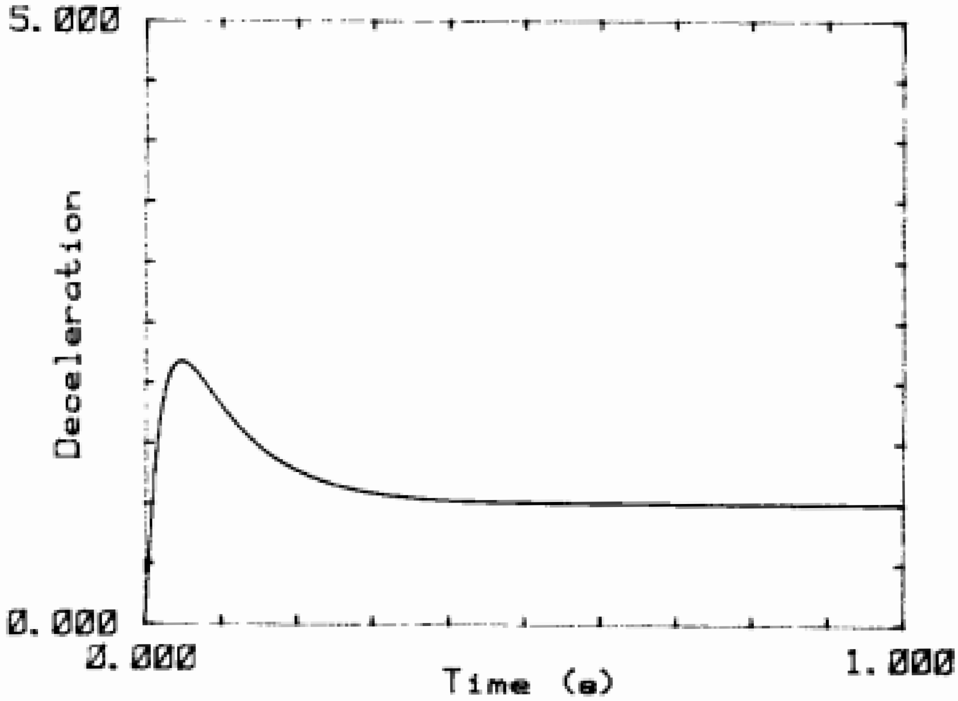


Figure 2.21 Predicted motorcycle deceleration response after a step of lever displacement.

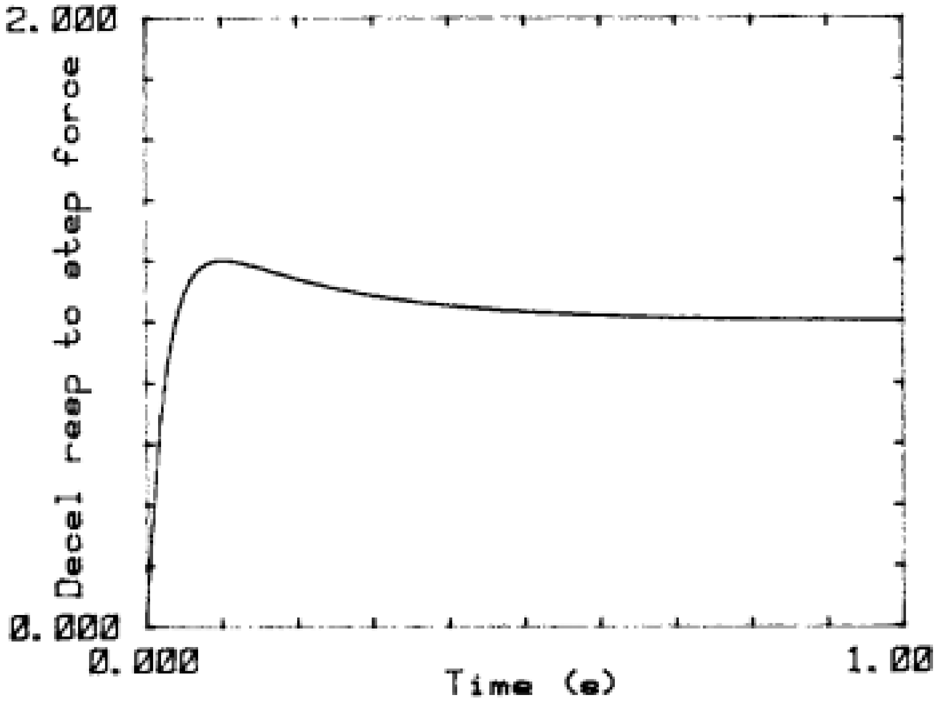


Figure 2.22 Deceleration response to a step input of brake lever force.

(shown in Figures 2.9, 2.7 and 2.8) it is shown in Appendix C that reasonable estimates of the transfer function parameters are:

$$a_1/2\pi = 0.8 \text{ Hz}$$
$$a_2/2\pi = 6.0 \text{ Hz}$$
$$a_3/2\pi = 0.6 \text{ Hz}$$
$$b_1/2\pi = 1.8 \text{ Hz}$$
$$b_2/2\pi = 8.0 \text{ Hz}$$

Bode plots of the frequency response functions predicted by equations (2.1) to (2.3) for these parameter values are shown in Figures 2.17, 2.18 and 2.19. The amplitude ratios in these plots have been normalised by the steady-state values.

Detailed comparison of the predicted and measured Bode plots shows that the proposed mathematical model is able to account for the main features of the measured front brake responses, in particular the relatively constant deceleration/force gain and the mid-frequency 'plateau' in deceleration/displacement and brake stiffness gains. The differences between the phase curves are also well accounted for.

2.6.3 Step Responses

Using the parameter values established in the last Section, the transfer functions in equation (2.1) and (2.2) may also be used to predict the lever force and motorcycle deceleration responses to a step input of lever displacement. These computed transient responses (normalised by the steady state values) are shown in Figures 2.20 and 2.21. The 'dynamic force magnification' effect, noted for the 400 ml motorcycle in Figures 2.3 and 2.10, is clearly evident in the predicted brake lever force.

The predicted deceleration response (assumed proportional to the disc clamping force) exhibits a similar initial peak. The experimental deceleration trace in Figure 2.3 also shows an initial peak, followed by some oscillations. An initial peak in the deceleration response to step inputs of brake control has been noted previously by Weir, Zellner and Teper (1978) and Zellner and Klaber (1981). Zellner (1980) attributes the peak to the transient weight transfer to the front wheel which momentarily increases the braking force available. It would seem that longitudinal tyre dynamics could play a part also. Figure 2.3 indicates a rather lightly damped oscillatory dynamic mode. Such dynamic effects are not considered in the simple mathematical model of Appendix C.

Taking it that this oscillatory behaviour is a result of dynamic effects not directly related to the brake mechanisms modelled in Appendix C, then the form predicted for the deceleration trace appears in reasonable accord with the experiment.

On the whole, it may be concluded that the mathematical model presented in Appendix C accounts for the important aspects of the transient and steady-state responses of the brake system. It is of some interest, therefore, to use the model to predict the motorcycle response to an input which could not be applied experimentally with any accuracy: a step input of brake lever force. The result, shown in Figure 2.22, suggests that the 400 ml motorcycle would respond very rapidly and accurately to such a force input.

2.7 MINIMUM TEST REQUIREMENTS FOR CHARACTERIZATION OF A MOTORCYCLE HYDRAULIC DISC BRAKE SYSTEM

From the experiments conducted with the 400 ml machine it was concluded that the following test program should be sufficient to identify the behaviour of a motorcycle disc brake:

(I) Static laboratory tests, to reveal force-displacement characteristics, quantifying stiffness, hysteresis, dynamic force magnification and leakage effects.

(II) Displacement modulation tests, carried out in the field, yielding displacement/deceleration gradient, force/deceleration gradient and displacement-deceleration and force-deceleration hysteresis loops.

(III) Step displacement tests to allow observation of recovery rate gradient (RRG) and the dynamic force magnification effect.

(IV) Swept sine displacement testing. This allows quantification of displacement/force, deceleration/displacement and deceleration/force transfer functions, and hence the magnitude and phase frequency response of the system.

2.8 DATA COLLECTION WITH 250 ml AND 750 ml MOTORCYCLES

The 250 ml and 750 ml machines were instrumented as described in Section 2.3., and Appendix A.

The test program outlined in Section 2.7 was completed with the 250 ml and 750 ml motorcycles. All experiments were conducted at the Australian Army Trials and Proving Wing at Monegeetta. One test rider was used for all experiments.

The swept sine displacement test was not performed with the 750 ml motorcycle due to lack of time and inclement weather during the data collection phase. However this motorcycle was fitted with organic pads of the same construction as those on the 400 ml motorcycle, and could be expected to behave in a similar manner.

2.9 RESULTS OF MOTORCYCLE BRAKE EXPERIMENTS

2.9.1 250 ml Motorcycle

The static laboratory tests were performed to study the force-displacement characteristics of the brake system on this motorcycle. Figure 2.23(a) shows front brake force as a function of time for a step input of lever displacement. A force magnification of 0.5 seconds duration is evident in the initial response to the rapid brake application. This effect is strongly dependent on the rate at which the brake is applied; the rate used in these experiments would be similar to that in an emergency stop. The peak amplification of the steady state force in this case is approximately 30%. The same force magnification effect was observed with the 400 ml motorcycle. Figure 2.23(b) shows the force magnification for the rear brake on the 250 ml motorcycle, and the peak amplication is smaller at about 12%.

Leakage of hydraulic fluid past ill-fitting master cylinder cups will result in a decreasing force level at constant displacement, and consequently reduced deceleration with time. Figure 2.24(a) shows no leakage problems with the 250 ml front brake. Figure 2.24(b) on the other hand, indicates some relaxation of force level over a period of about 7 seconds for the 250 ml rear brake.

Displacement cycling of the brakes in the laboratory was used to quantify hysteresis effects. Figures 2.25(a) and (b) show plots of brake lever force versus displacement for the 250 ml front and rear brakes. In each case a hysteresis loop is clearly evident. The upper part of each curve corresponds to brake application. During brake release, the brake force decreases until coulomb friction forces in the system are overcome and then the displacement decreases. As can be seen from Figure 2.25 the hysteresis force was about 25N for the front brake and 60N for the rear brake.

The force-deceleration and displacement-deceleration gradients were obtained from the dynamic displacement modulation test procedure outlined in Section 2.5.3. The brake displacement and force gradients were determined by digitizing and storing the data thus obtained on a PDP 11/23 computer system. A program was written which accessed the force, displacement and deceleration data during the brake onset phase, and used linear regression analysis to fit a straight line which yielded the required gradients. Figures 2.26(a) and (b) show deceleration-displacement and deceleration-force data respectively for the 250 ml front brake. The regression lines are included on these graphs. The front brake displacement gradient was 2.62 mms^2/m and the force gradient was 16.8 Ns^2/m. These front brake results, and those for the rear brake, are set out in Table 2.2.

The step displacement data were also digitized and stored on the PDP 11/23 computer system. This enabled the recovery rate gradient (RRG - see Section 2.5.2) to be studied. The RRG has been interpreted in this work as the rate of change of deceleration force gain with speed. The force gain is plotted against speed in Figures 2.27(a) and (b) for the front and rear brakes respectively. The force gain is observed to increase with decreasing speed for both the front and rear brakes with this motorcycle. This machine is fitted with metal sintered pads, which Zellner and Klaber (1981) found may yield a positive RRG under dry conditions. This did in fact occur on most occasions with this motorcycle, and Figures 2.27(a) and (b) are indicative of typical performance. The RRG for these runs was measured to be $1.0 \times 10^{-3}\ N^{-1}\ s^{-1}$ on average, for both front and rear brakes. These results are presented in Table 2.2. However, RRG was observed to change from run to run, and also during a run, so that positive, zero and negative RRGs were all observed at some time with this motorcycle. This somewhat erratic behaviour cannot be explained at this stage, and warrants further investigation.

The swept-sine displacement test was also performed, and the data processed with the laboratory computer system to obtain force/displacement, deceleration/displacement and deceleration/force transfer functions. The useful frequency range is from zero to about 7 Hz, which was the maximum modulation frequency the rider could produce. The results for the front and rear brakes are shown in Figures 2.28 (a), (b) and (c), and 2.29 (a), (b) and (c) respectively. As was noted with the 400 ml motorcycle (see Section 2.5.4), the force gain is approximately constant over the range of rider control frequencies, and the displacement gain and dynamic stiffness are frequency dependent in the range 0 to 1.5 Hz.

2.9.2 750 ml Motorcycle

The static step displacement tests for this motorcycle revealed dynamic force magnification for the front brake of 13%, and 6% for the rear brake (Figures 2.30 (a) and (b)). Observation of the step displacement traces over a longer time period indicated hydraulic fluid leakage with the front brake. The lever force decreased by 40 N in 8.4 seconds. Negligible leakage, however, was observed with the rear brake.

The dynamic displacement modulation data were used to investigate force hysteresis effects (as the static data collected for this purpose were unacceptably noisy). Plots of brake force versus displacement for the front and rear brakes are shown in Figures 2.31(a) and (b) respectively. Force hysteresis was measured to be 20 N with the front brake and 35 N with the rear brake.

