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ON
ANTILOCK ANALYSES

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Section I

INTRODUCTION

This report provides supplementary documentation for the current phase of antilock analysis, Ref. 1. It supports the main, overall documentation for the current phase described in Ref. 2. Taken together, the two reports present the results and status of the recent analyses of toggle, modulator and overall system integration.

The two reports build on the results described in earlier documentation. Ref. 3 was a literature review of earlier fluidic antilock work. Ref. 4 and 5 described a computer simulation and initial analyses of antilock dynamics. Ref. 6 and 7 presented the results of the preliminary analyses and conceptual design of the antilock system. The current reports carry this work forward, recommending a specific design configuration and parameter values.

Specifically the objectives of the most recent analyses were to:

- Perform generic modulator analysis, to quantify the effects of dump and reapply pressure rates on antilock stability and performance. Analysis will include dump and reapply rates, and lumped modulator delay.
- Based on results of this and earlier toggle optimization analysis (with Mitsubishi modulator), synthesize a recommended preliminary antilock design and simulate its response and performance.
- Document the results of these analyses.

The next section of this report gives an overview of the analyses, aimed at these objectives. This is keyed to the appropriate sections of Ref. 2, which describes the overall results, and the third section of this report, which gives more detailed results. The fourth section presents the conclusions and recommendations.

Section II

ANALYSIS OVERVIEW

A. APPROACH

The analytical approach, as in earlier phases, involved a combination of techniques, including: time domain and FFT analysis of simulated time histories; FFT's of selected full scale data collected by JPL; and gain-phase analyses based on the former, and as described in Ref. 2.

B. FULL SCALE VERSUS SIMULATION COMPARISON

Comparison of the dynamic response of the braked front wheel on a high mu surface was performed to help vailidate the simulation. Results are shown herein. Also, the dynamic effects of high versus low mu are shown for the simulation case only.

Reference 7 compared the full scale and simulated responses of the Mitsubishi modulator.

C. EFFECTS OF FEEDBACK CONTROL STRUCTURE

This was analyzed in some detail in Ref. 7. Figures 5 to 7 of Ref. 2 also verify that: angular acceleration is an appropriate feedback; and angular jerk is not a suitable feedback. The possibility of angular velocity feedback is described below.

D. EFFECTS OF TOGGLE DESIGN

This was shown and discussed in Fig. 11 in Ref. 2; further supporting detailed results are shown below.

E. EFFECTS OF FEEDBACK AMPLITUDE, INPUT AMPLITUDE AND COMPONENT LINEARITY

Describing functions of systems component responses shown below are used to establish the linearity of the key components.

F. SYSTEM STABILITY BOUNDARIES

The boundaries of feasible antilock control were shown and discussed in Fig. 8 of Ref. 2.

G. SYSTEM OPTIMIZATION WITH MITSUBISHI MODULATOR

With this relatively slow automotive type modulator, the toggle design was adjusted across a wide range, and the resulting best achievable performance is shown below.

H. EFFECTS OF MODULATOR DUMP AND REAPPLY RATES

A "generic modulator" was analyzed with regard to the effects of its response on antilock stability and performance. The generic modulator consisted of mathematical expressions which gave:

- A linearly decreasing pressure dump mode, from some initial pressure value, triggered by a dump signal from the controller,
- A linear increasing pressure reapply mode triggered by a reapply signal from the modulator,
- A fixed time delay (simulating solenoid or other switching time delay) between the dump or reapply signal, and the initiation of the dump or reapply mode, and
- Suitable logic to prevent the pressure from exceeding the input pressure from the master cylinder; and to prevent the pressure from dropping below zero pressure.

The FORTRAN implemented version of these math expressions are given in the Appendix.

The generic modulator models the main response features of simple, single rate antilock modulators used in automotive applications. The dump and reapply rates and time delay were variable parameters, entered by the analyst.

A range of dump and reapply rates were analyzed, to determine their effects on antilock stability and performance on high and low mu surfaces.

The overall results are shown in Figs. 9 and 10 of Ref. 2; more detailed results are presented below.

I. OPTIMIZATION OF TOGGLE AND GENERIC MODULATOR

Based on the results of the toggle and modulator analyses described above, the more promising combinations of design parameters were used to explore a nominal, preliminary design. During this process it was found that the modulator time delay had a relatively large effect on stability and performance and therefore, affected the choice of design parameters. As discussed below, it was decided to use a representative, "rapid" time delay value of 20 msec, to define the preliminary design.

Once the preliminary design was defined and its response and performance simulated, a sensitivity analysis was performed. This involved independently perturbing each of the nominal design parameter values by an increment (e.g., about ± 10 to 30 percent), to assess the sensitivity with respect to performance and stability. These results were presented in Figs. 10 and 11 of Ref. 2 and are further discussed below.

Section III

FURTHER ANALYSIS RESULTS

A. FULL SCALE VERSUS SIMULATION COMPARISON

Figure A- 1 shows full scale and simulated wheel acceleration frequency responses, for a pulse brake input. These are derived from the corresponding time histories, while the motorcycle was undergoing near limit braking, with a short pulse of increased brake pressure applied. The test surface was a dry, high mu paved surface. Note that the frequency response for a pulse input is not necessarily representative of the vehicle response during antilock cycling, because of nonlinear effects. A pulse input was used mainly for testing convenience, and to provide a comparison case, for an example input waveform.

The results show that the simulation and full scale responses have very similar shapes. At a more detailed level, the simulation has a somewhat higher amplitude ratio, and somewhat more phase lag, than the full scale response. This can be attributed to the values used for several of the motorcycle parameters in the simulation - such as brake pad and tire/roadway friction coefficients and brake-line delay - which were not directly measured but rather estimated. Note that the tire/roadway friction was based on considering data such as presented in Ref. 8. Analytically, these relatively small inaccuracies can be accounted for by adjusting the estimated parameters to get a better match; or by shifting the gain-phase data appropriately in the subsequent analyses. These refinements should be considered in a more refined, final design analysis; they were not included in the preliminary design analysis. Overall, the results support the validity of the vehicle simulation, for assessing anti-lock dynamics.

Figure A-2 compares the simulated wheel response for a pulse input for the high versus low mu surfaces described in Ref. 6. Surprisingly, the amplitude response is essentially identical on the

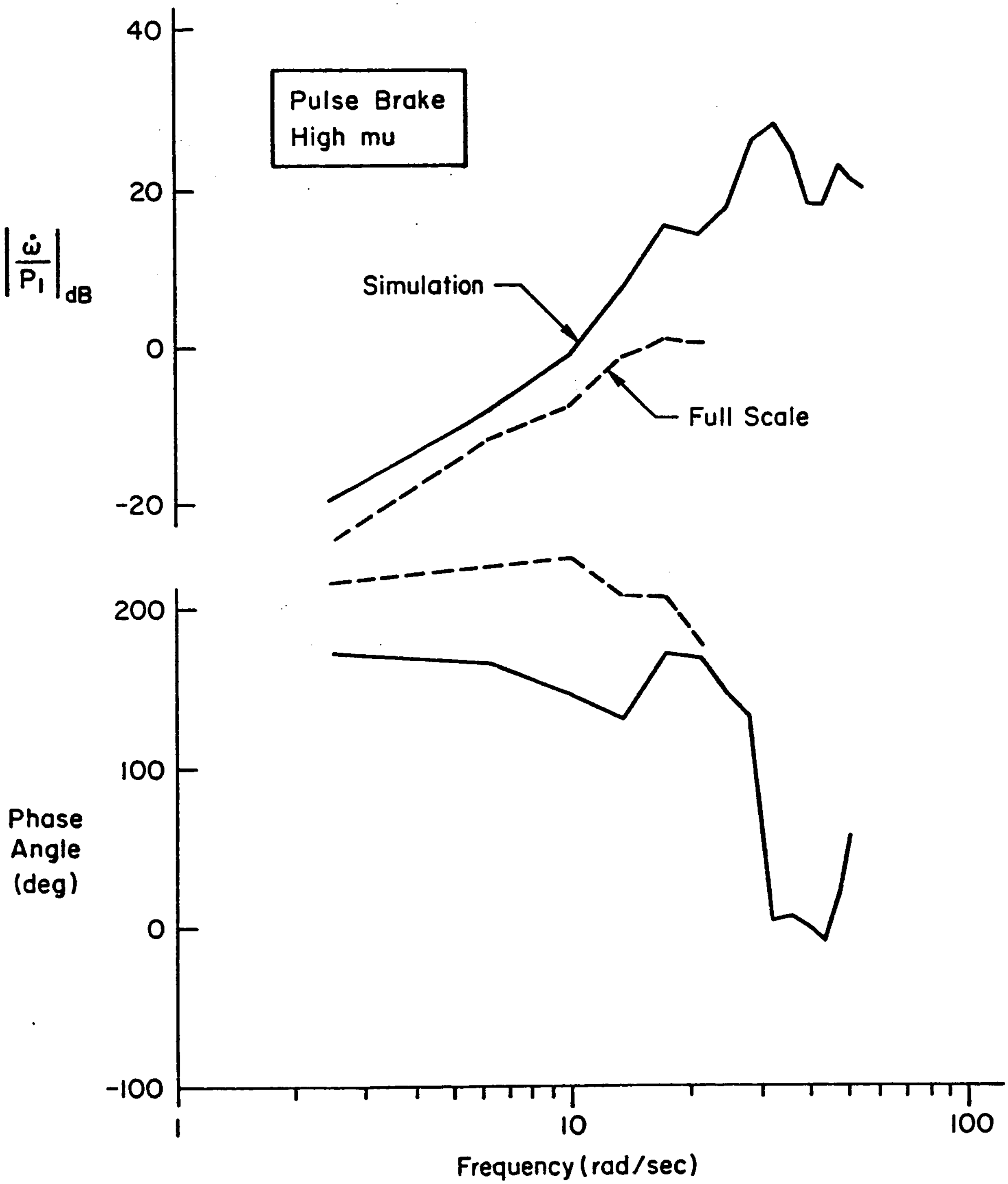

Figure A-1. Comparison between Simulated and Full Scale Wheel Acceleration Frequency Responses

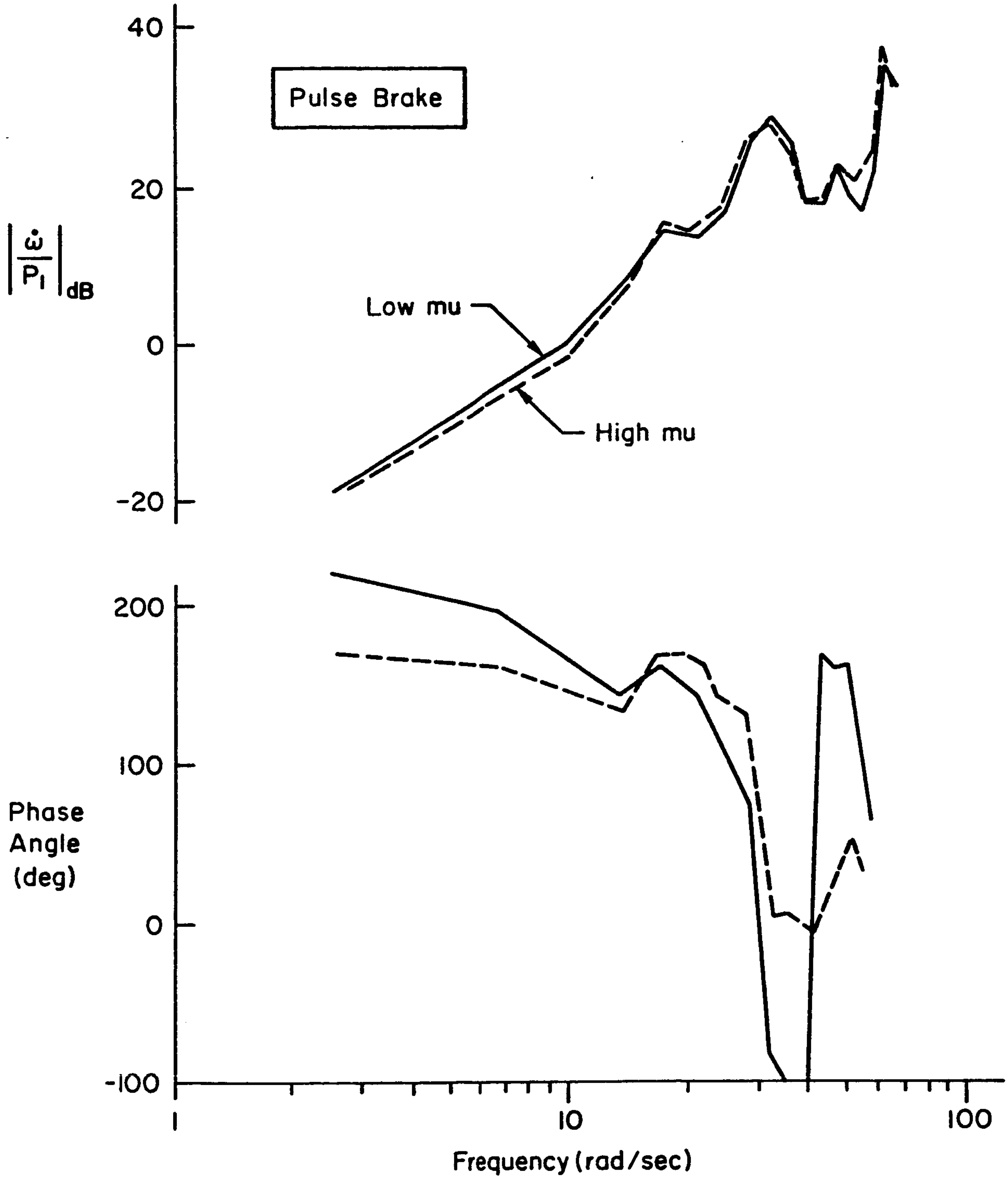

Figure A-2. Comparison between High and Low Mu Simulated Wheel Acceleration Frequency Response two surfaces, and the main difference for the low mu surface is seen to be less phase lag at low frequencies, and more phase lag at frequencies above 2 Hz(which is typical for antilock operation). As seen in Fig. A-5 below, this has direct effects on antilock phase-gain crossover and selection of an appropriate design compromise between high and low mu performance.

B. EFFECTS OF FEEDBACK CONTROL STRUCTURE

As described in Ref. 2, phase-gain analysis can be used to determine the feasibility of various potential feedback variables. Those results examined angular acceleration feedback (which is feasible), and angular jerk feedback (which is not suitable). Wheel speed feedback was also considered on a very preliminary basis, and an initial gain-phase plot example is shown in Fig. A-3.