The force/deceleration and displacement/deceleration gradients were obtained by a similar procedure to that used for the 250 ml machine. The results, together with those obtained for the 250 ml and 400 ml motorcycles, are shown in Table 2.2.

The dynamic step displacement data were used to obtain the RRG for the 750 ml machine. The results are shown in Figure 2.32(a) and (b). The RRG is seen to be almost zero, as was the case with the 400 ml motorcycle.

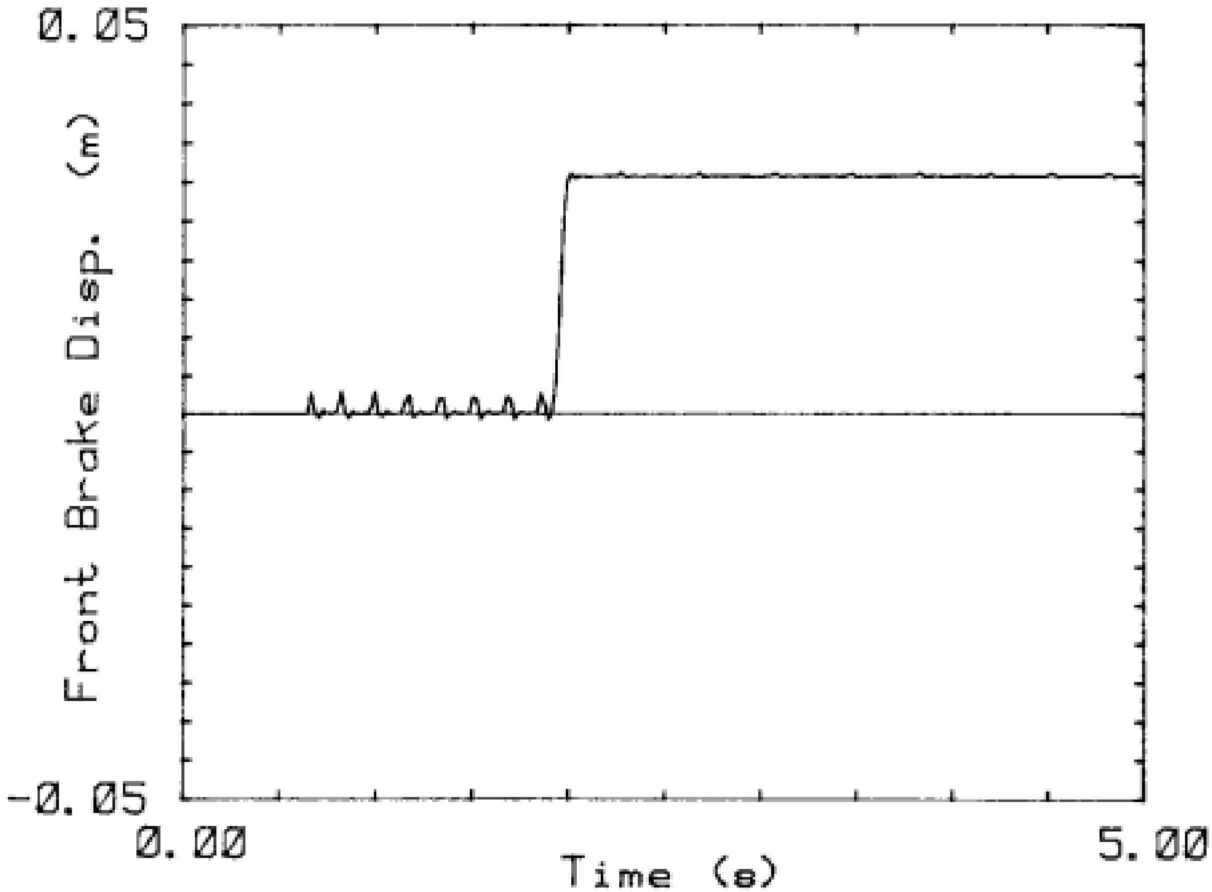
2.9.3 Comparison of 250 ml, 400 ml, and 750 ml Brake System Performance

The force magnification phenomenon was observed with all the hydraulic disc brakes tested. The maximum amplification observed was approximately 30%, for the 250 ml front brake.

Leakage effects were noticed with three brake systems. The 750 ml front brake force dropped by 40 N in 8.4 seconds at constant displacement. Similar problems were encountered, to a lesser extent, with the 400 ml front brake and the 250 ml rear brake.

Force hysteresis was investigated, and a wide range of values was observed, as can be seen from Table 2.2. The largest hysteresis force was 70 N with the 400 ml front brake, and the smallest was 20 N with the 750 ml front brake. This represents a 3.5 times variation in magnitude. The largest rear brake hysteresis force was 60 N with the 250 ml motorcycle.

A comparison of front brake displacement gradients showed that the 250 ml machine had the largest value (2.62 $mm.s^2/m$), and the 750 ml the smallest (2.53 $mm.s^2/m$). This represents only about 5% difference between the largest and smallest values of front brake displacement gradient. For the rear brakes, the 250 ml machine had the largest displacement gradient (4.42 $mm.s^2/m$), which was 2.2 times larger than the minimum value (1.72 $mm.s^2/m$) found with the 400 ml rear brake. The latter has a mechanical linkage rather than an hydraulic system.



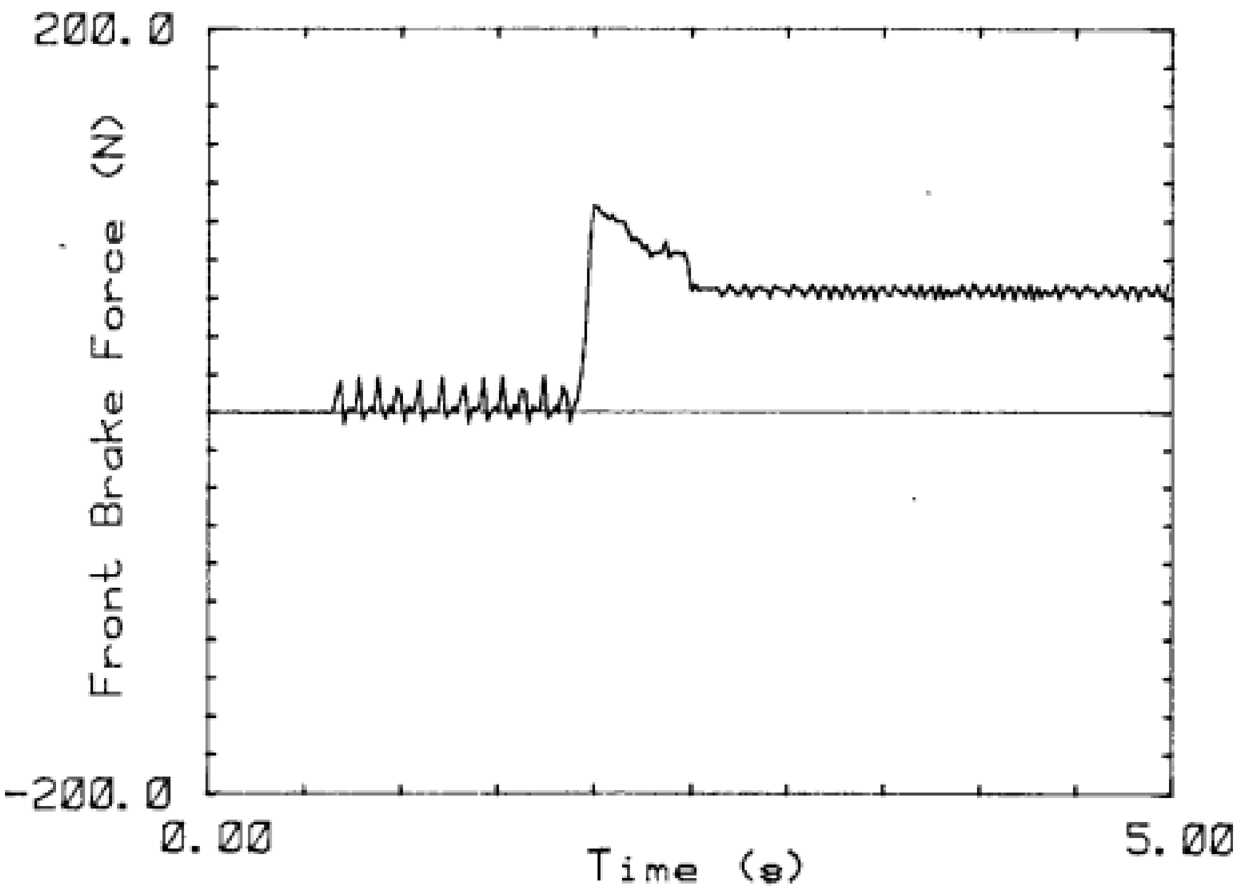
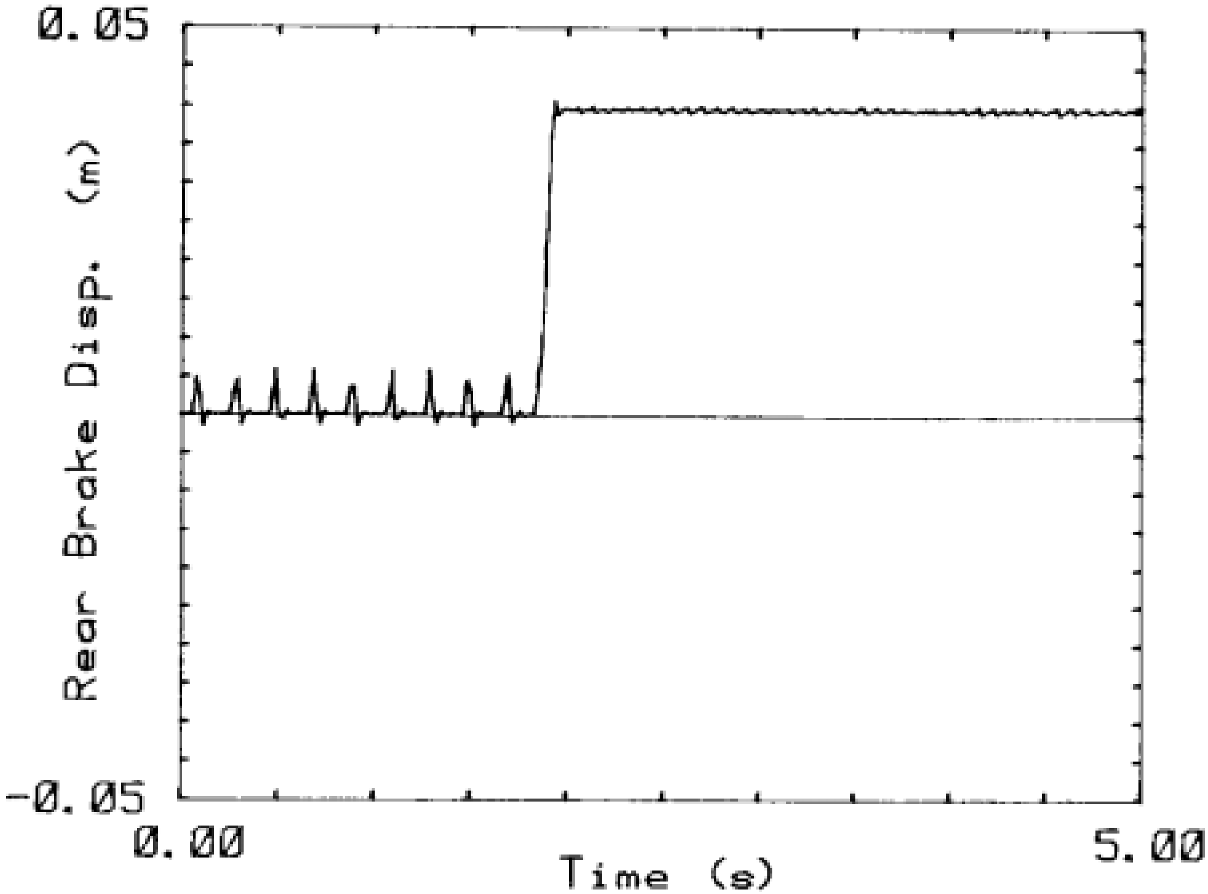


Figure 2.23 (a) Dynamic force magnification effect, front brake 250 ml motorcycle.



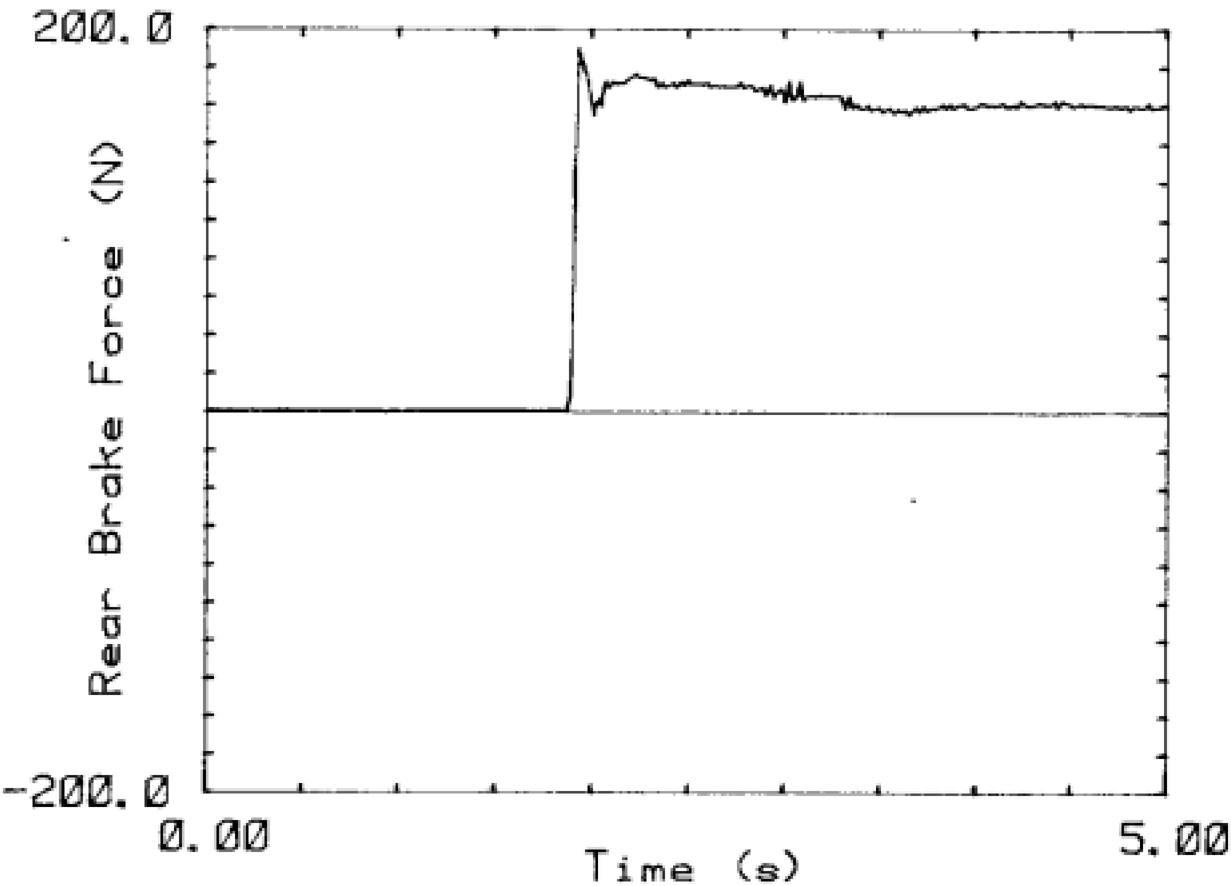


Figure 2.23 (b) Dynamic force magnification effect, rear brake 250 ml motorcycle.

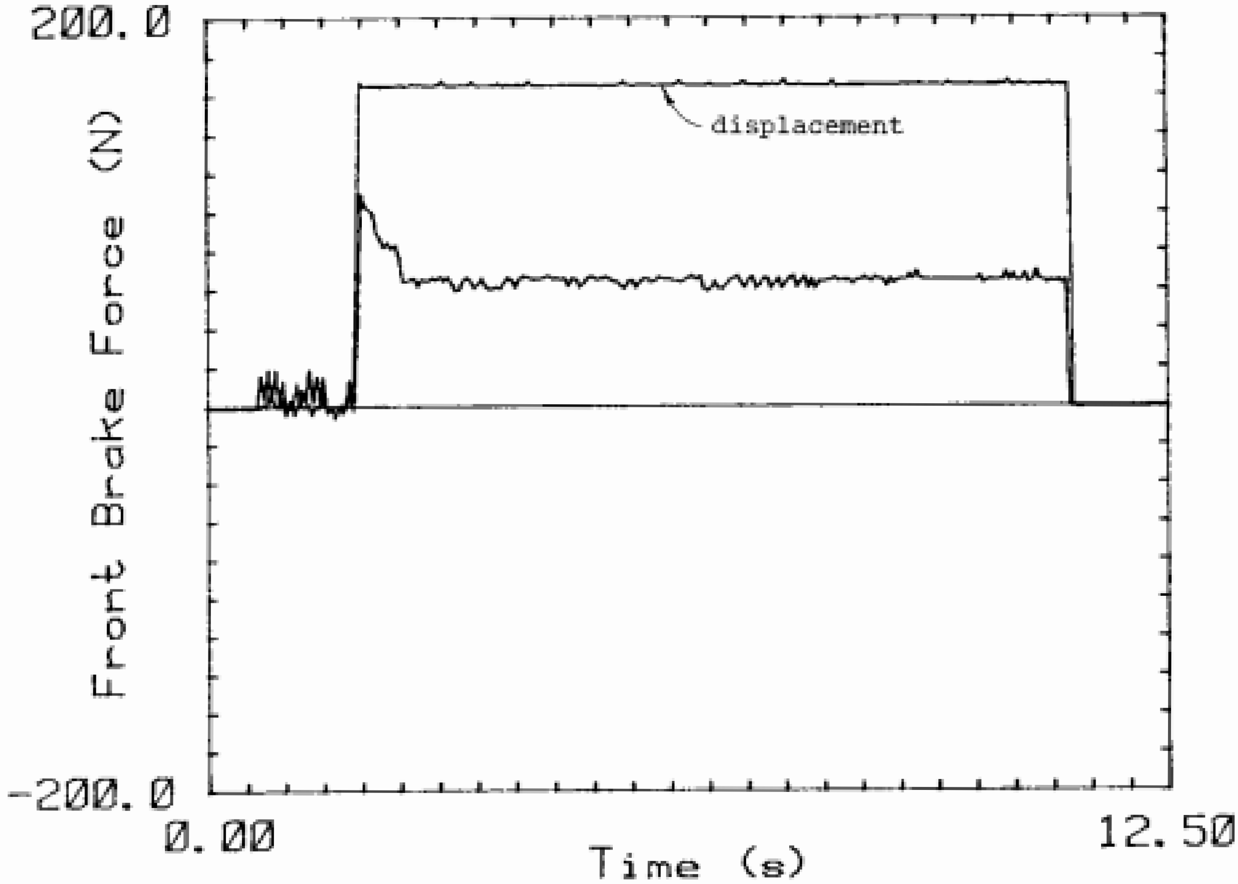


Figure 2.24 (a) Front brake force behaviour over 9 s, 250 ml motorcycle

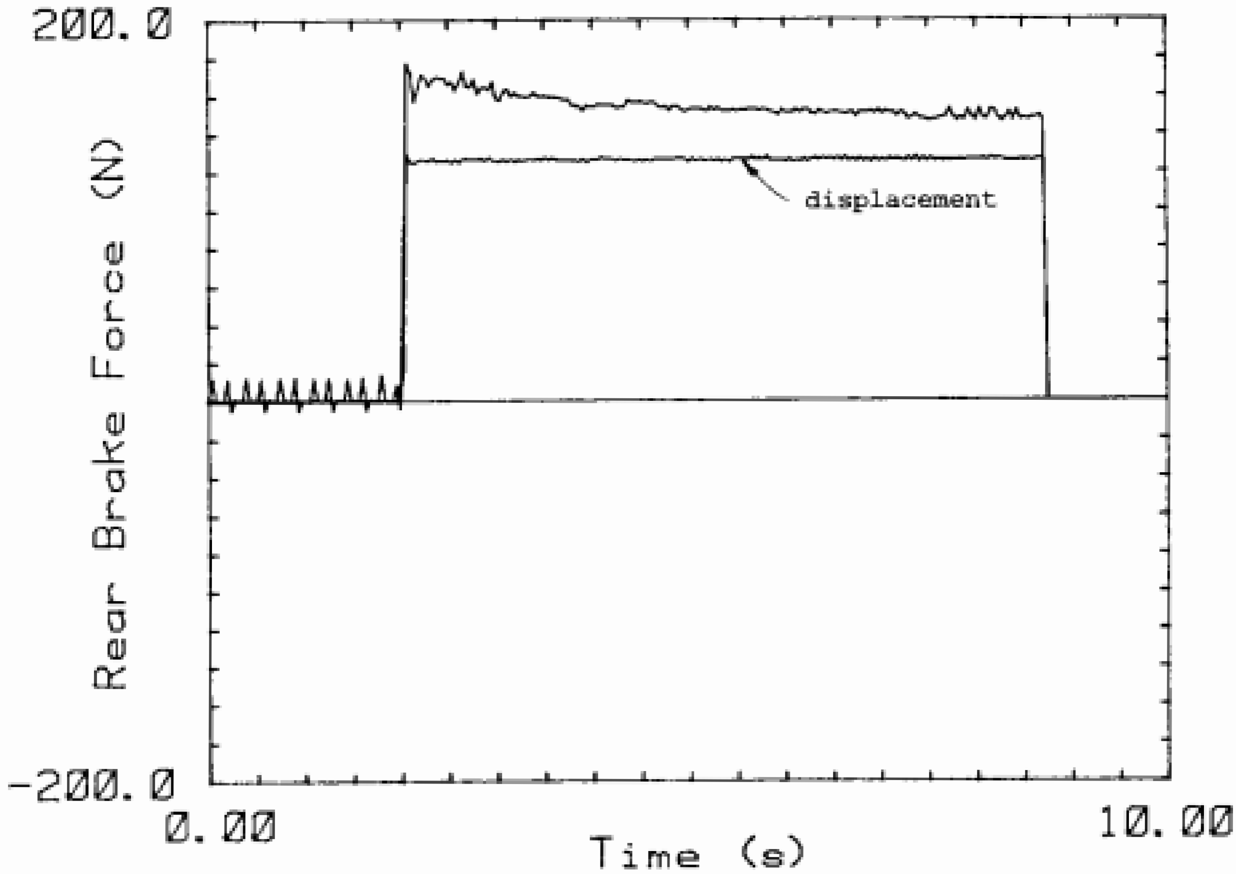


Figure 2.24 (b) Rear brake force behaviour over 7 s, 250 ml motorcycle

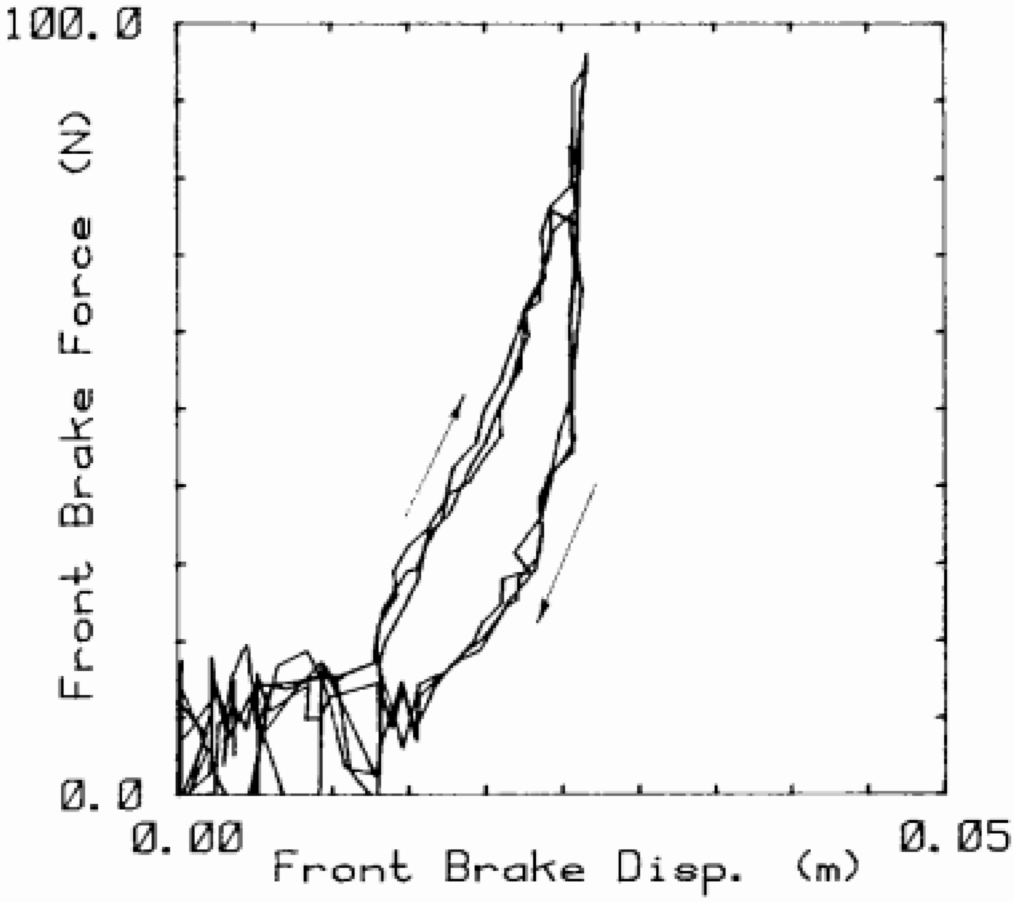


Figure 2.25 (a) Front brake force-displacement characteristics 250 ml motorcycle.