The data for wheel angular speed response to dump commands shows a gain-phase curve which may be compatible with toggle type feedback control. In the region of toggle effectiveness (-90 to -180 degrees phase lag), the wheel speed gain-phase data seem to give stable intersections for a limited range of toggle widths. The angularity of the intersection appears to be near orthogonal and this is desirable, as discussed in Ref. 2. For toggle halfwidths(i.e,trigger values) of 2 to 4 ft/sec antilock limit cycles in the region of 2.5 to 3.5 Hz appear possible. So, using a wheel speed sensor for antilock control - which seems to be a new result, and could potentially have significant impact on design simplification - may be feasible, at least on a first look basis.

Several words of caution need to be mentioned in considering this possibility. First, the suggested toggle trigger values are quite small, perhaps similar to the noise level present in some existing electromagnetic or fluidic speed sensors. Second, the effect of the low mu vehicle response has not been addressed here. Third, and fundamentally, though not immediately apparent from the gain-phase analysis, the low frequency-high gain nature of the wheel speed response must be accounted for. That is, the average value of wheel

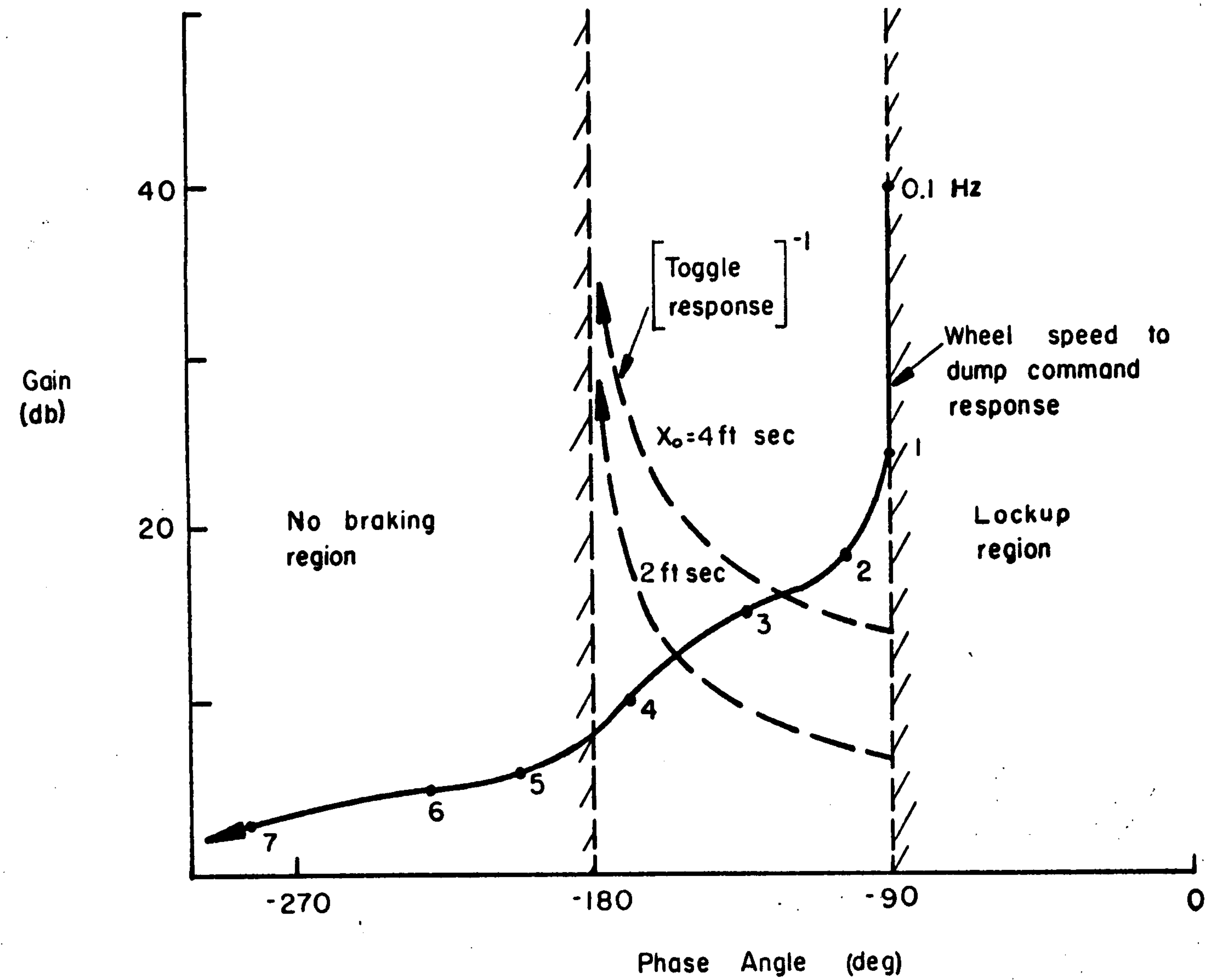

Figure A-3. Preliminary Gain-Phase Plot for Wheel Speed Feedback Control speed will be decreasing as the vehicle decelerates, and this must be distinguished from higher frequency wheel locking motion. From a design standpoint, this might be achievable by providing a washout (or AC coupling) filter. This could attenuate the low frequency response, so that it wouldn't affect the triggering action. Additional analysis would be needed to verify this.

Assuming a suitably filtered wheel speed sensor did have potential for antilock usage, there are several potential design approaches. One would be to develop a fluidic speed sensor, and washout filter, based on analog principles. Another approach would be to develop a wheel acceleration sensor with a midfrequency lag. This could potentially provide the necessary response shape, when viewed as a speed sensor. Note that, coincidentally,the fluidic transducer developed under the current effort may be such a lagged acceleration sensor.

In any case additional analysis of this area is indicated; and it is conceivable that such could lead to simplified antilock designs.

C. EFFECTS OF TOGGLE DESIGN

The shape of a toggle can be described by its width (ie., difference between dump and reapply trigger levels), and its bias (ie., value of its midpoint, relative to zero). The effects of these parameters on system response was analyzed.

Past textbook analyses of toggles, such as those cited in Ref. 2, have indicated that the effect of increasing width is to increase the phase lag of the toggle. The gain is unaffected by the width, and is only a function of the input amplitude. These theoretical characteristics are verified numerically, with the simulation model, in Fig. A-4. This shows the toggle describing function for 2 toggle half widths (ie., zero, that is, a contactor switch; and 90 per cent of the input amplitude. The gain and phase valuse are in very close agreement with theoretical values, as would be expected. Of course, when the width of the toggle exceeds 100 per cent of the input amplitude, the device no longer triggers (ie., the gain is zero); so that the cases in Fig. A-4 span most of the useful design range.

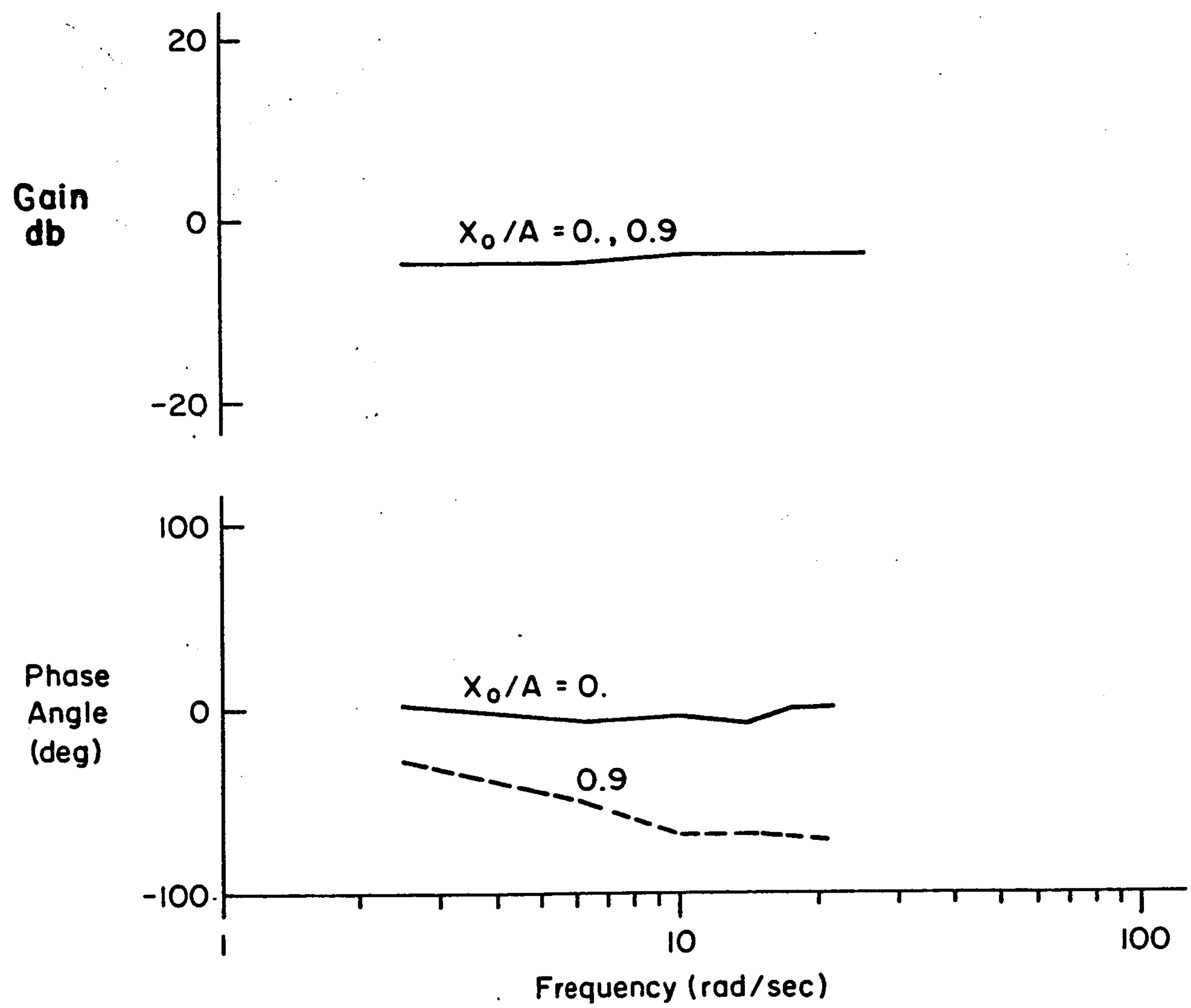

Figure A-4. Effect of Toggle Relative Width, X_0/A, on ToggleSinusoidal Frequency Response

The cross plotted gain-phase characteristics for several pertinent toggle widths (ie., 0.5, 1.0 and 2.0g) are shown in Fig A-5. Also shown for comparison are the gain-phase data for the motorcycle/ Mitsubishi modulator part of an antilock system, on low and high mu surfaces, for wheel acceleration feedback. Recalling that toggles only operate across a 90 degree phase range, it becomes clear that only a limited range of toggle widths will intersect the vehicle curves,which is a necessary condition for limit cycling. In this particular case, lesser or greater toggle widths would tend to result in no(or little) braking or lockup, respectively. A toggle half width of about 1.0g (width of 2.0g) would seem to represent a good compromise between braking and antilock stability, low and high mu, with the Mitsubishi modulator.

With respect to the vehicle response, several factors are apparent in Fig. A-5. For a given toggle, the high mu limit cycling is generally at a higher frequency than low mu, and this has been observed in various past full scale prototypes. Also, on high mu, the system operates at lower gain margins than on low mu(ie., a smaller change in gain can destabilize it). On the other hand, Fig. A-5 shows that on low mu, the limit cycle amplitude will tend to be greater, and this is also observable in extant full scale antilocks.

The general effects of toggle bias are shown in Fig. A-6. This shows that bias affects the dwell time of both the dump and reapply modes. Since the latter have essentially ramp-like time histories, bias can be used to either truncate the ramp, or once the ramp has reached its final value, hold the final value (ie.,either zero pressure, or maximum applied pressure). The bias also tends to affect the center point of the limit cycle, in the expected way. For a negative bias, which is the case for acceleration feedback, a more negative value results in a shorter dump mode and a longer reapply mode, that is more braking of the wheel, for equal dump and reapply pressure rates. Obviously, if the toggle is too negative or too positive, the system will become either unstable or have no braking, although no clear boundaries were uncovered.