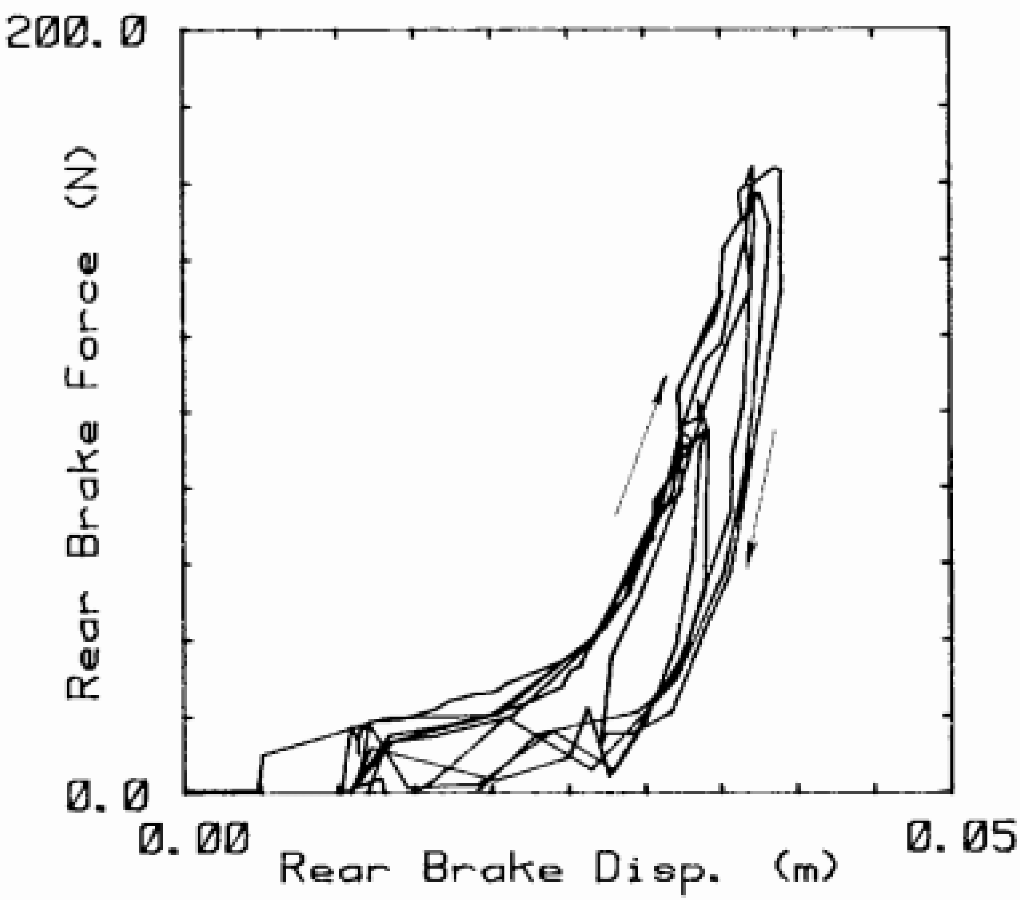


Figure 2.25 (b) Rear brake force-displacement characteristics, 250 ml motorcycle.

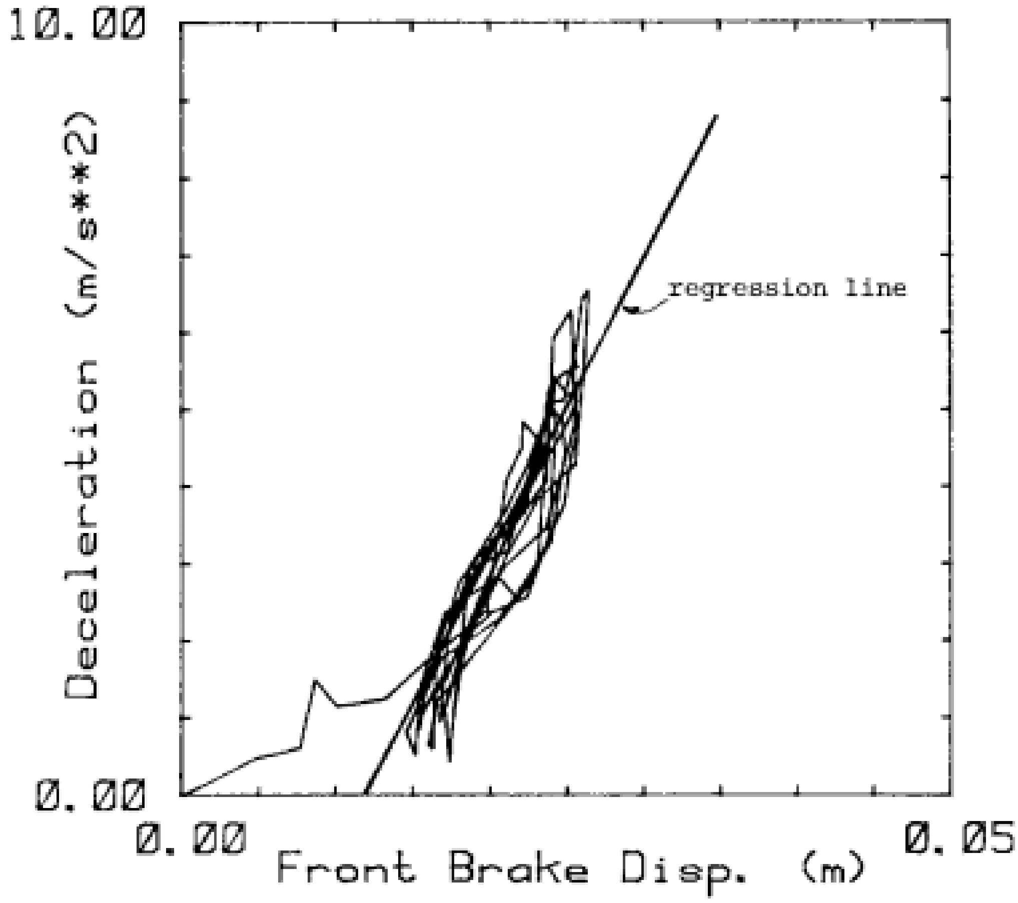


Figure 2.26 (a) Front brake deceleration-displacement characteristics, 250 ml motorcycle.

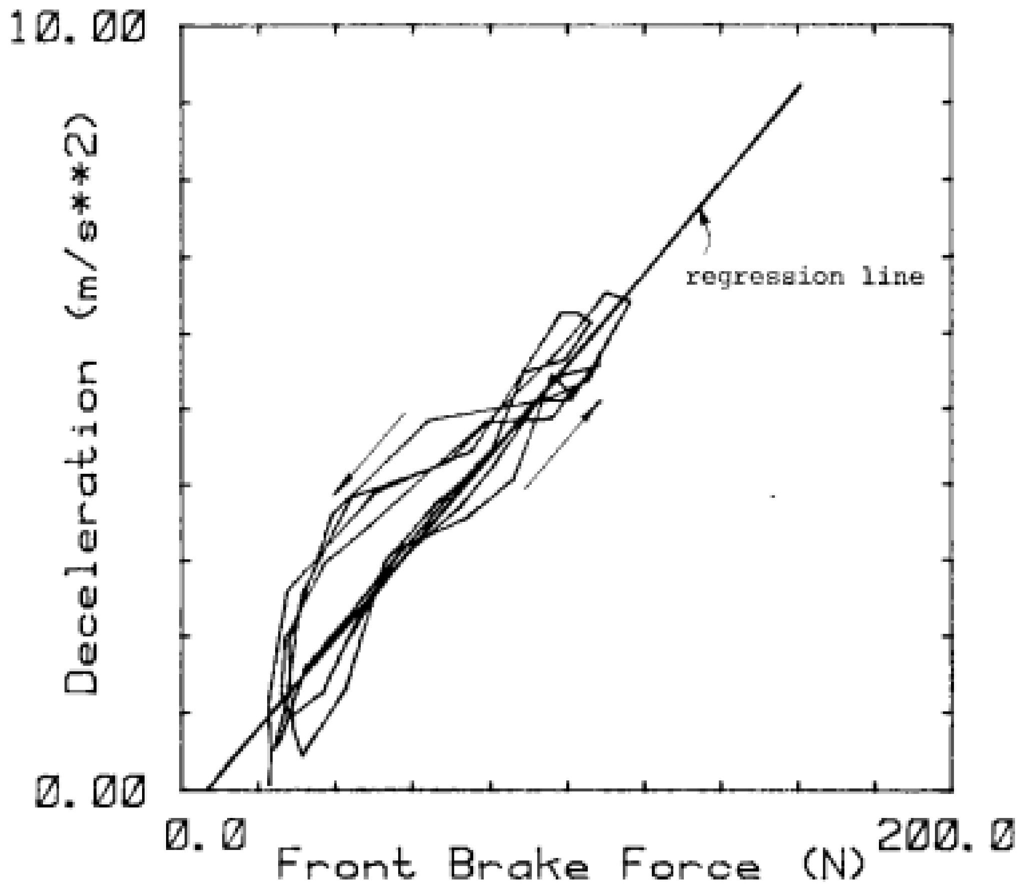


Figure 2.26 (b) Front brake deceleration-force characteristics, 250 ml motorcycle.

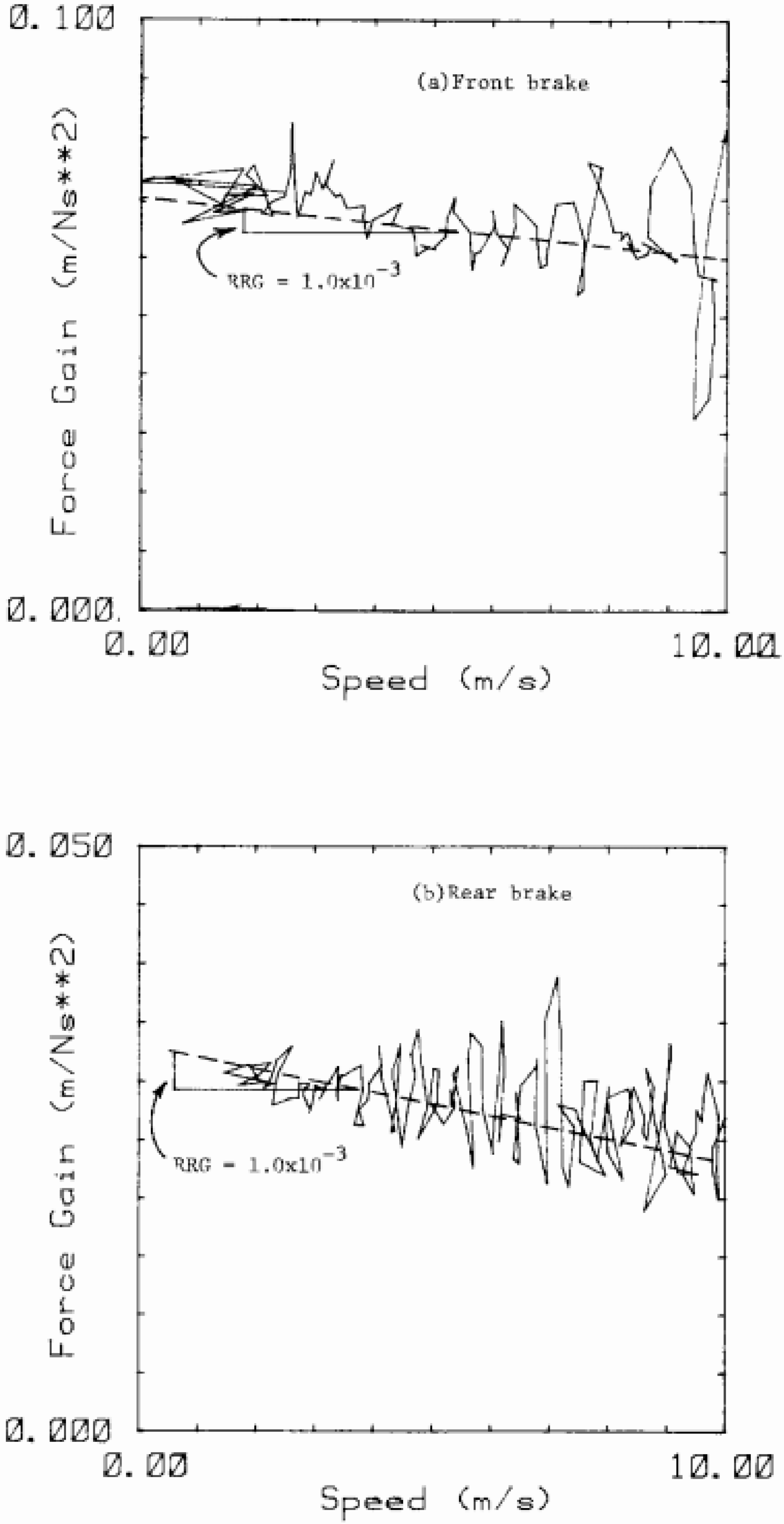


Figure 2.27 Force gain versus speed, 250 ml motorcycle.

(a) Deceleration/displacement.

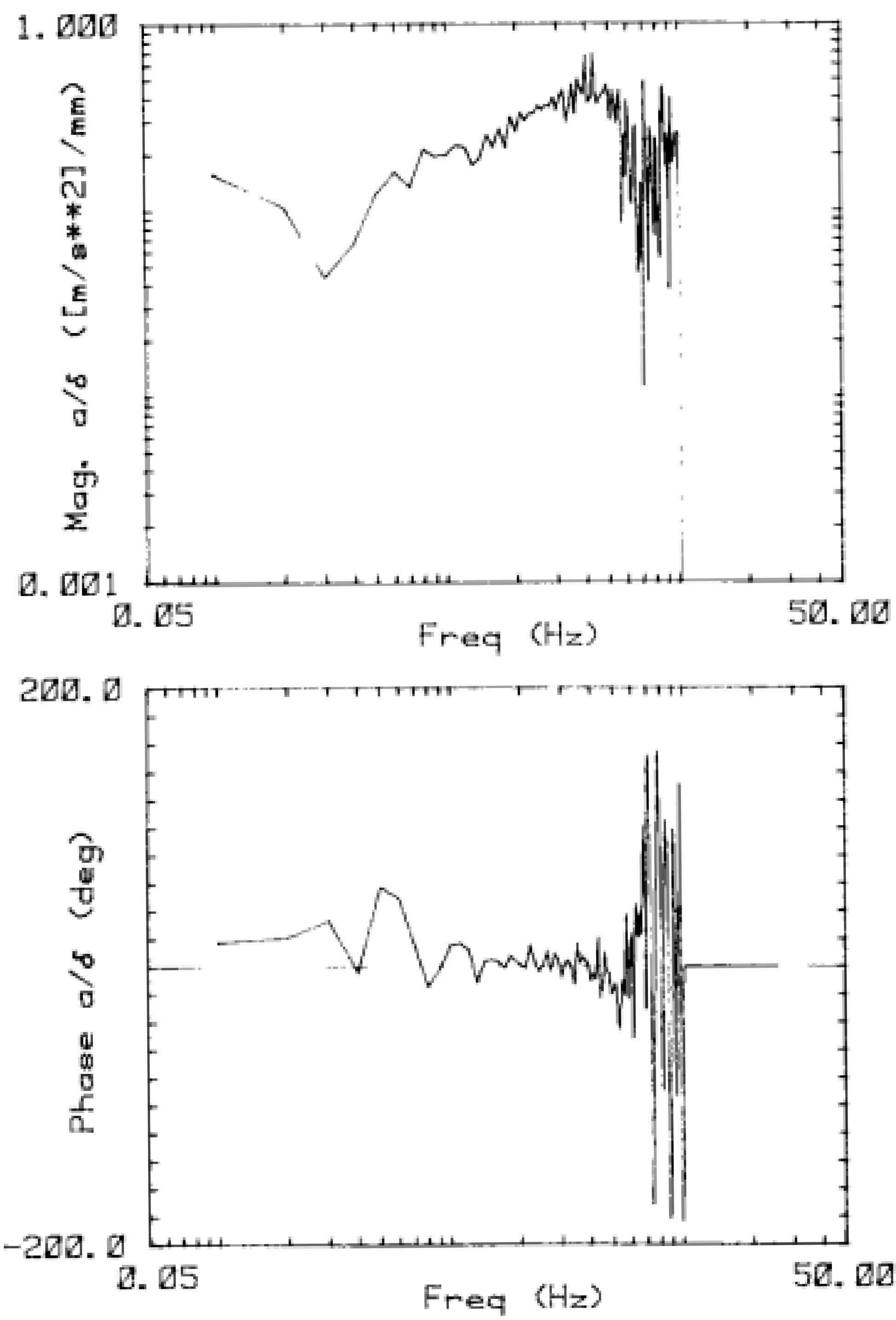


Figure 2.28 Frequency response functions, 250 ml motorcycle, front brake.

(b) Deceleration/force.

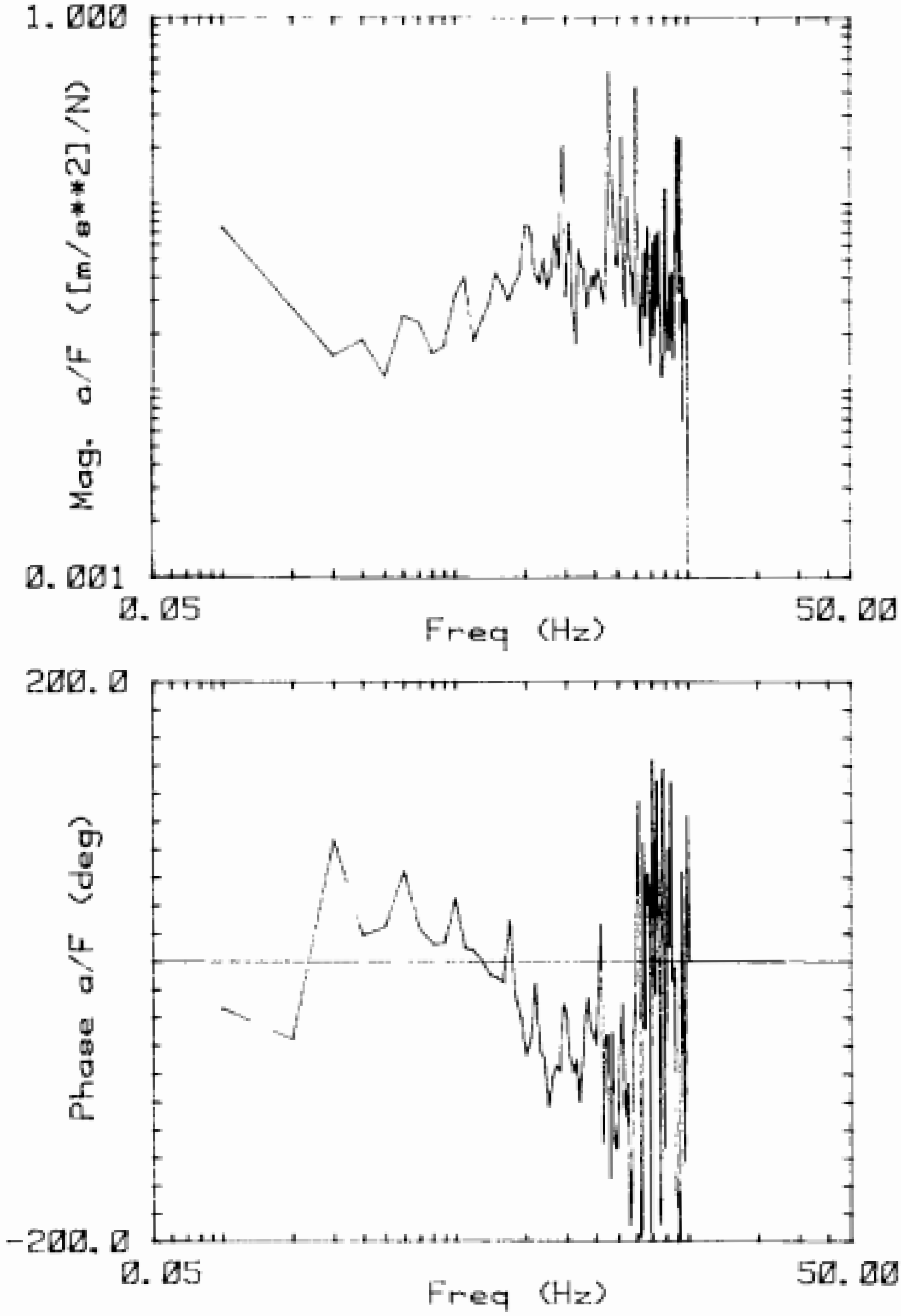


Figure 2.28 (cont)

(c) Force/displacement.

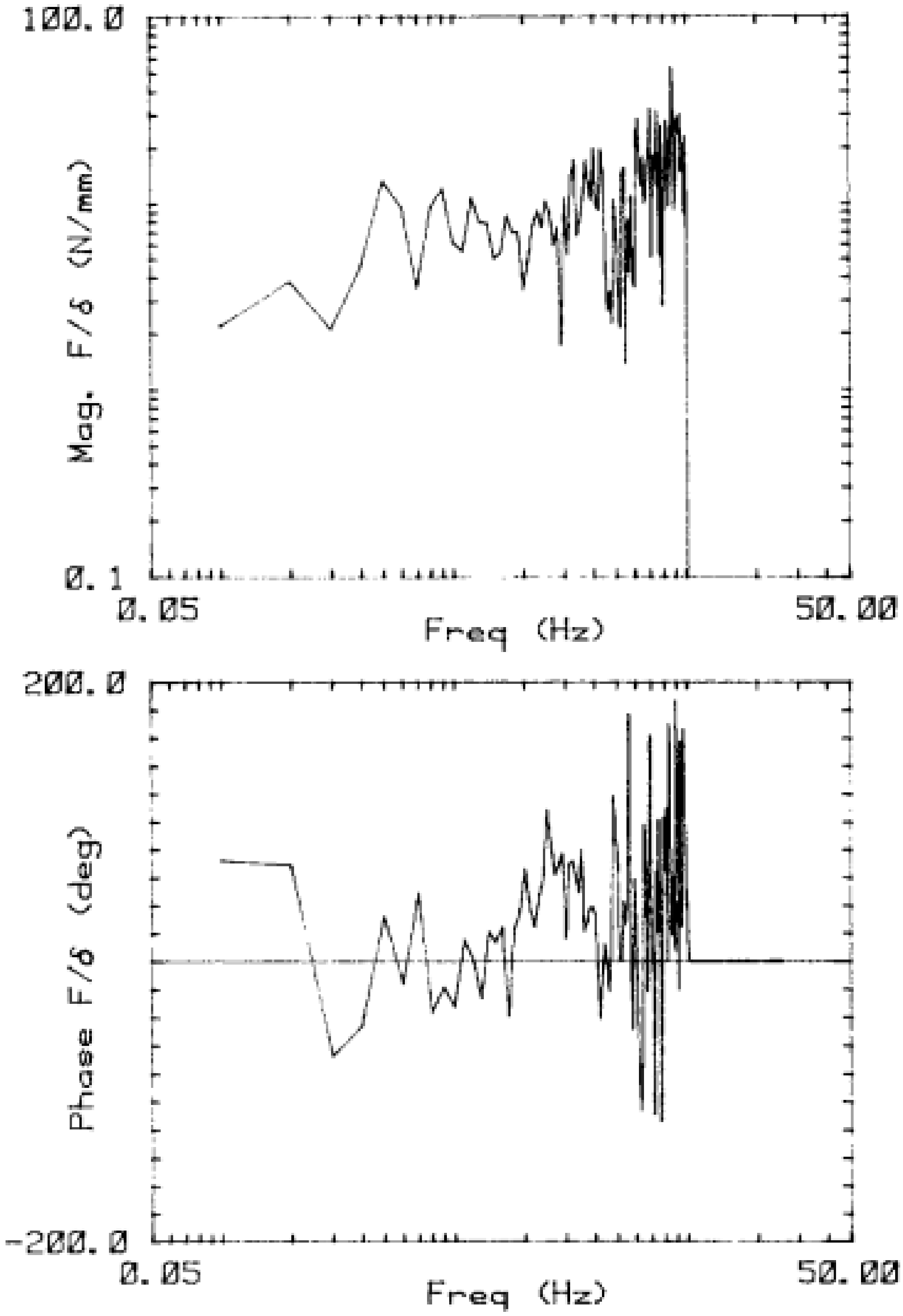


Figure 2.28 (cont.)

(a) Deceleration/displacement.

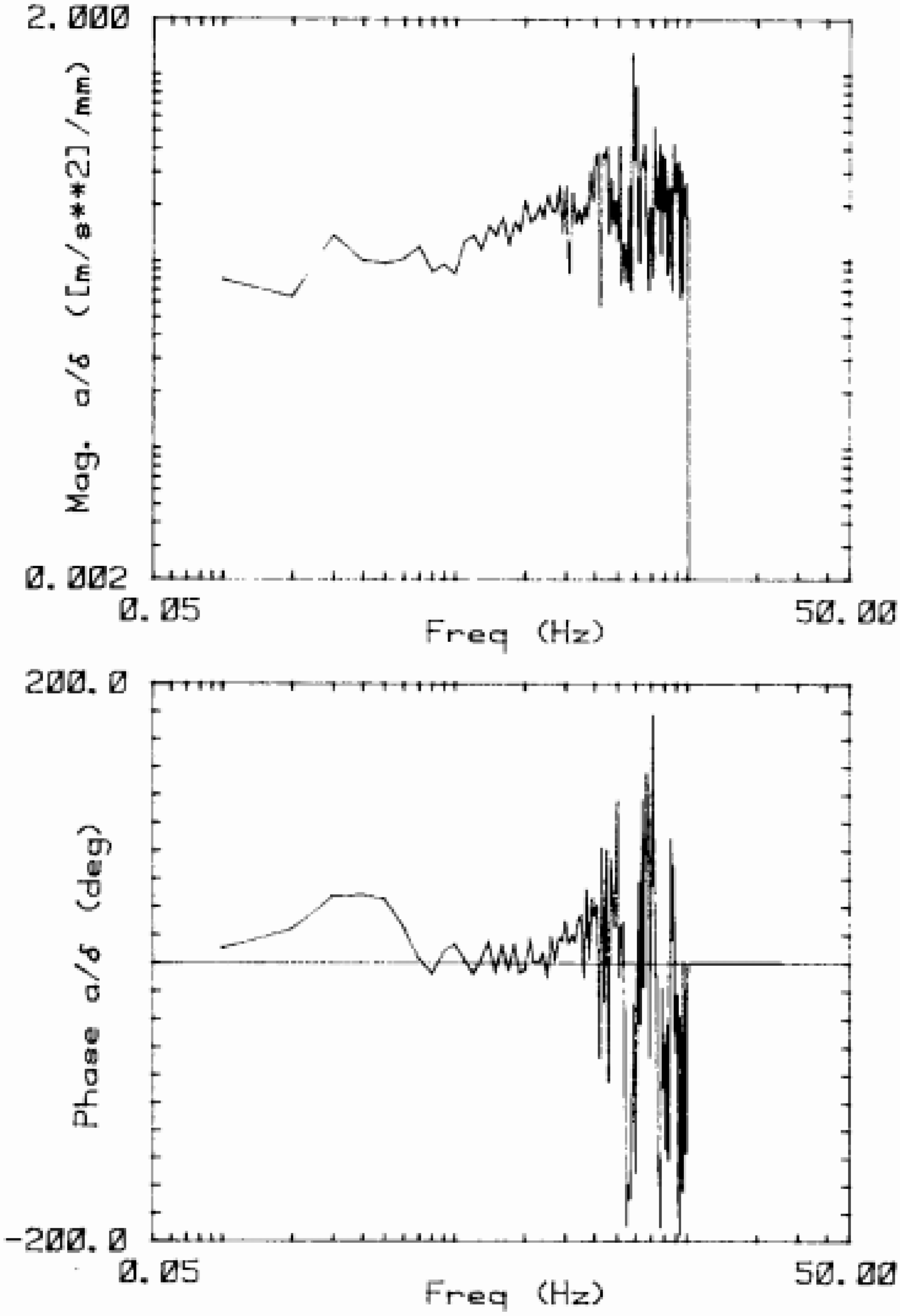


Figure 2.29 Frequency response functions, 250 ml motorcycle, rear brake.