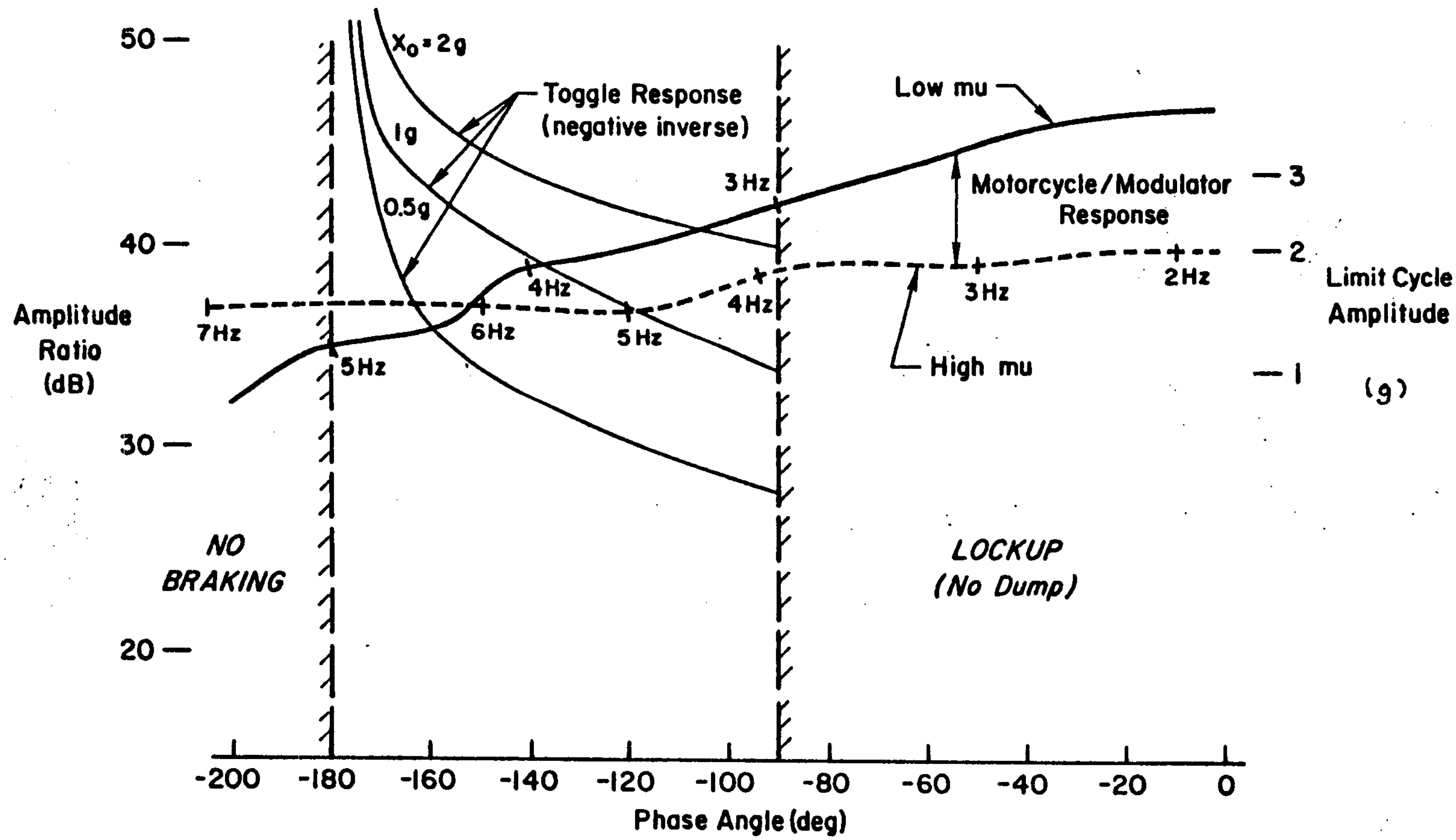

Figure A-5. Effect of Toggle Width on Low and High Mu Gain-Phase Plot Crossovers

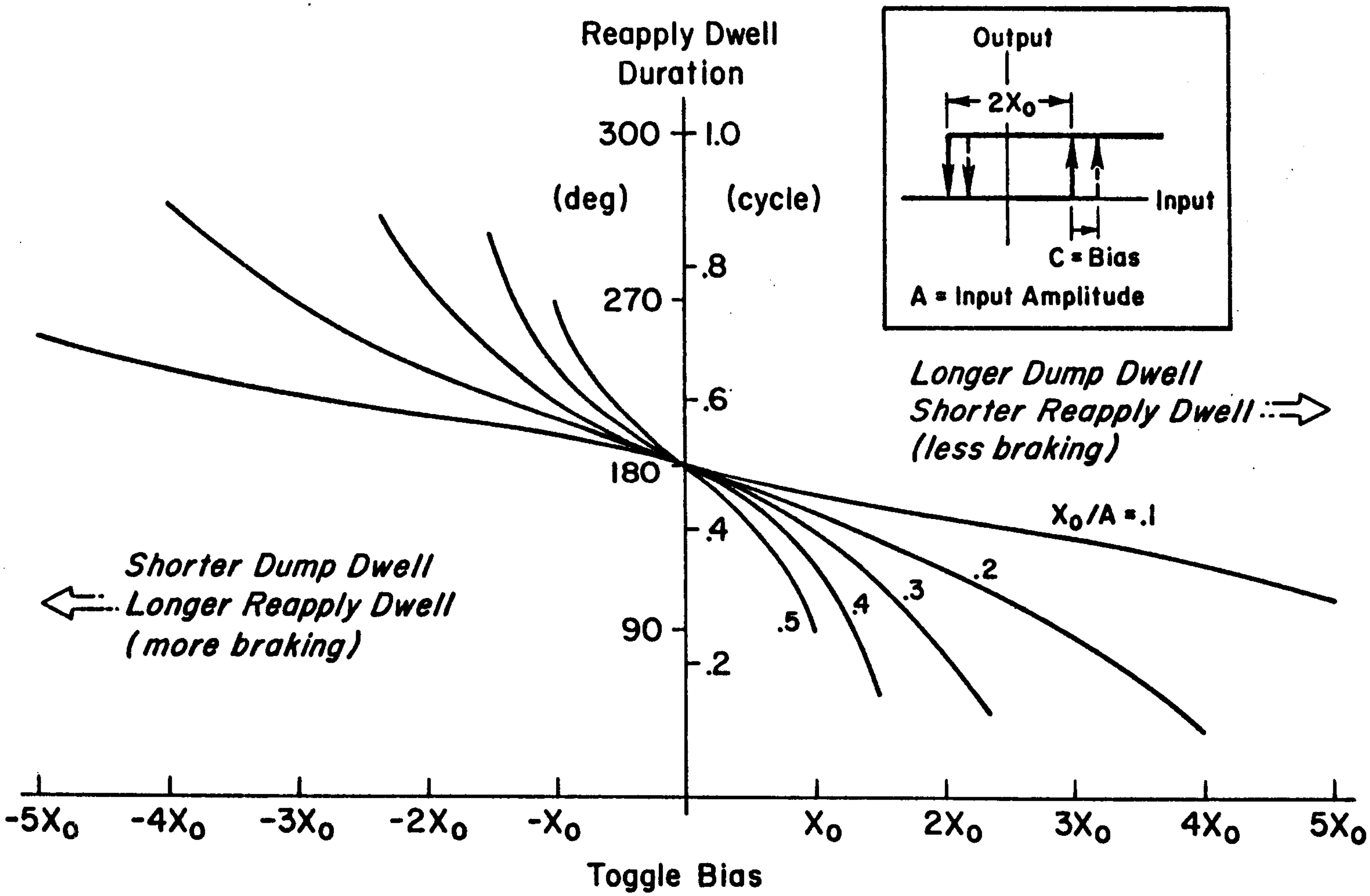

Figure A-6. Effects of Toggle Shape on Pressure Reapply Dwell Duration

E. EFFECTS OF FEEDBACK AMPLITUDE, INPUT AMPLITUDE, AND COMPONENT LINEARITY

The amplitude of the feedback signal - which may have various frequency components in it, as well as harmonics and noise - directly affects only the toggle element of the antilock, since the toggle has only a discrete, on/off output. Fig. A-7 shows the effect of increasing wheel acceleration feedback amplitude on the toggle frequency response. This has the expected effect on gain (the phase was unchanged and is not shown). So, for example, large harmonics present in the wheel acceleration signal, can reduce the effective gain of the toggle. This again underlines the fundamental nonlinear nature of the toggle. Another amplitude effect which could potentially affect antilock operation - but which doesn't - is input amplitude (that is the command pressure from the master cylinder). Figure A-8 shows the frequency response of the Mitsubishi modulator plus vehicle, for different brake lever forces, below and above values corresponding to lockup on a low mu surface. Some differences are seen at frequencies below 2 Hz, but this is below the frequency of antilock operation. At higher frequencies, there is essentially no difference due to input force level. This suggests that the modulator and vehicle elements are essentially linear.

This is verified in Fig. A-9, which shows the modulator, vehicle, and combined response to periodic square wave inputs (eg., as generated by a toggle). The combined response is virtually equal to the sum of the individual responses, demonstrating linearity.

E. SYSTEM OPTIMIZATION WITH MITSUBISHI MODULATOR

A wide range of toggle designs were tried in combination with the Mitsubishi modulator, and wheel acceleration feedback. As suggested in Fig. A-5 above, it was found that a stable limit cycle was readily obtainable. On the other hand, corresponding stopping decelerations were quite low. After considerable tuning efforts, the best achievable high mu deceleration was as shown in Fig. A-10, namely 0.17g which is far below values of 0.6 - 0.7g attainable by conventional (non antilock) front wheel braking, as shown in, for example, Ref. 9.