(b) Deceleration/force.

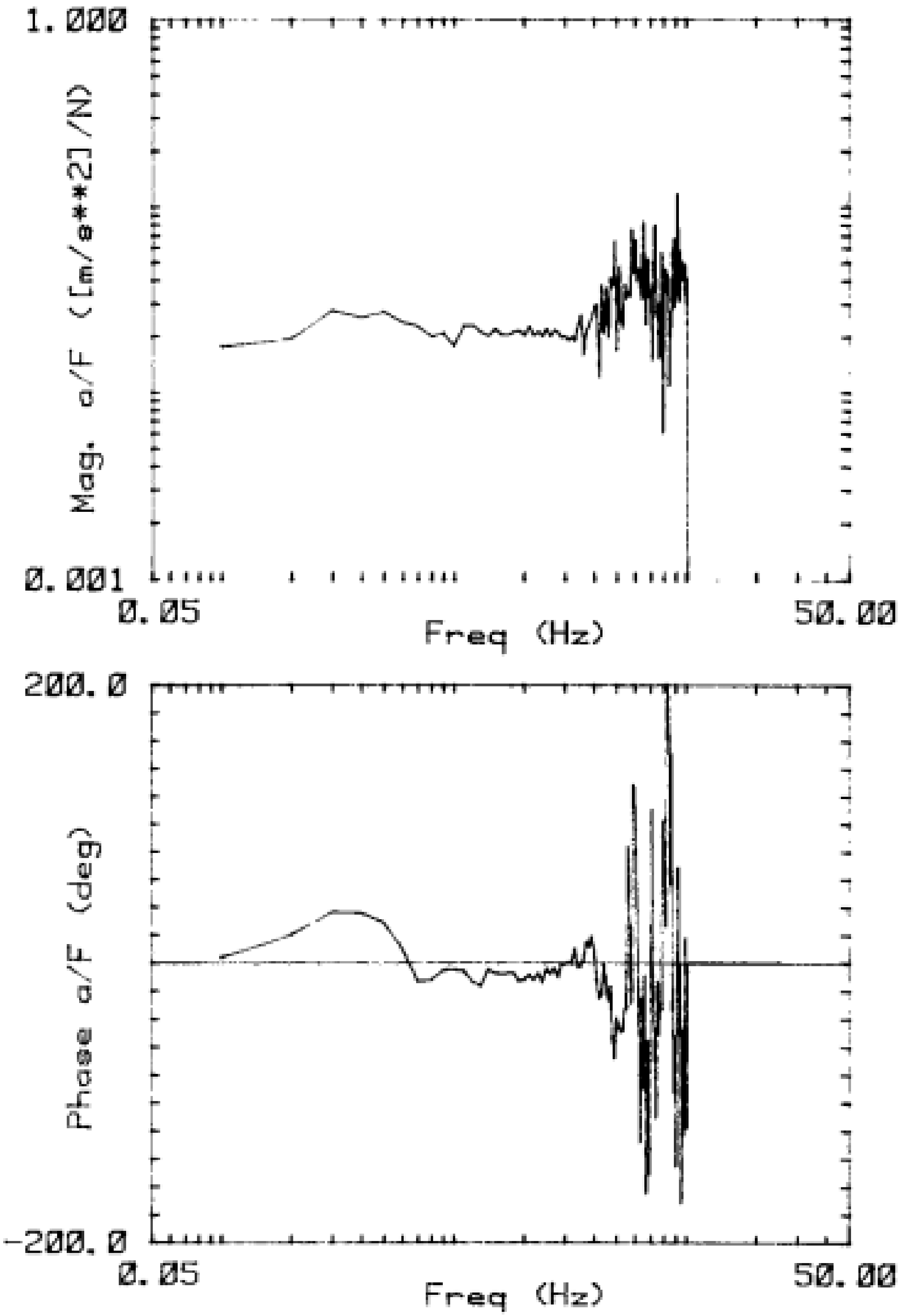


Figure 2.29 (cont.)

(c) Force/displacement.

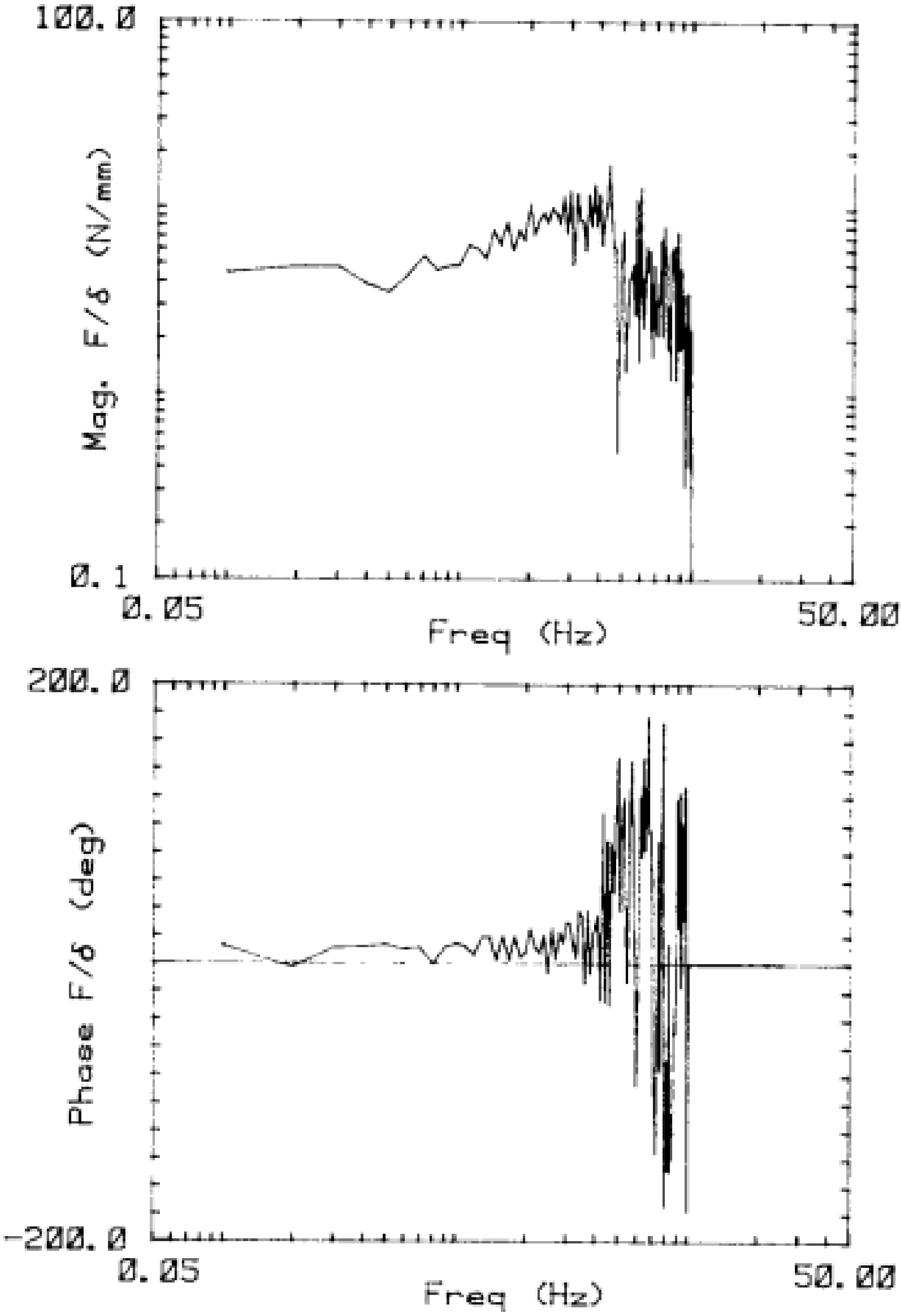
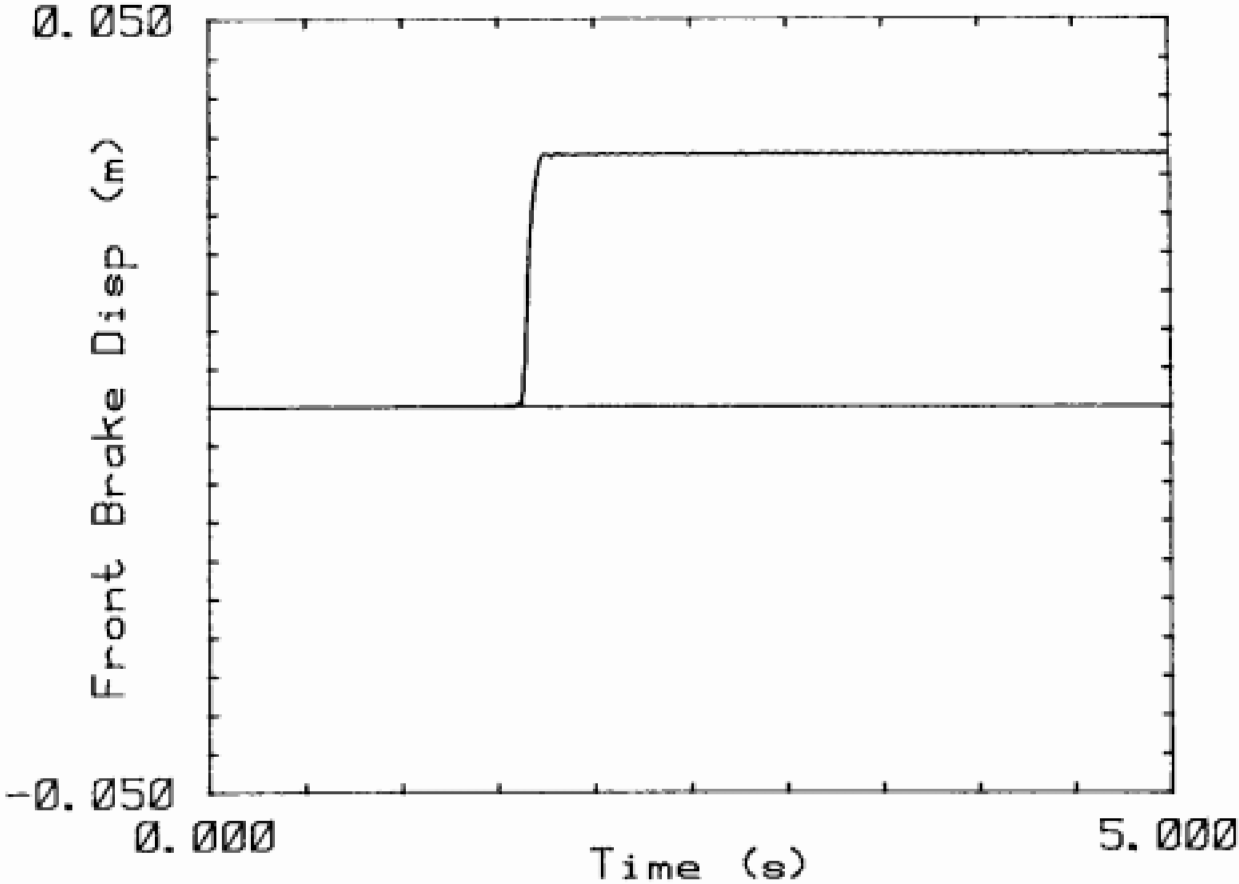


Figure 2.29 (cont.)



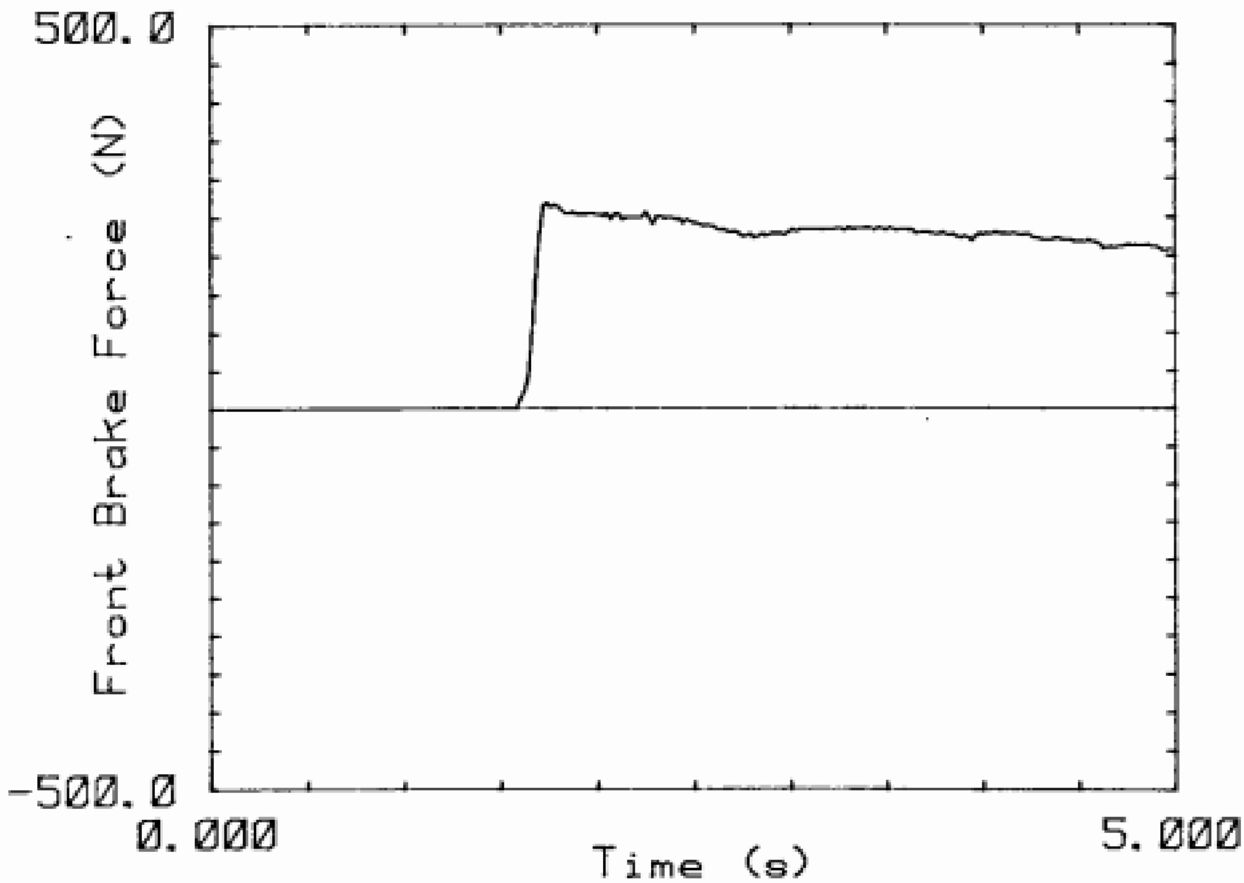
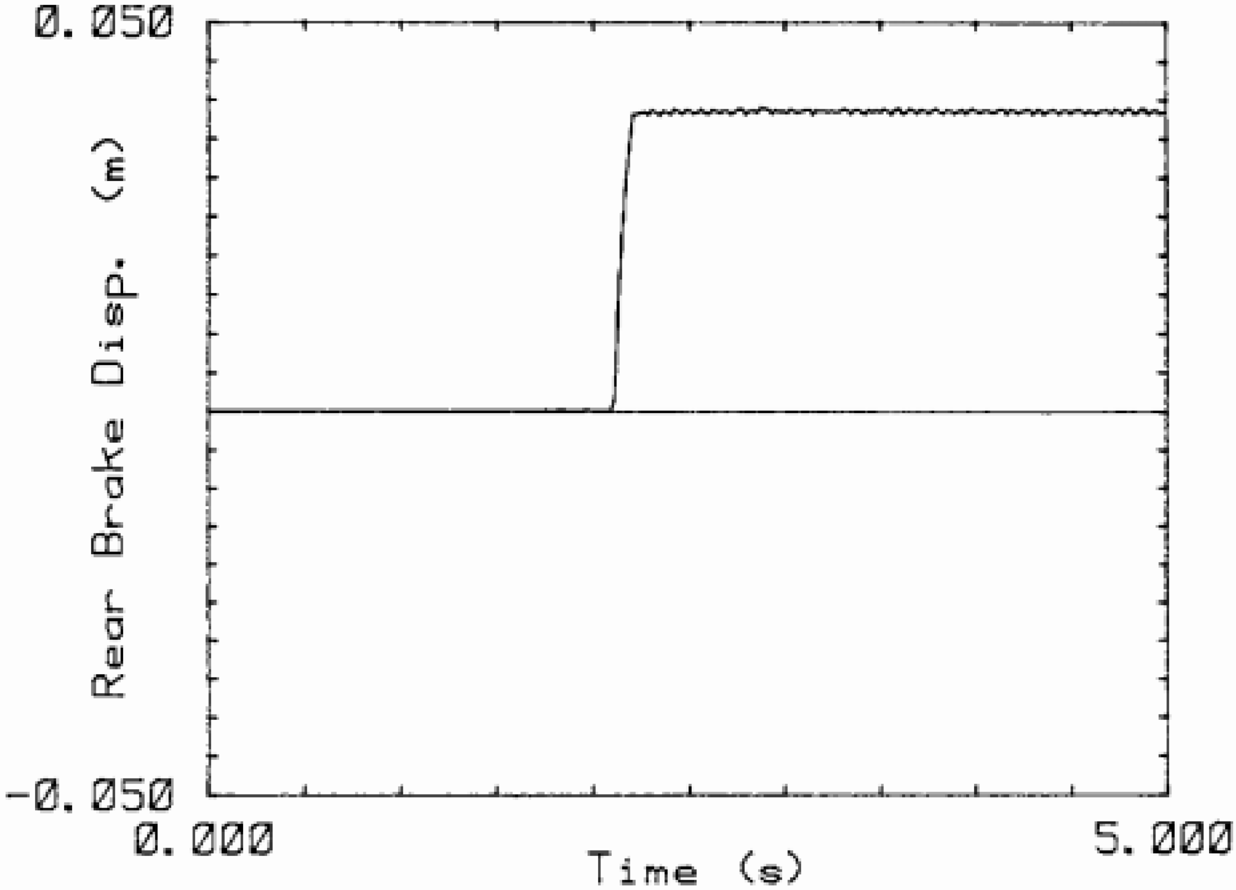


Figure 2.30 (a) Dynamic force magnification effect, front brake 750 ml motorcycle.



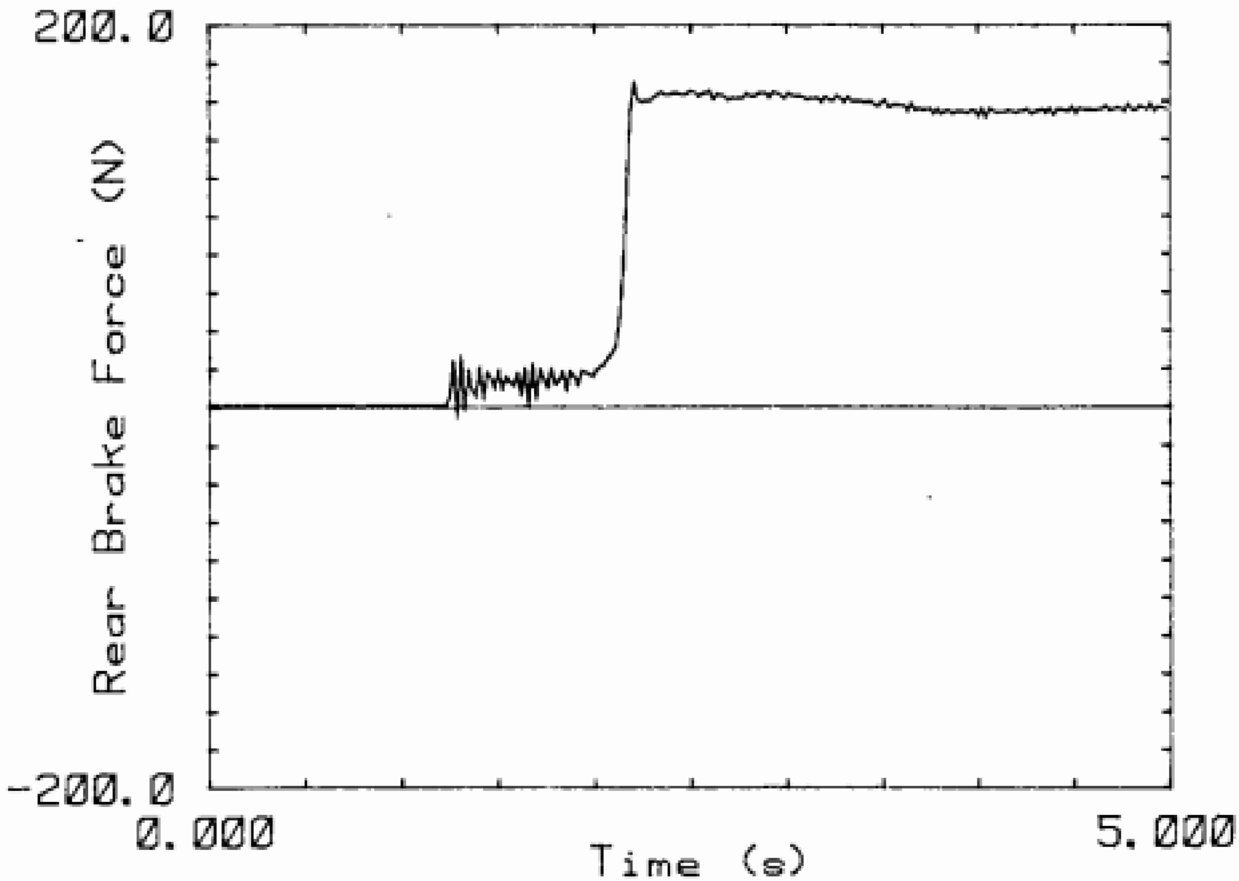


Figure 2.30 (b) Dynamic force magnification effect, rear brake 750 ml motorcycle.

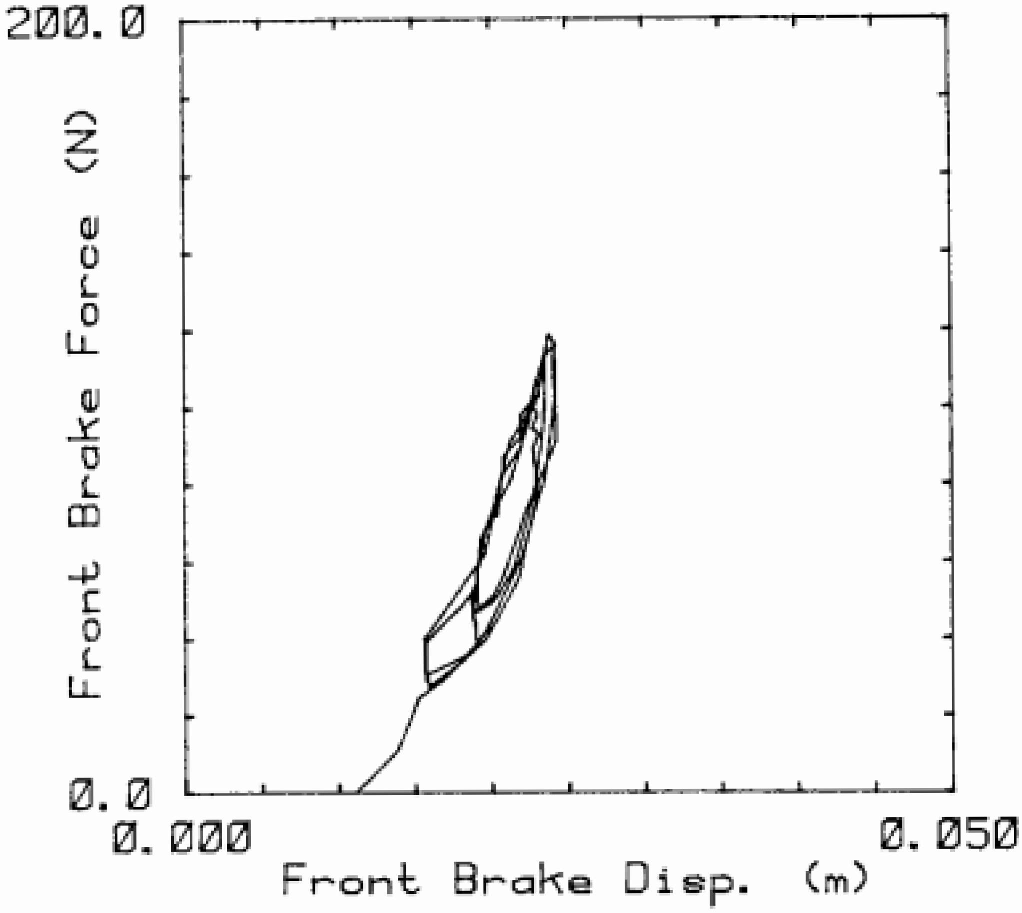


Figure 2.31 (a) Front brake force-displacement characteristics 750 ml motorcycle.