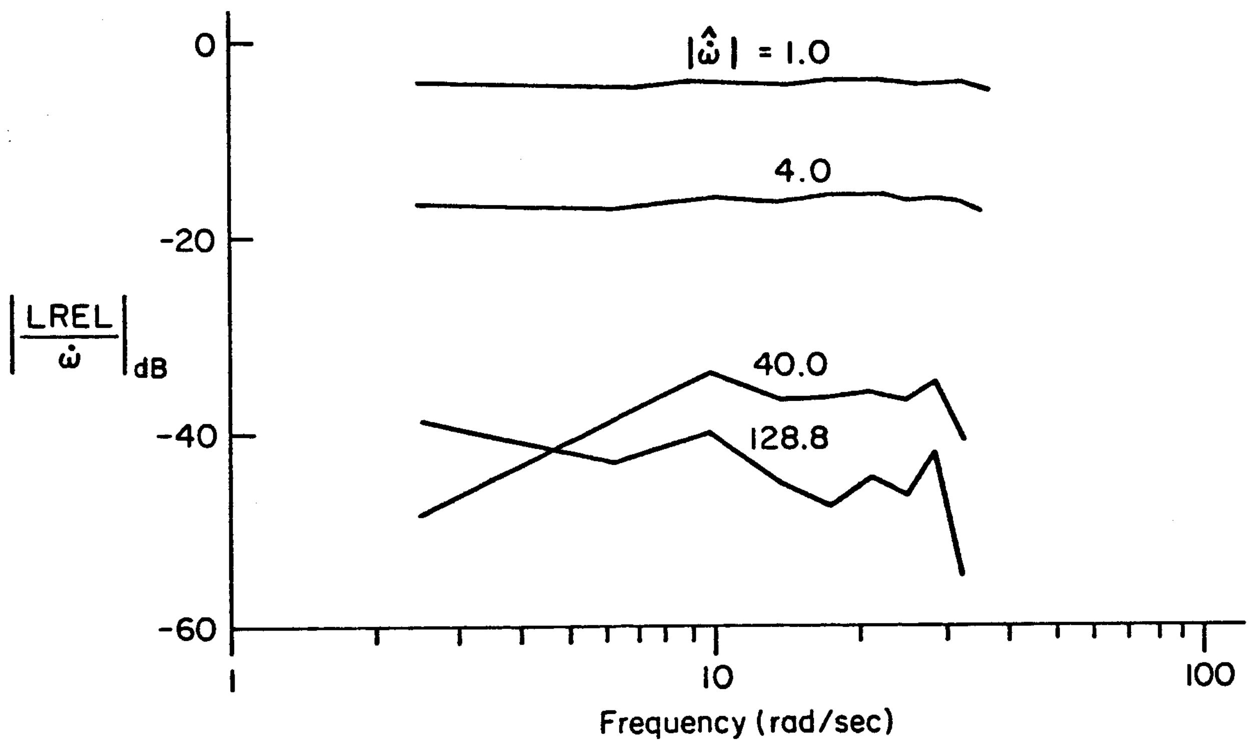

Figure A-7. Effects of Feedback Signal Amplitude on Toggle Frequency Response

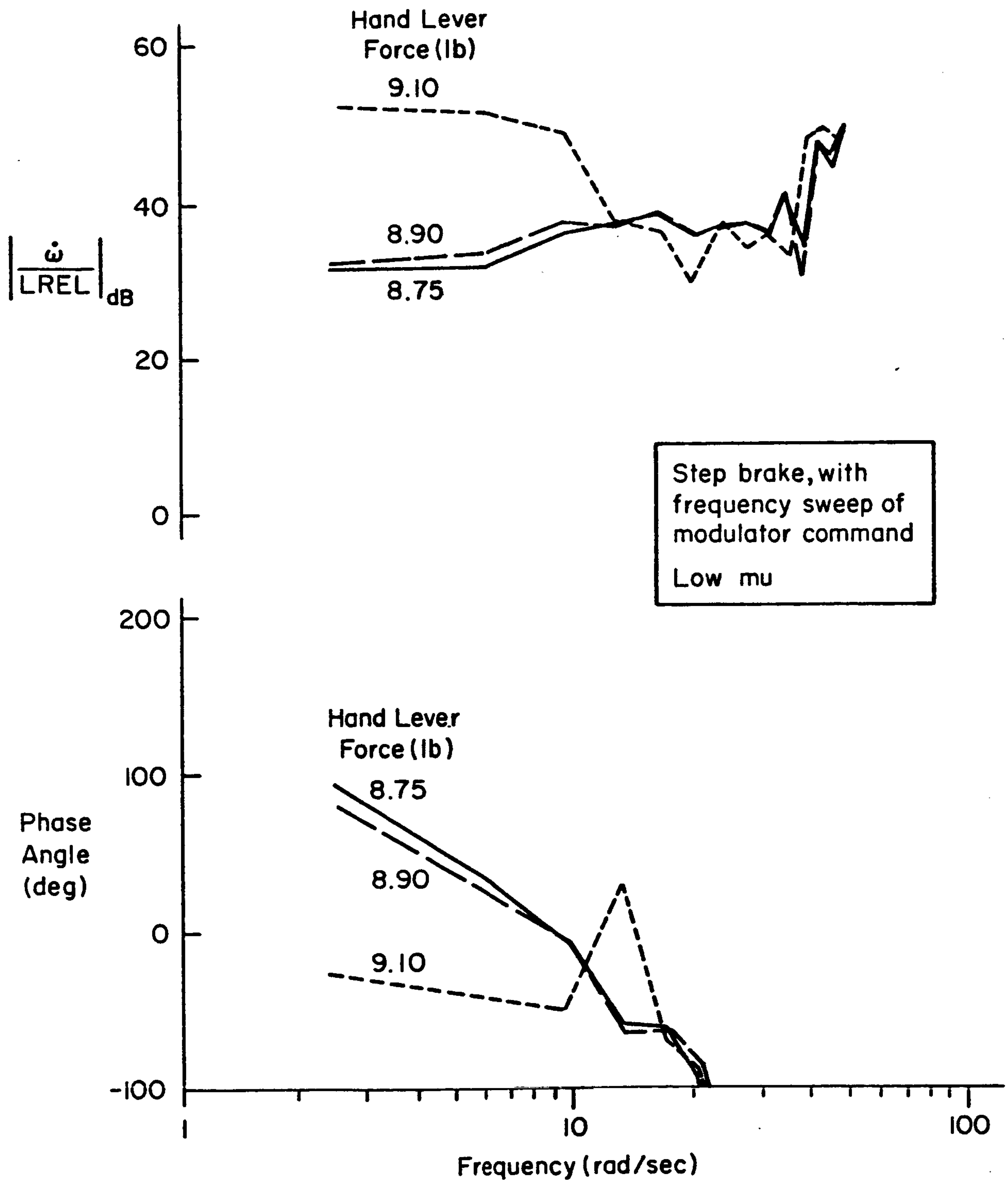

Figure A-8. Effects of Input Force Level on Modulator/Vehicle Frequency Response

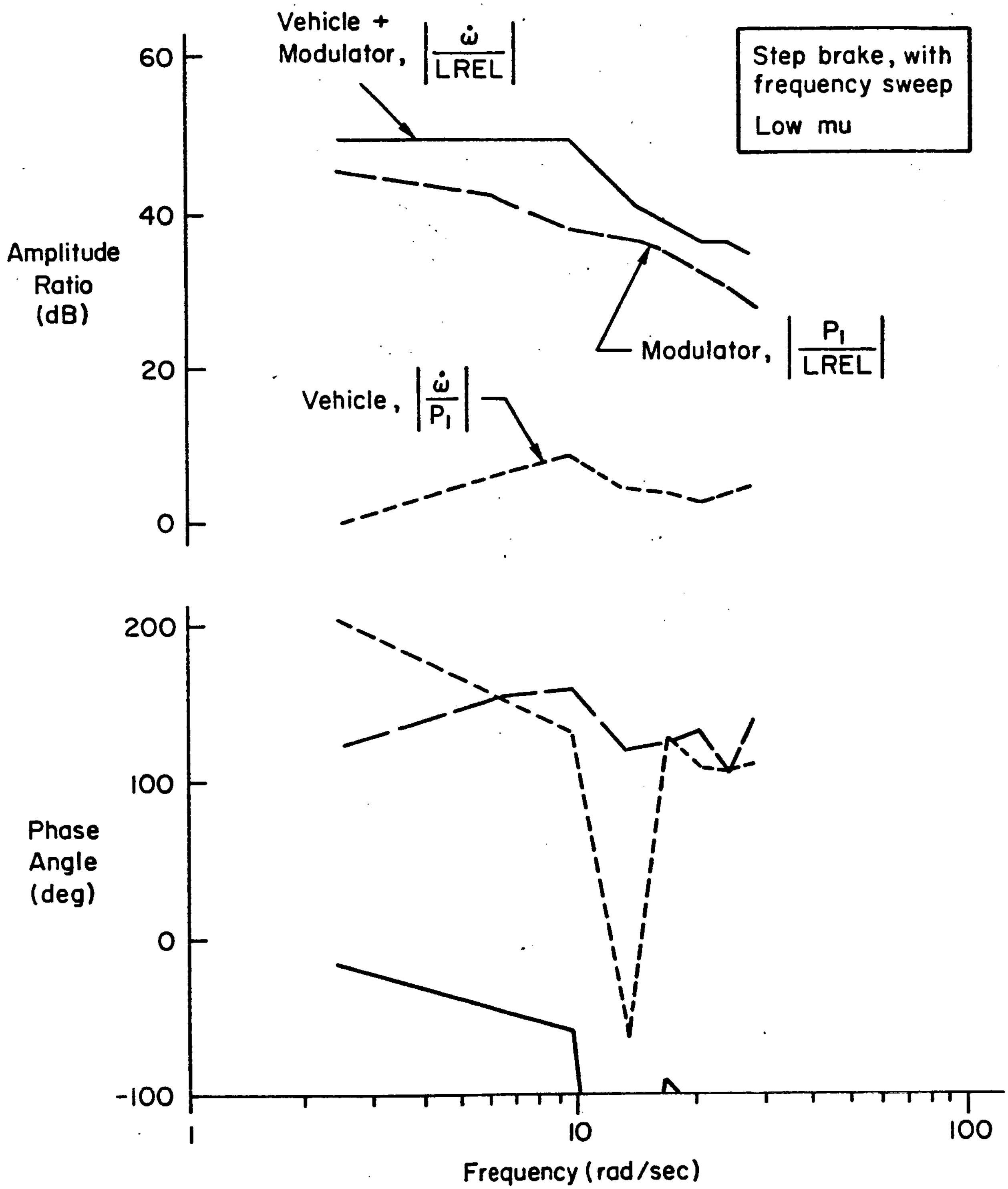

Figure A-9. Frequency Responses of Vehicle, Modulator, and Their Series Combination, Demonstrating Superposition

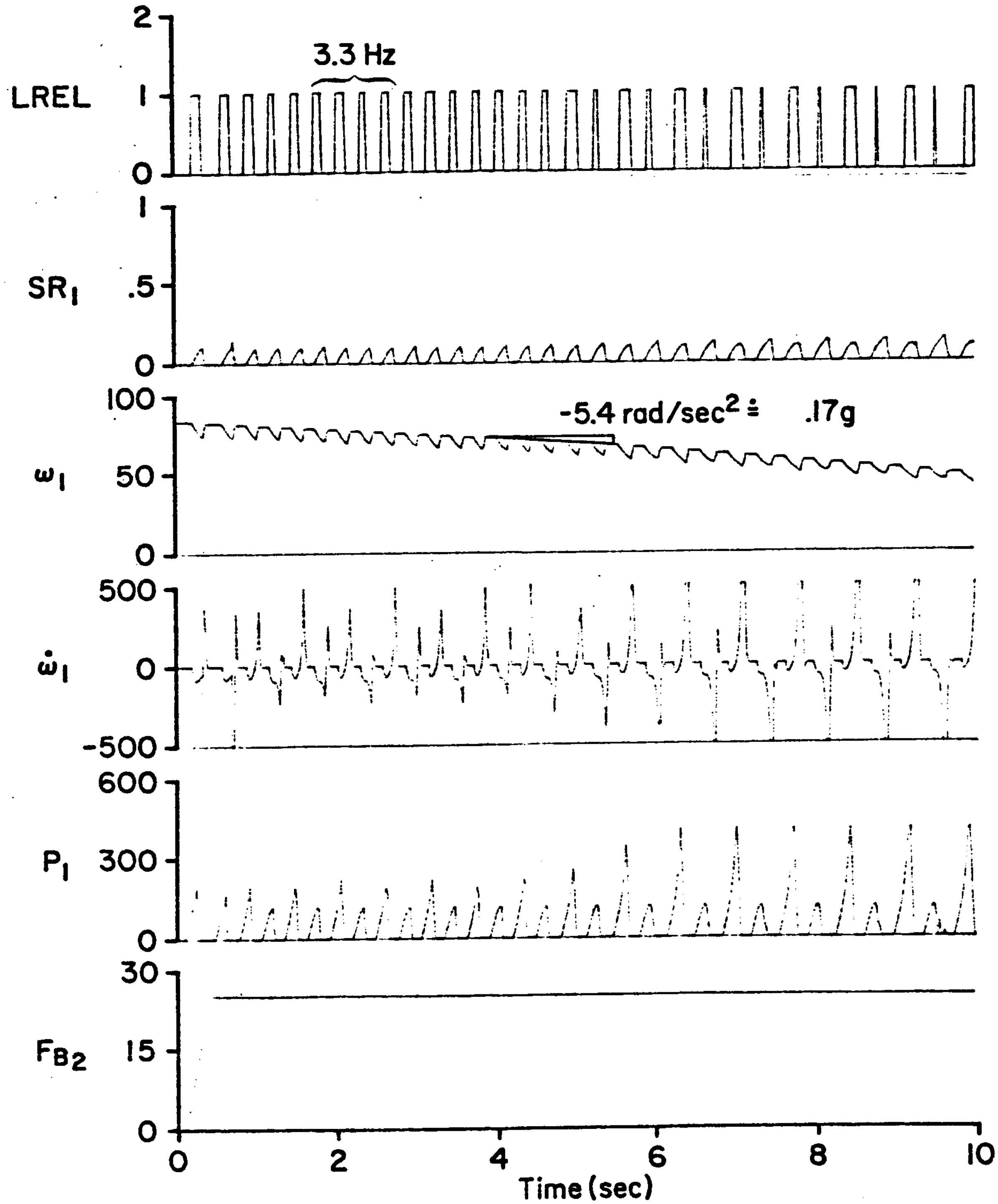

Figure A-10. Closed Loop Response of Optimized System, Based on Mitsubishi Modulator, High Mu Surface

A series of exploratory cases were run to see whether varying the dump and reapply rates, or solenoid time delay would help this situation. These were unsuccessful and also began to exceed the validity assumptions of the math model of the modulator mechanics.

It was concluded, and later verified, that the effective time delay of this particular automotive modulator is too slow for use on a motorcycle front wheel brake. As a result, a "generic" modulator was analyzed, having variable dump and reapply rates, and time delay, recognizing that a new modulator would be needed for the current application.

F. EFFECTS OF MODULATOR DUMP AND REAPPLY RATES

After developing a generic modulator model, open loop frequency response runs were made with various dump and reapply rates, and the results are shown in Figs. A-11, A-14 and A-15. The pressure rates were selected to span a range above and below those found in past motorcycle antilocks, such as in Ref. 9. The gain-phase plot of Fig. A-11 shows a pronounced effect of dump rate on antilock dynamics. High dump rates give higher amplitude, higher frequency limit cycles, for a given toggle, on high mu. Reapply rate seems to have little systematic effect. Subsequent analyses, discussed in Ref. 2, suggested that low mu results are quite different or even converse from these. So, that should be kept in mind in viewing these data.

The effects on roughness and deceleration performance on high mu are shown in Figs. A-12 to A-15. Generally speaking, increasing both the dump and reapply rates, as in Figs. A-12 and A-13, increased the roughness and deceleration level. When the open loop deceleration was mapped as a function of pressure rates, as in Figs. A-14 and A-15, it appeared that the more sensitive way to increase deceleration on high mu was to increase reapply rate. Later, it was found that this is not necessarily true throughout the parameter space, as shown in Fig. 11 of Ref. 2.

It was also clear from these last data that the deceleration levels are higher at lower frequencies; yet are still not close to the target level of about 0.6g. In order to increase deceleration, it was decided to reduce the net time delay of the vehicle brake system, from 100ms

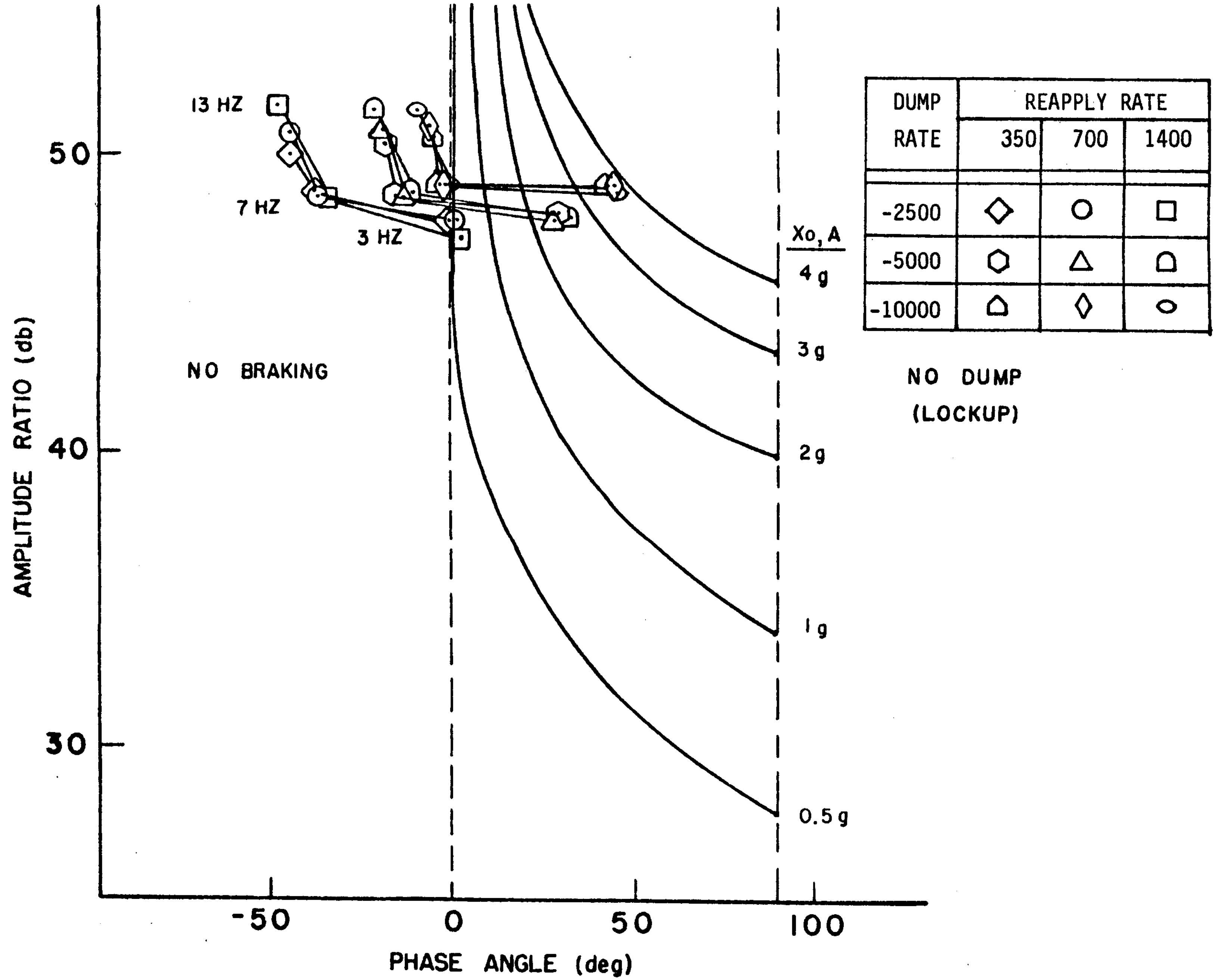

Figure A-11. Effects pf Dump and Reapply Rates on Antilock Gain-Phase Crossovers, High Mu

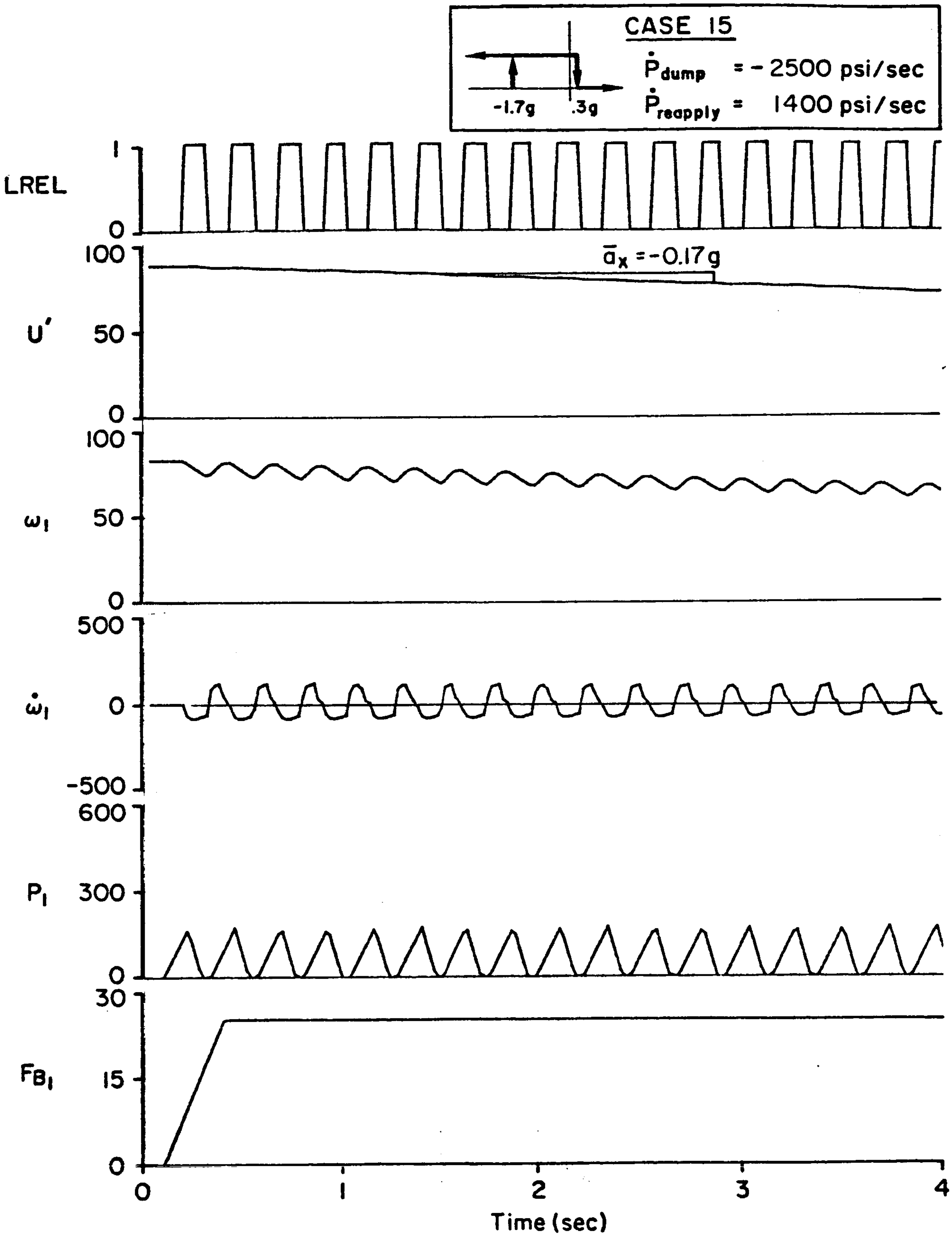

Figure A-12. Antilock Closed Loop Time History for Slow Dump and Reapply Rates, High Mu