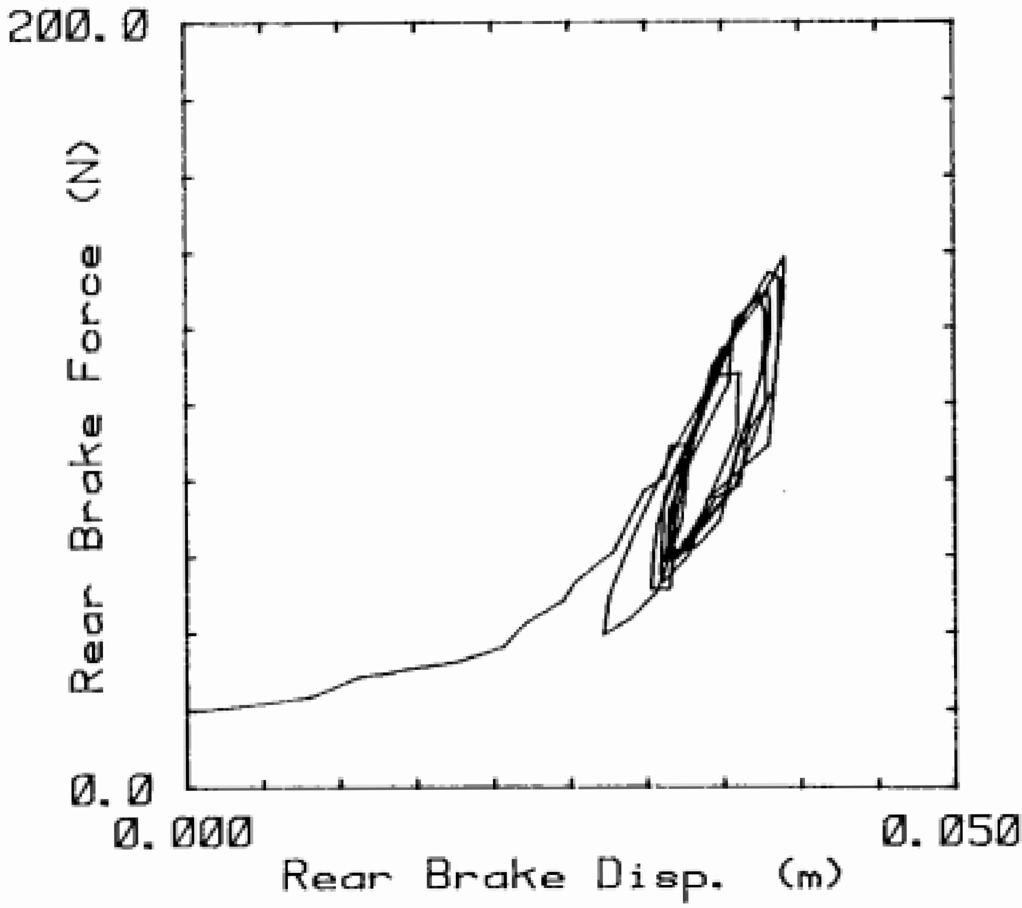


Figure 2.31 (b) Rear brake force-displacement characteristics 750 ml motorcycle.

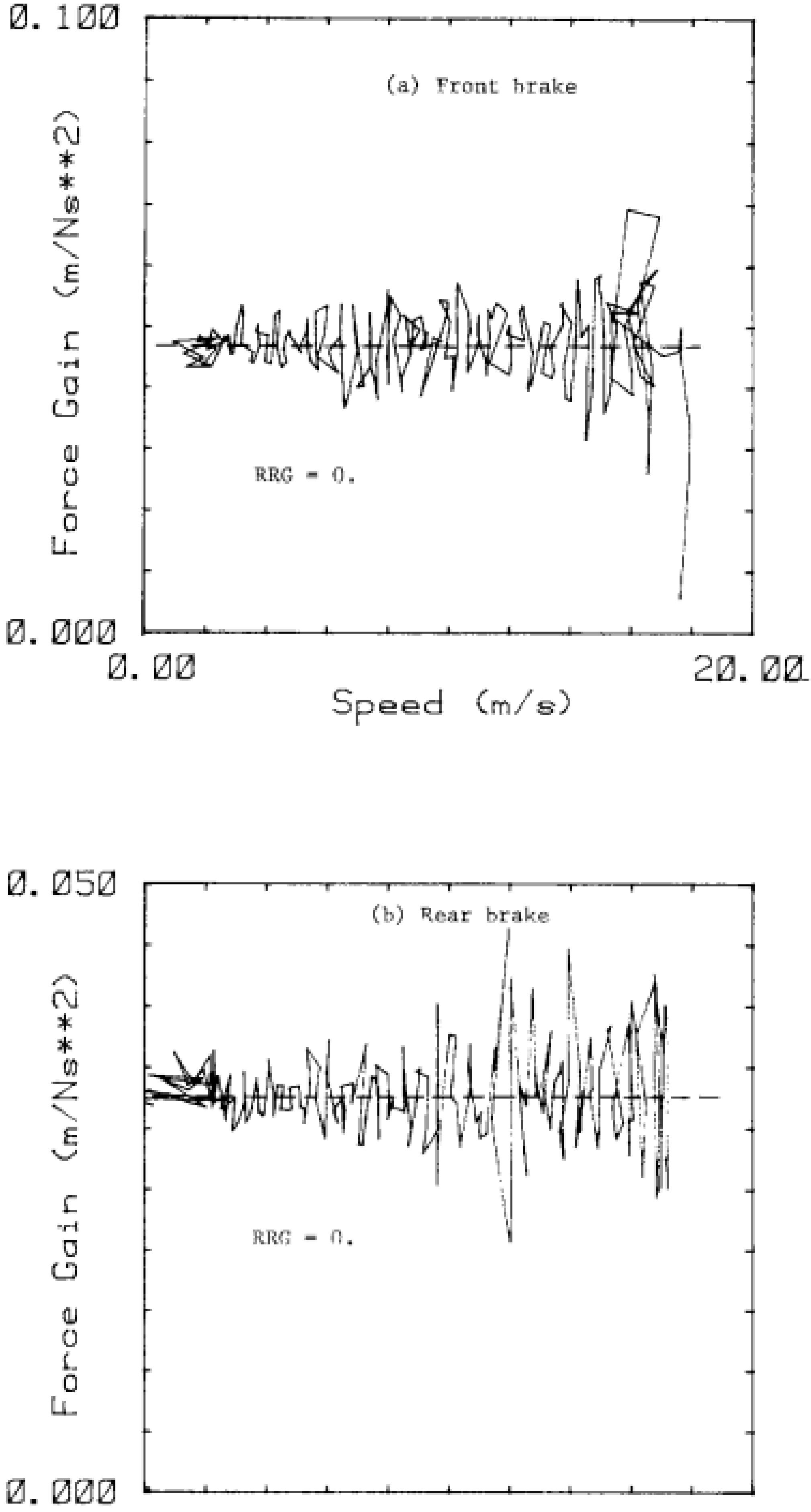


Figure 2.32 Force gain versus speed, 750 ml motorcycle.

TABLE 2.2.

PRODUCTION MOTORCYCLE BRAKE RESPONSE PARAMETERS.

Brake	Machine Capacity (ml)	Displacement Gradient ($mm.s^2/m$)	Force Gradient ($N.s^2/m$)	Brake Stiffness (N/mm)	Force Hysteresis (N)	Recovery Rate Gradient (1/Ns)
Front	250	2.62	16.8	6.4	25	1.0×10^{-3}
	400	2.60	36.5	14.0	70	0.0
	750	2.53	25.1	9.9	20	0.0
Rear	250	4.42	49.0	11.2	60	1.0×10^{-3}
	400	2.00	38.3	19.2	--	0.0
	750	3.25	25.5	7.9	35	0.0

The largest value of front brake force gradient was 36.5 $N.s^2/m$ for the 400 ml motorcycle, and the smallest value 16.8 $N.s^2/m$ for the 250 ml machine. Of the rear brake force gradients, the 250 ml had the largest value of 49.0 $N.s^2/m$, and the 750 ml the smallest at 25.5 $N.s^2/m$.

Thus, for displacement gradients, there was considerably more variation between the rear brakes of these machines than for the front brakes. The variation in force gradients was similar for the front and rear brakes.

Brake stiffness was also assessed. The 250 ml front brake had the lowest stiffness of 6.4 N/mm, with the 400 ml having the 'stiffest' front brake with 14 N/mm. The lowest rear brake stiffness occurred with the 750 ml machine, being 7.9 N/mm, and the maximum value was for the 400 ml motorcycle with 19.2 N/mm. There was a large variation in stiffness, with a maximum to minimum ratio of 2.2 for the front brakes, and 2.4 for the rear brakes.

The motorcycles with organic disc pads (400 ml and 750 ml) exhibited zero RRG. The 250 ml motorcycle with metal sintered pads had a significant positive RRG (front brake and rear brake $1.0 \times 10^{-3}\ N^{-1}s^{-1}$). These results confirm those of Zellner and Klaber (1981) which suggest similar differences between organic and sintered metal friction characteristics.

The swept sine displacement modulation data revealed no differences in the form of the force/displacement, deceleration/displacement and deceleration/force transfer functions between motorcycles.

2.10 SUMMARY AND CONCLUSIONS

A test program was designed for dynamic characterization of motorcycle disc brake performance. The minimum requirements were found to be as follows:

* Static tests

(a) Step input of displacement. By monitoring brake force during this procedure, two phenomena can be observed. Firstly, force magnification is evident during the initial application phase; secondly, long term observation will reveal leakage problems (if they exist).

(b) Displacement cycling, which allows assessment of force-displacement hysteresis.

* Dynamic Tests

(a) Step input of displacement. The change of force gain, G_F, with speed, V, can be computed from these data, yielding the Recovery Rate Gradient (RRG).

(b) Low frequency (<2.0 Hz) displacement cycling. These data enable displacement/deceleration gradient, force/deceleration gradient and brake system stiffness to be measured. Furthermore the data may be used to investigate deceleration-displacement and deceleration-force hysteresis effects.

(c) Frequency-modulated displacement input (from zero to about 5 Hz) allows force/displacement, deceleration/force and deceleration/displacement frequency response functions to be calculated.

This static and dynamic test program was performed with three sample motorcycles. To characterize the response properties of the brakes, two steady-state control gradients have been selected, namely displacement gradient and force gradient.

The overall range for the displacement gradient was found to be 2.0 mm.s^2/m to 4.4 mm.s^2/m, which is a 2.2 times variation. The force/deceleration gradients were found to be in the range 16.8 N.s^2/m to 49.0 N.s^2/m, which is a three-fold variation. The rear brakes were a greater source of variability than the front brakes for both these control gradients. Brake stiffness was measured and found to vary between 19.2 N/mm to 6.4 N/mm for the motorcycles tested. This range represents a ratio of 3:1. When this comparison is made excluding the mechanical rear brake on the 400 ml machine, the range is 14.0 N/mm to 6.4 N/mm, a ratio of 2.2:1.

The data obtained from the dynamic low-frequency displacement cycling show the deceleration-displacement and deceleration-force characteristics. It was seen that whereas deceleration followed the modulated displacement input quite closely, there was substantial hysteresis in the response to force inputs. The effect of hysteresis is loss of precision in fine braking control. The typical force hysteresis was measured to be about 40 N. The maximum value observed was 70 N for the 400 ml front brake.

The frequency response functions computed from the swept sine displacement data reveal that the force gain was approximately constant over the range of rider control frequencies, whereas the dynamic stiffness and the displacement gain were frequency dependent. The latter increased by a factor of about two from 0.5 to 1 Hz and then remained relatively constant at higher frequencies. This characteristic was independent of the type of disc brake pad material used.

The variation of force gain with speed was interpreted as RRG. This parameter was found to be zero for the motorcycles with organic disc pads. The 250 ml motorcycle had metal sintered 'all weather' disc pads, which generally exhibited a positive RRG, with an average value of 1.0×10^{-3} $N^{-1}s^{-1}$ for both the front and rear brakes.

Leakage of hydraulic fluid past the master cylinder cups was observed with three of the five hydraulic brakes tested. It was most severe with the 750 ml front brake, where at constant displacement the brake force dropped by 40 N in 8.4 seconds. Thus, the brake system with leakage presents a time varying stiffness to the rider.

To further describe the dynamic behaviour of a system, it is usual to specify a measure of the rapidity of the system response to control inputs. The deceleration response of the motorcycles was very rapid, the difference between the 63% rise times of deceleration and lever displacement being of the order of 25 ms. In human operator control terms, therefore, the deceleration response to brake lever movement can be regarded as effectively instantaneous. The presence of force hysteresis results in some phase lag for small amplitude modulation of the rider's force input.

The various phenomena described above have been accounted for by a mathematical model of the brake system dynamics. The model accounted for the main features of the responses, such as:

* dynamic force magnification
* time-varying stiffness
* hysteresis loops
* frequency response functions