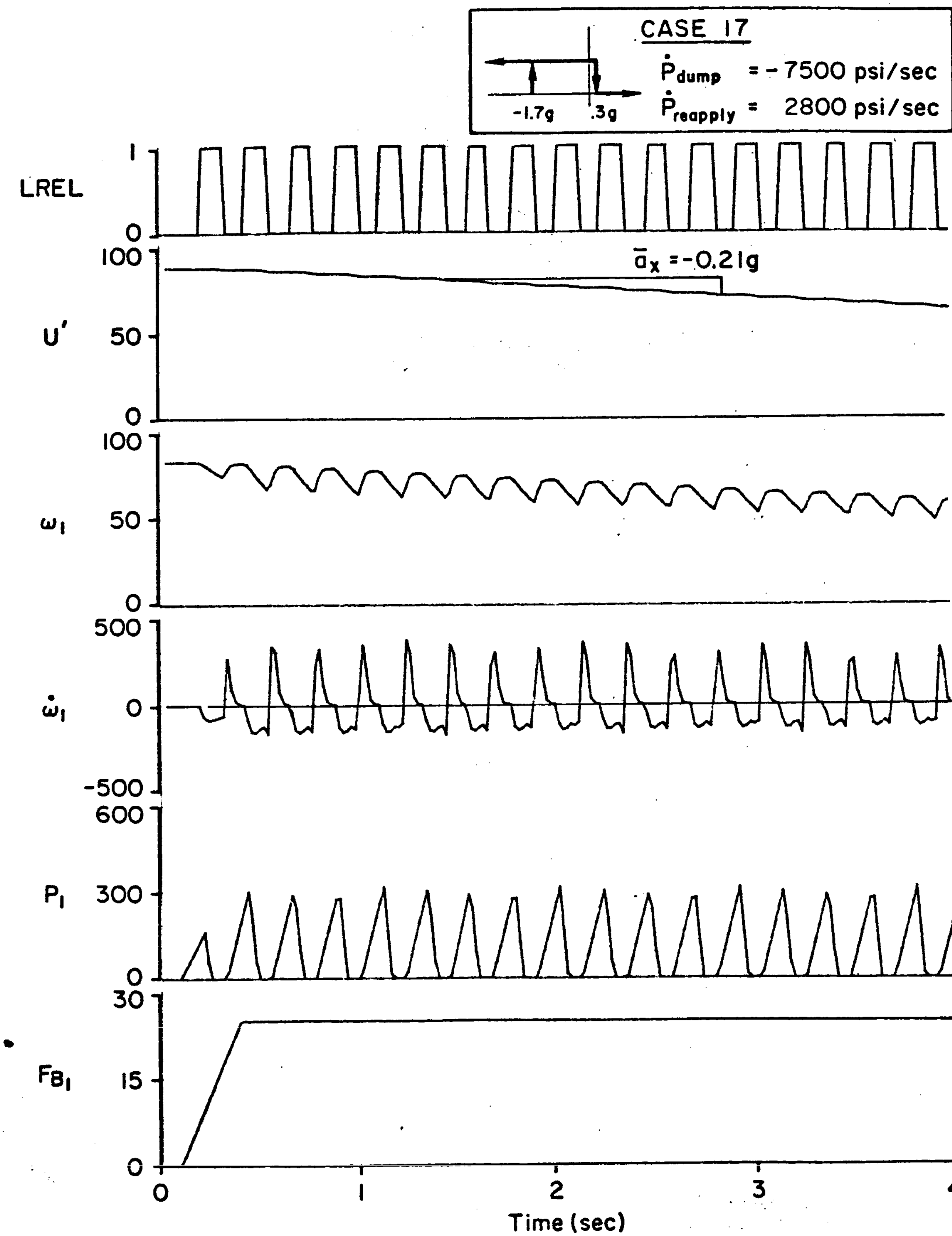

Figure A-13. Antilock Closed Loop Time History for Rapid Dump and Reapply Rates, High Mu

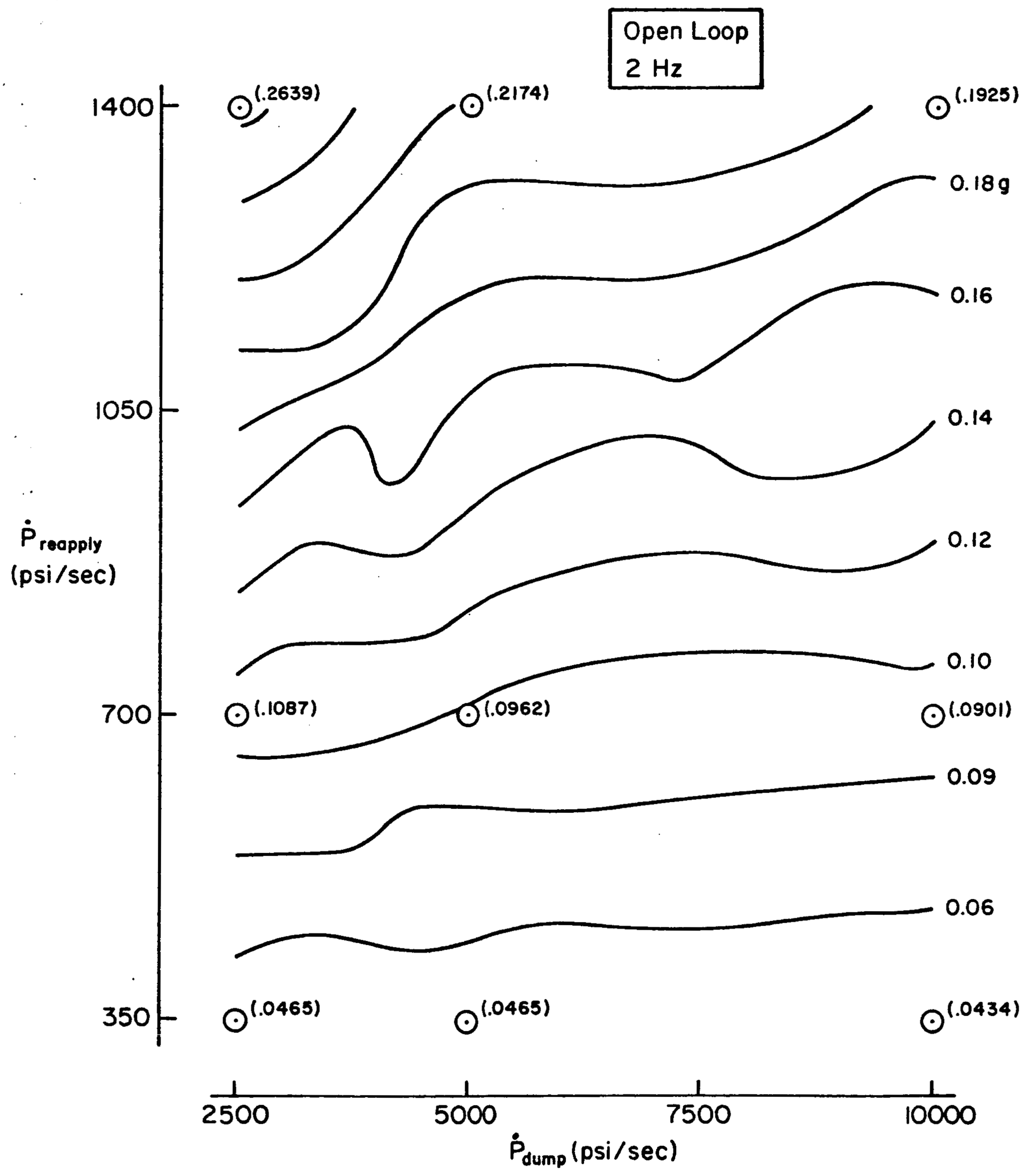

Figure A-14. Effects of Modulator Dump and Reapply Rates on Vehicle Average Deceleration, for 2 Hz Open Loop Command into Modulator, High Mu

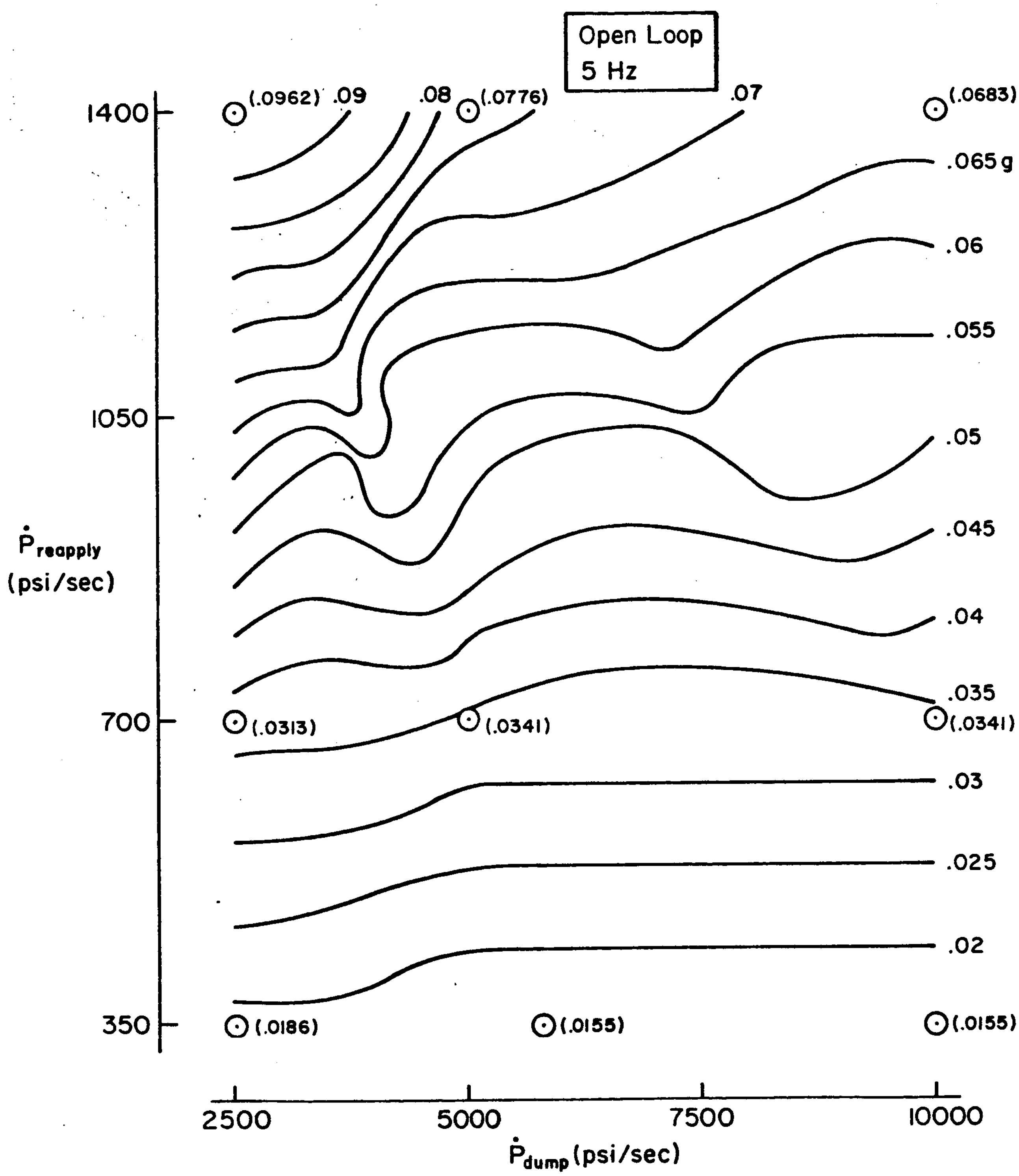

Figure A-15. Effects of Modulator Dump and Reapply Rates on Vehicle Average Deceleration, for 5 Hz Open Loop Command into Modulator, High Mu (in the above data) to 10ms, which is an estimate of the minimum practical limit. Note that the generic modulator delay for all the analyses was fixed at 10ms, which is probably a typical value for an antilock solenoid.

A large variety of pressure rates and toggle shapes were assessed, with the faster brake system response, in order to find higher performance levels.

G. OPTIMIZATION OF TOGGLE AND GENERIC MODULATOR

An extensive, though not exhaustive search for higher performance - accomplished by varying toggle and modulator parameters - resulted in a nominal design configuration, defined as follows:

- Feedback: Wheel angular acceleration
  (assumed to have no sensor dynamics)
- Dump rate: -3600 psi/sec
- Reapply rate: 2000 psi/sec
- Toggle width: 3.0g
- Toggle bias: -1.5g
- Modulator to caliper delay: 20 msec

This gave low mu stops of -0.23g at 13 Hz, and high mu stops of -0.54g at Hz. Subjectively, these were felt to be reasonable performance levels for an initial design; these are not intended to imply minimum acceptable levels, or maximum attainable levels. They are somewhat less than single wheel brake performance levels seen in previous tests (e.g., Ref 9). They do not include the effects of aerodynamic drag or rear tire rolling resistance, which could account for some of the difference.

In order to assess the degree of optimization, and also to quantify the design sensitivity (e.g., oversensitivity to small variations is not desirable), the toggle and modulator parameters were varied about their nominal values as follows: for the modulator,

Dump Rate (psi/s)	Reapply Rate (psi/s) 1500	2000(Nom.)	2500
-3100		X	
-3600(Nom.)	X	X	X
-4100		X	

and for the toggle,

Bias (g)	Width(g) 2.5	3.0	3.5
-1.0		X	
-1.5	X	X	X
-2.0		X	

For the modulator variations, the nominal toggle was used, and vice versa for the toggle variations. Both high and low mu surfaces were simulated.

The results of the sensitivity analyses have already been presented in Figs. 10 and 11 of Ref. 2. The corresponding detailed time histories are collected in Figs A-16 to A-33.

CONCLUSIONS AND RECOMMENDATIONS

Considering the results of the antilock analyses accomplished to date, leads to the following conclusions and recommendations:

- Comparisons with full scale test data show the vehicle and modulator elements of the simulation to be quite accurate. Refinement of such accuracy is readily acheivable, also.
- Wheel angular acceleration feedback provides a feasible single loop feedback design.
- Wheel angular jerk feedback is not desirable as a primary feedback control varibale, in part because it results in excessive sensitivity to small variations in vehicle and systems parameters.
- Wheel angular speed feedback may potentially provide a feasible control structure, if its low frequency characteristics are accounted for. Equivalently, a lagged wheel acceleration feedback could provide such a system. This would be a high priority area for further analyses, and could potentially lead to simplified antilock sensors, fluidic or otherwise.
- For single loop antilock control, design compromises amoung high versus low mu, and deceleration versus

roughness, appear to be fundamental.

- The combined effects of toggle and modulator design parameter values on antilock performance are complex and dependent on the shape of the local parameter space. They can be quantified by means of computer simulation and maps of deceleration and wheel speed roughness. In general, percentage changes in toggle parameters have relatively larger effects than similar percentage changes in modulator parameters.
- Net time delay between the modulator and caliper seems to be a key design parameter affecting performance and stability, and should be analyzed more completely to more precisely define fluidic and other antilock design requirements.
- A set of controller and modulator characteristics was found that gave a reasonable balance amoung performance, stability, and stability margin on both high and low mu surfaces.
- One way to potentially achieve higher performance and stability levels on both high and low mu surfaces could involve use of mu dependent, adaptive controller or modulator, as may be found on some existing electro-mechanical antilock systems. Such a feature is difficult to provide on all mechanical antilocks, but may be achievable with fluidic systems.

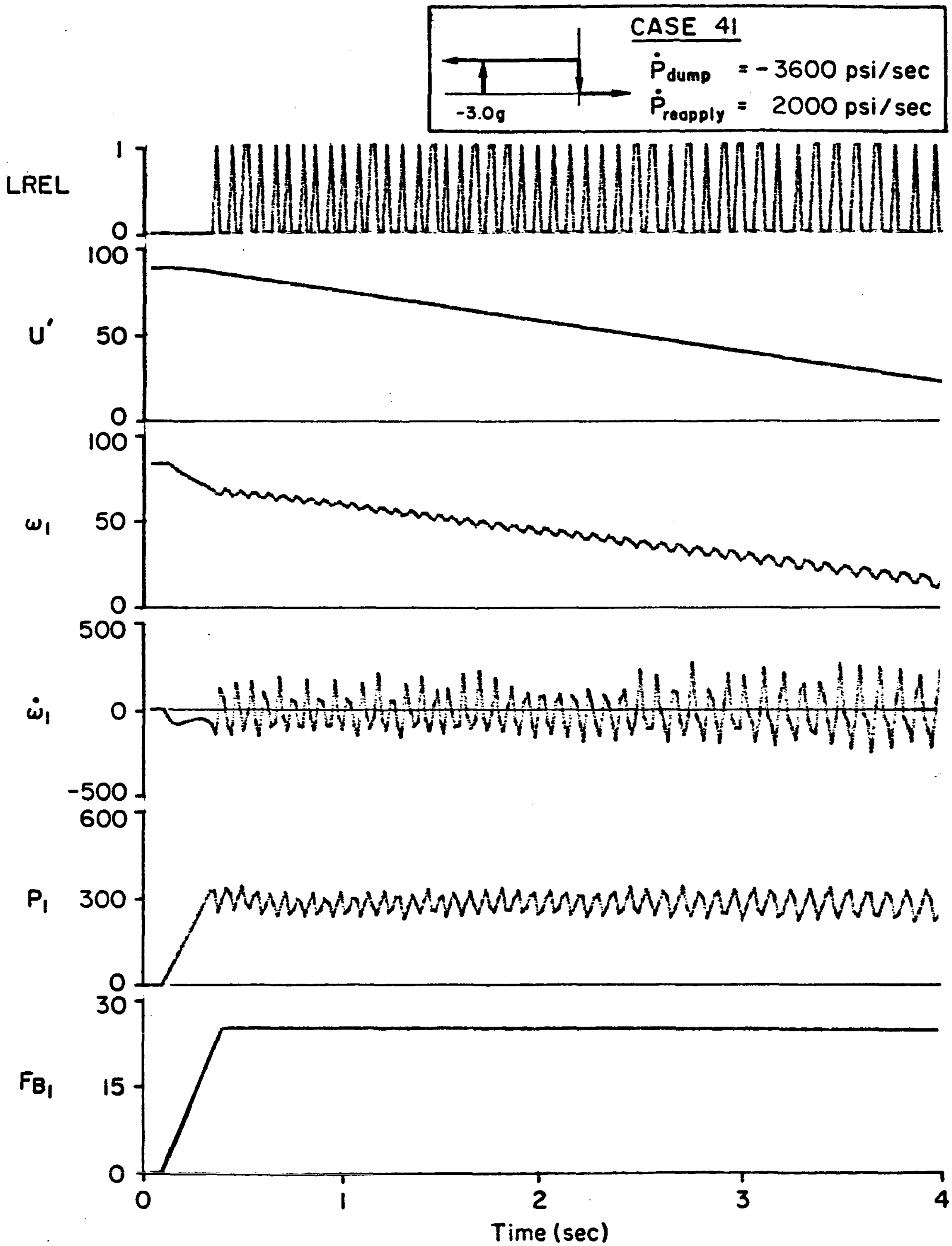

Figure A-16. Step Brake Time History for Preliminary Antilock Design, High Mu Surface

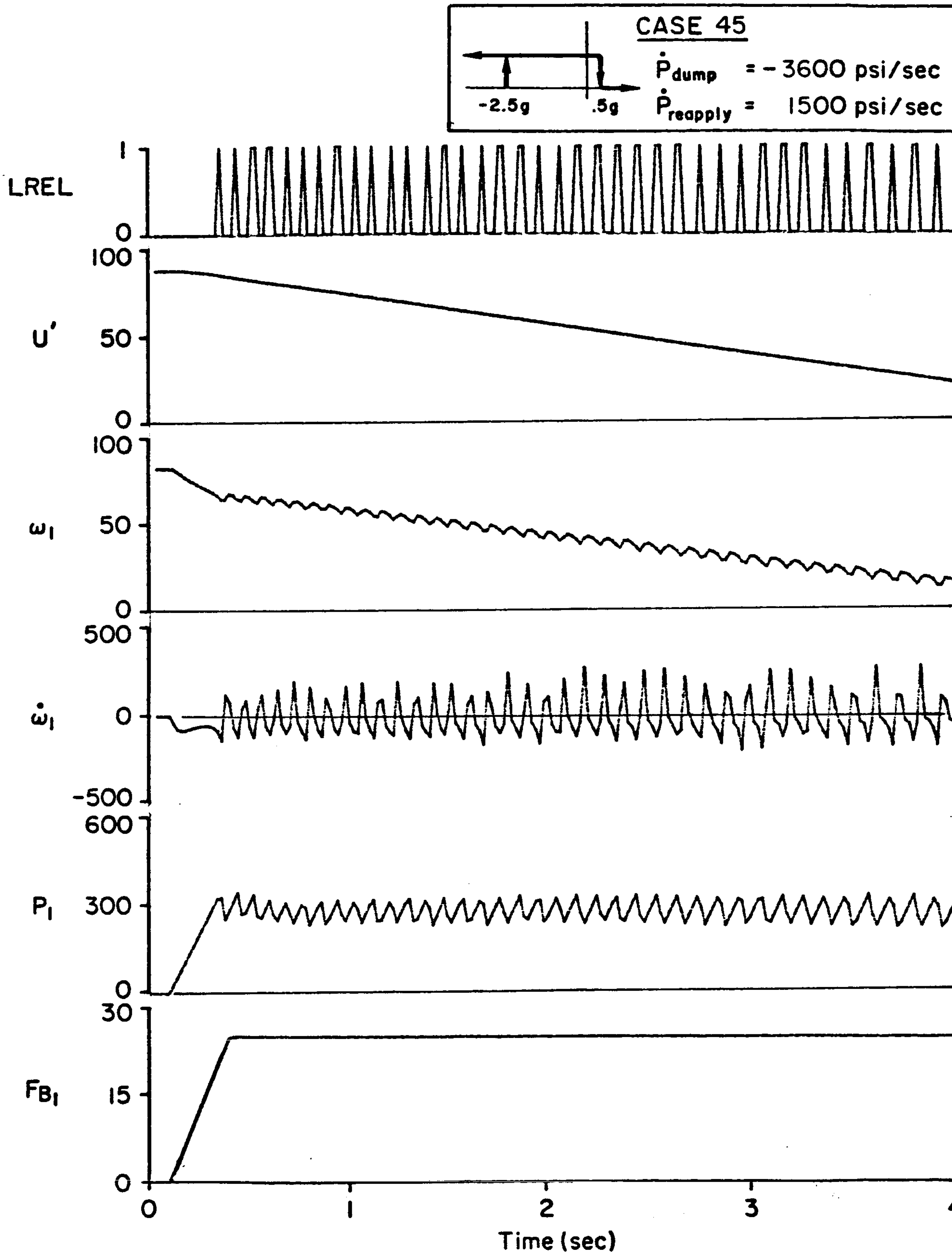

Figure A-17. Time History Showing the Effect of Reduced Reapply Rate, High Mu

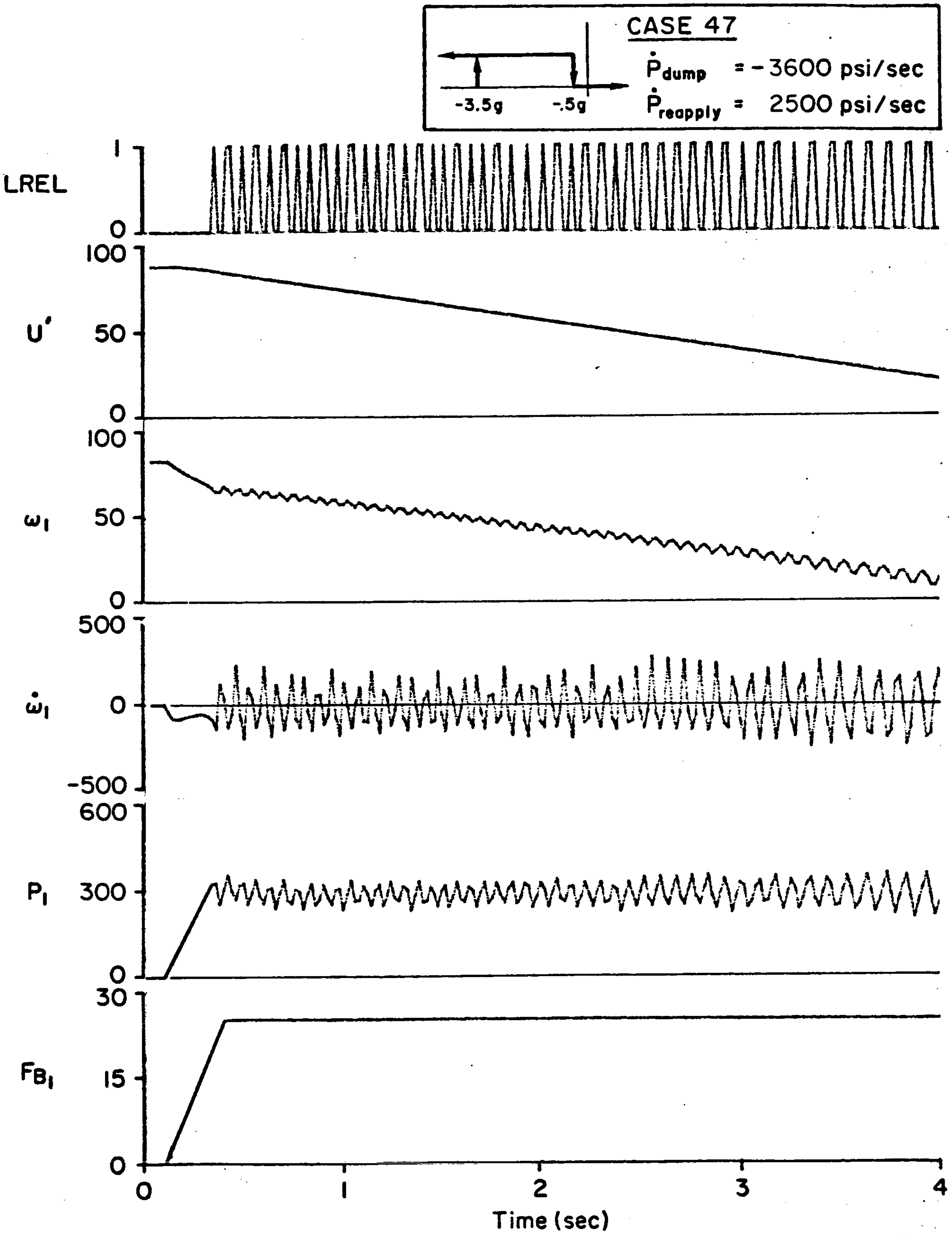

Figure A-18. Time History Showing the Effect of Increased Reapply Rate, High Mu

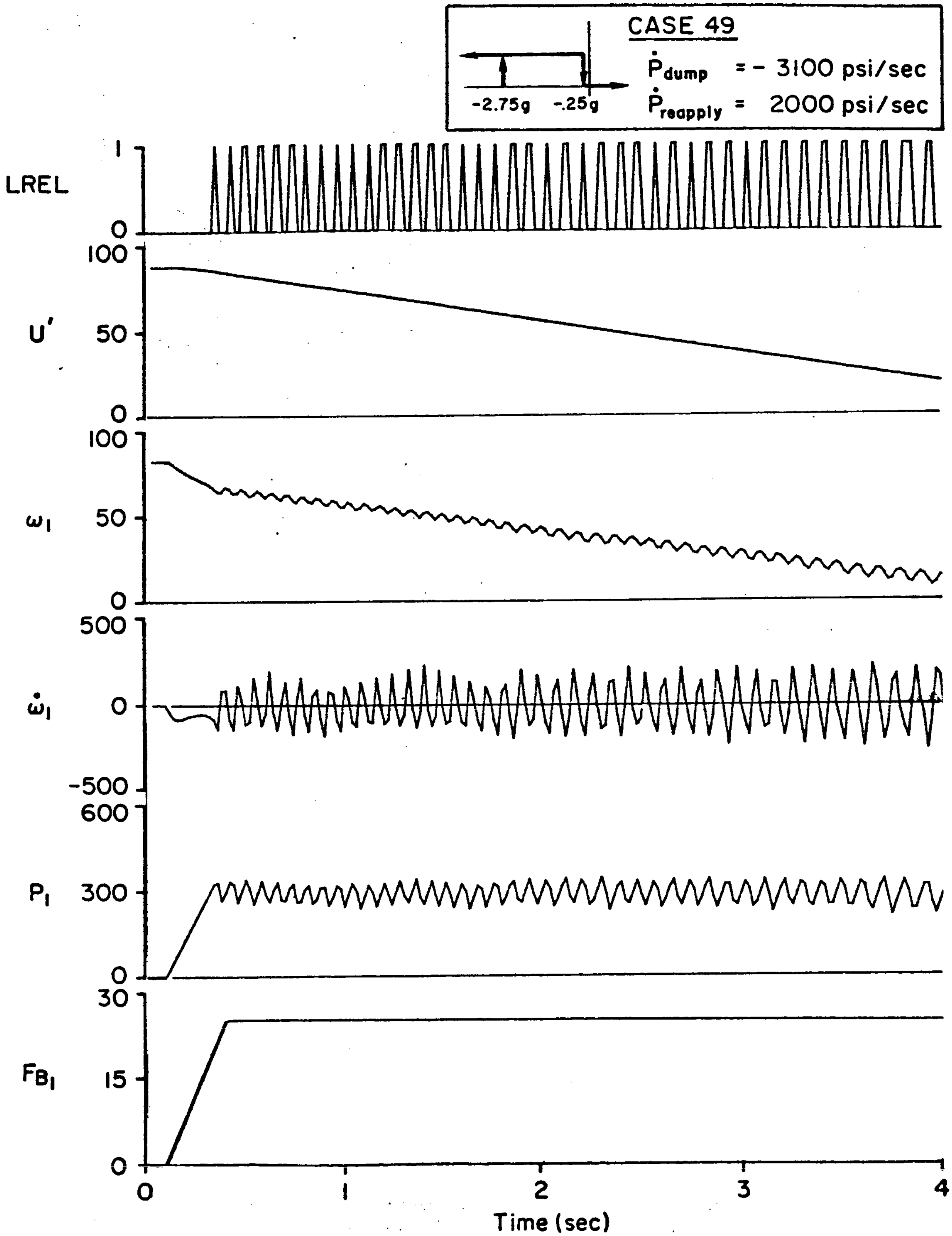

Figure A-19. Time History Showing the Effect of Reduced Dump Rate, High Mu

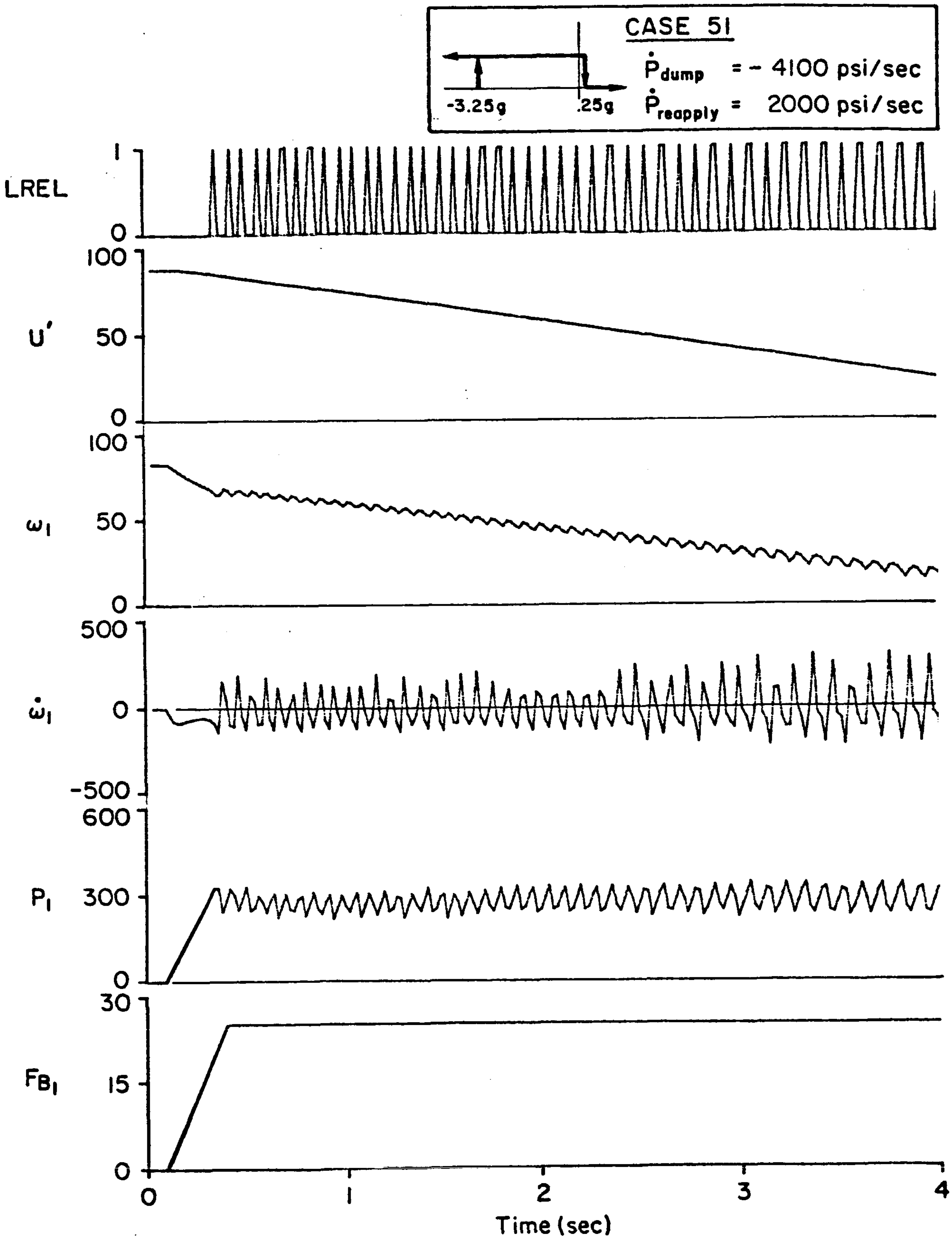

Figure A-20. Time History Showing the Effect of Increased Dump Rate, High Mu

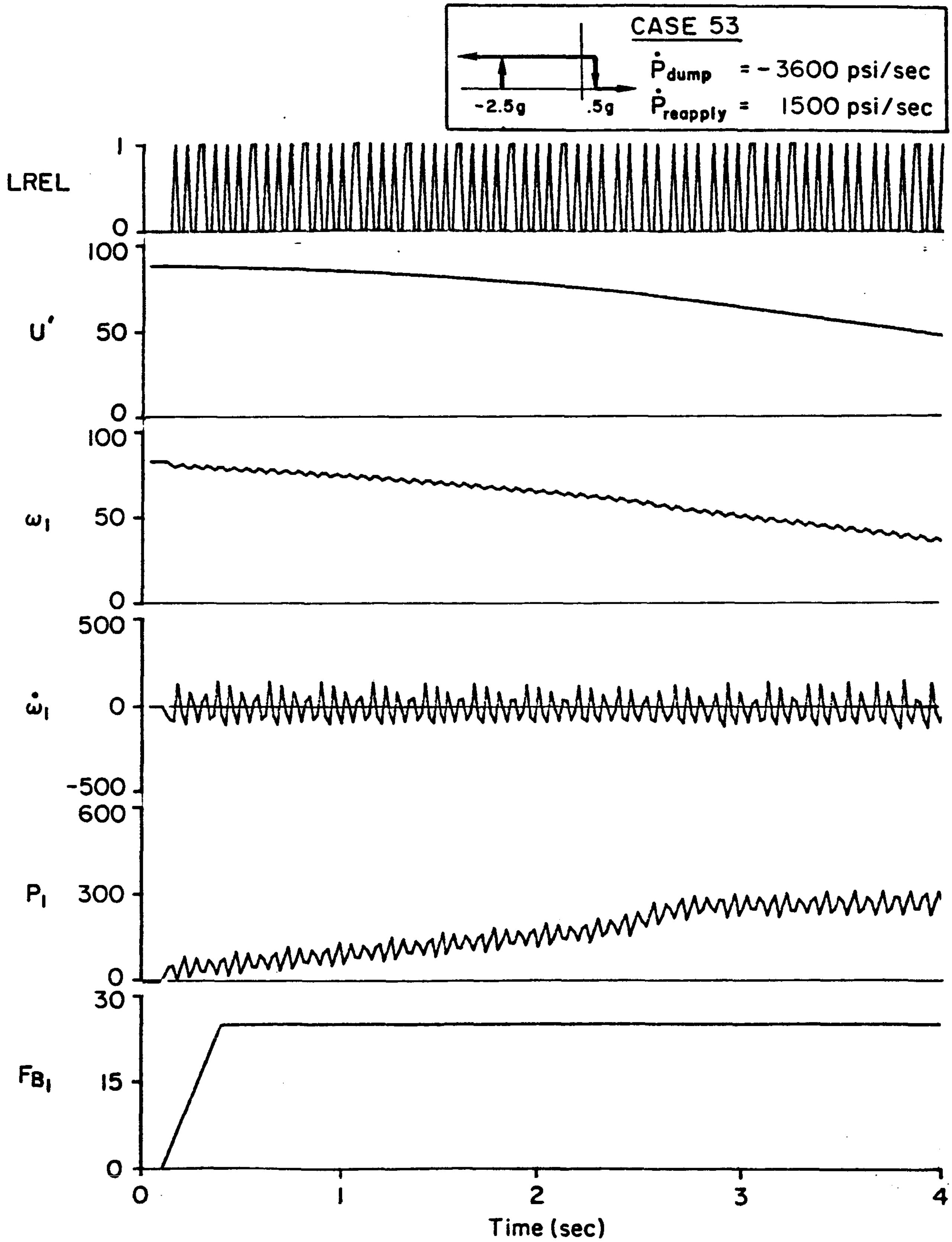

Figure A-21. Time History Showing the Effect of Less Negative Toggle Bias, High Mu

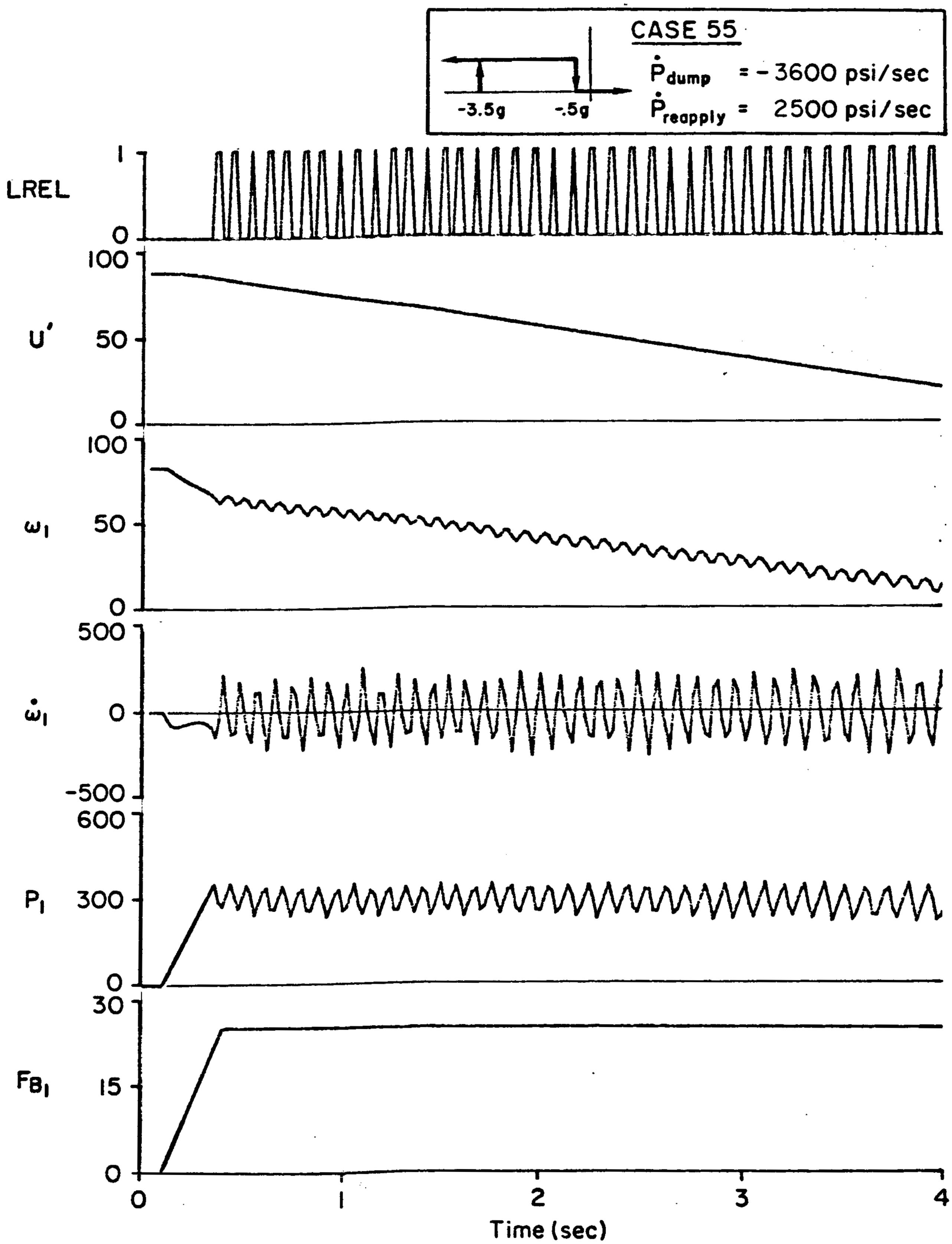

Figure A-22. Time History Showing the Effect of More Negative Toggle Bias, High Mu

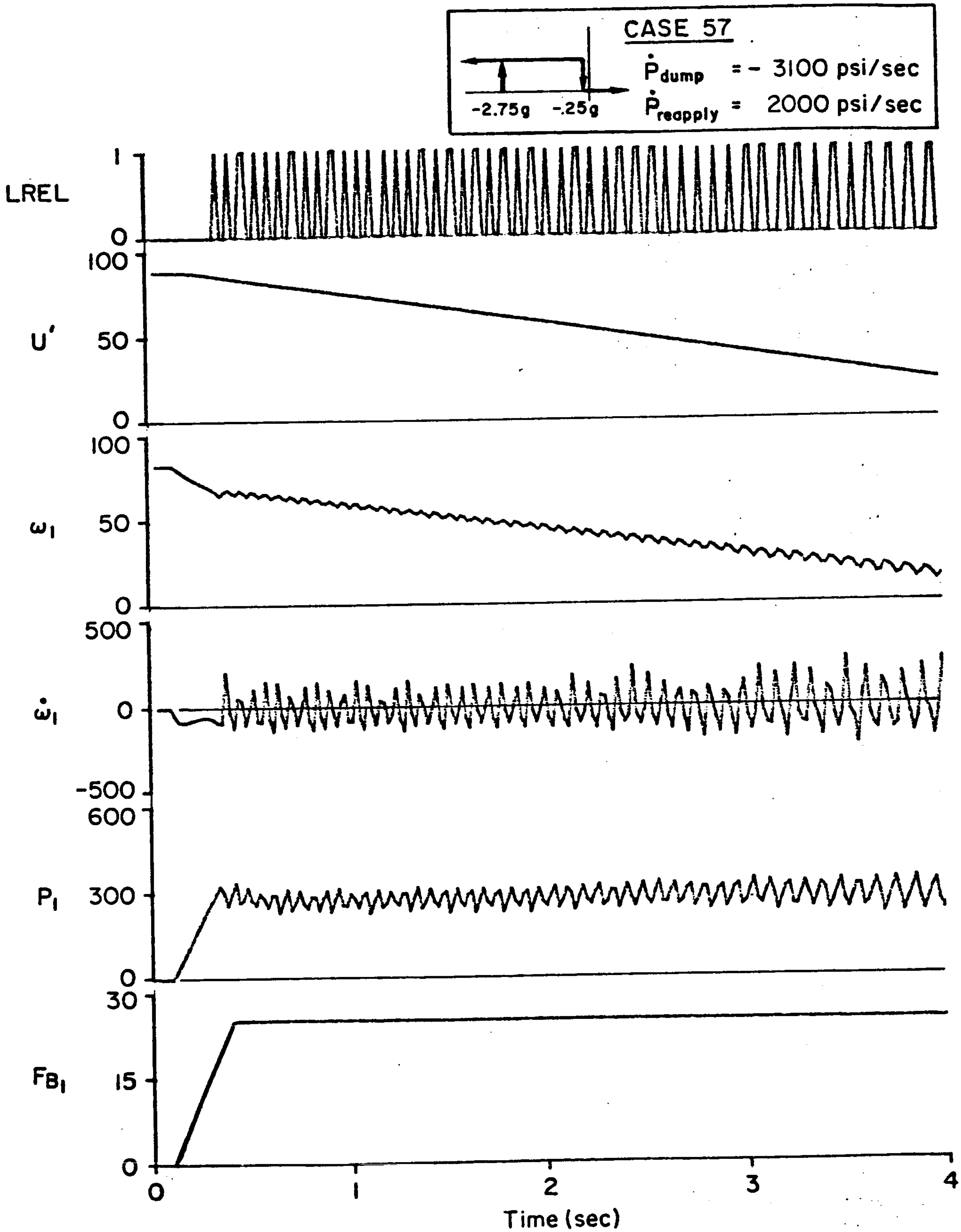

Figure A-23. Time History Showing the Effect of Narrower Toggle Width, High Mu

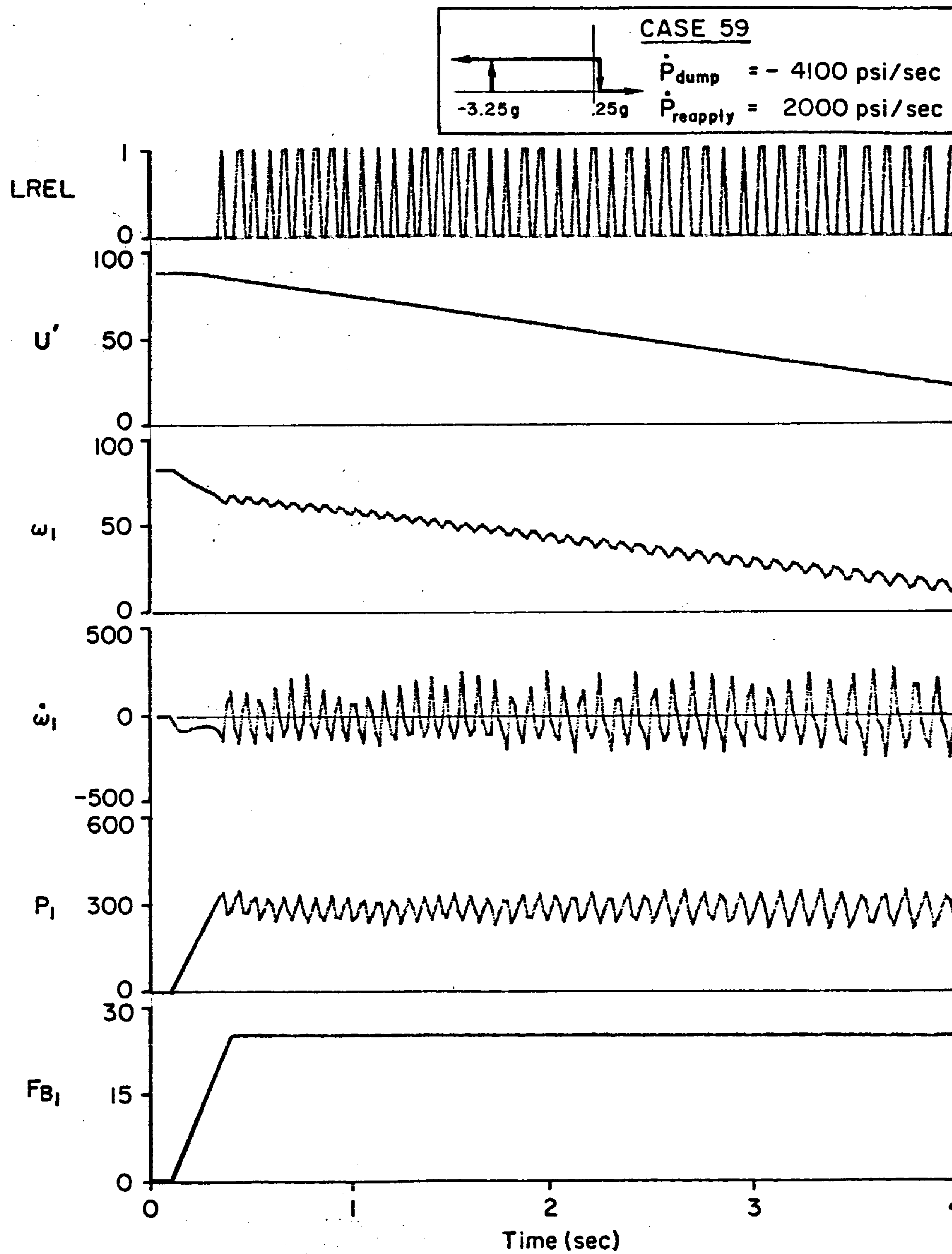

Figure A-24. Time History Showing the Effect of Wider Toggle Width, High Mu

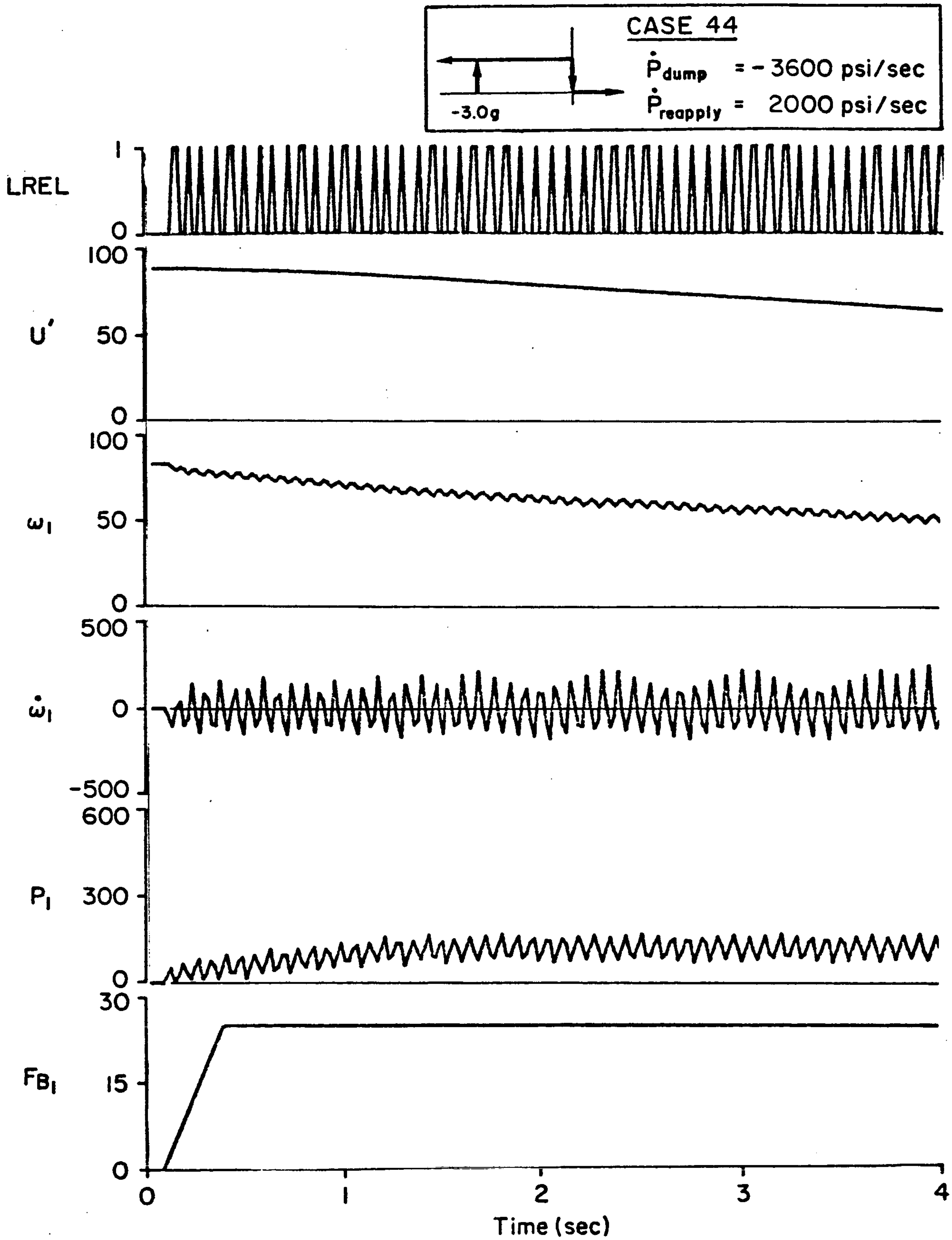

Figure A-25. Step Brake Time History for Preliminary Antilock Design, Low Mu

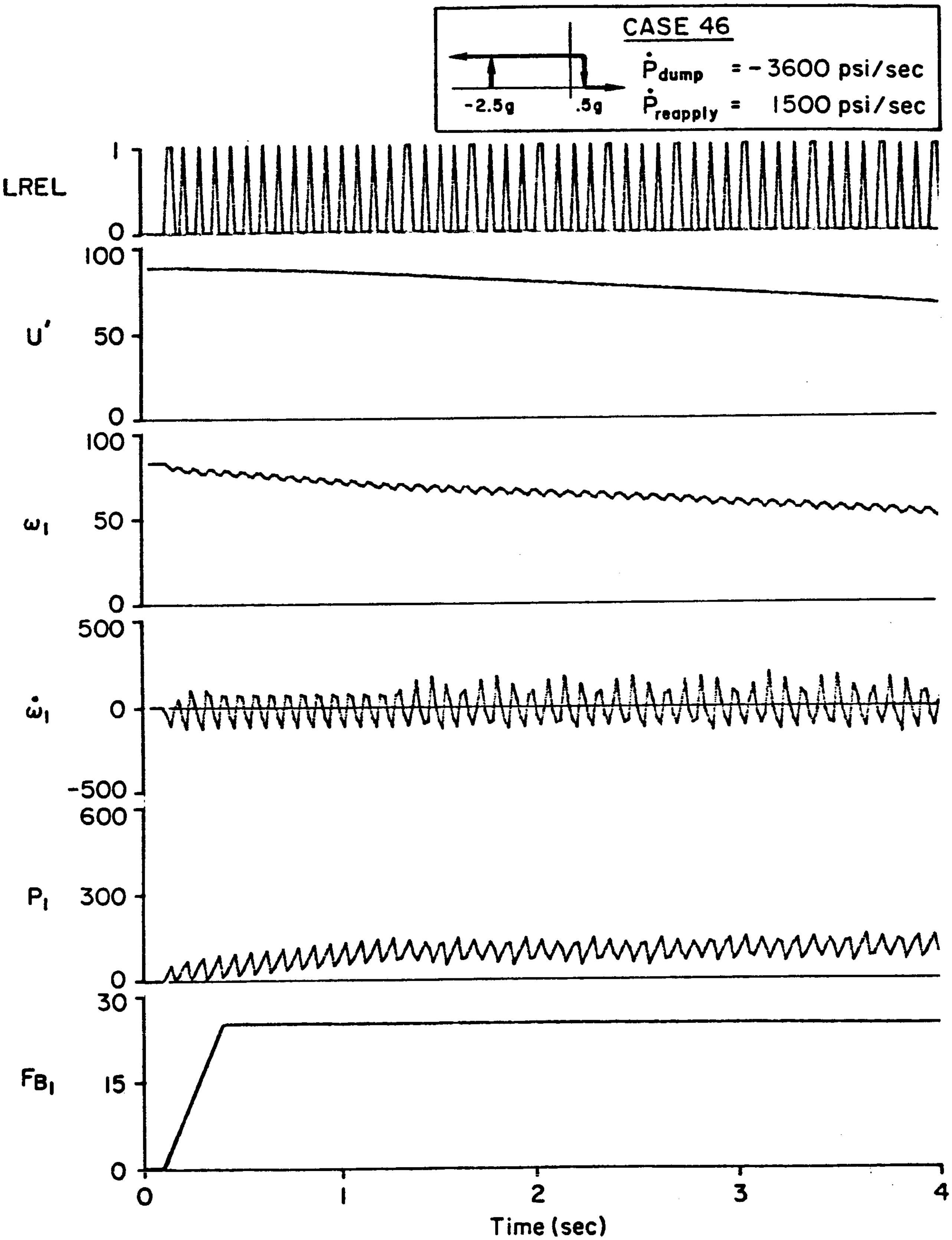

Figure A-26. Time History Showing the Effect of Reduced Reapply Rate, Low Mu

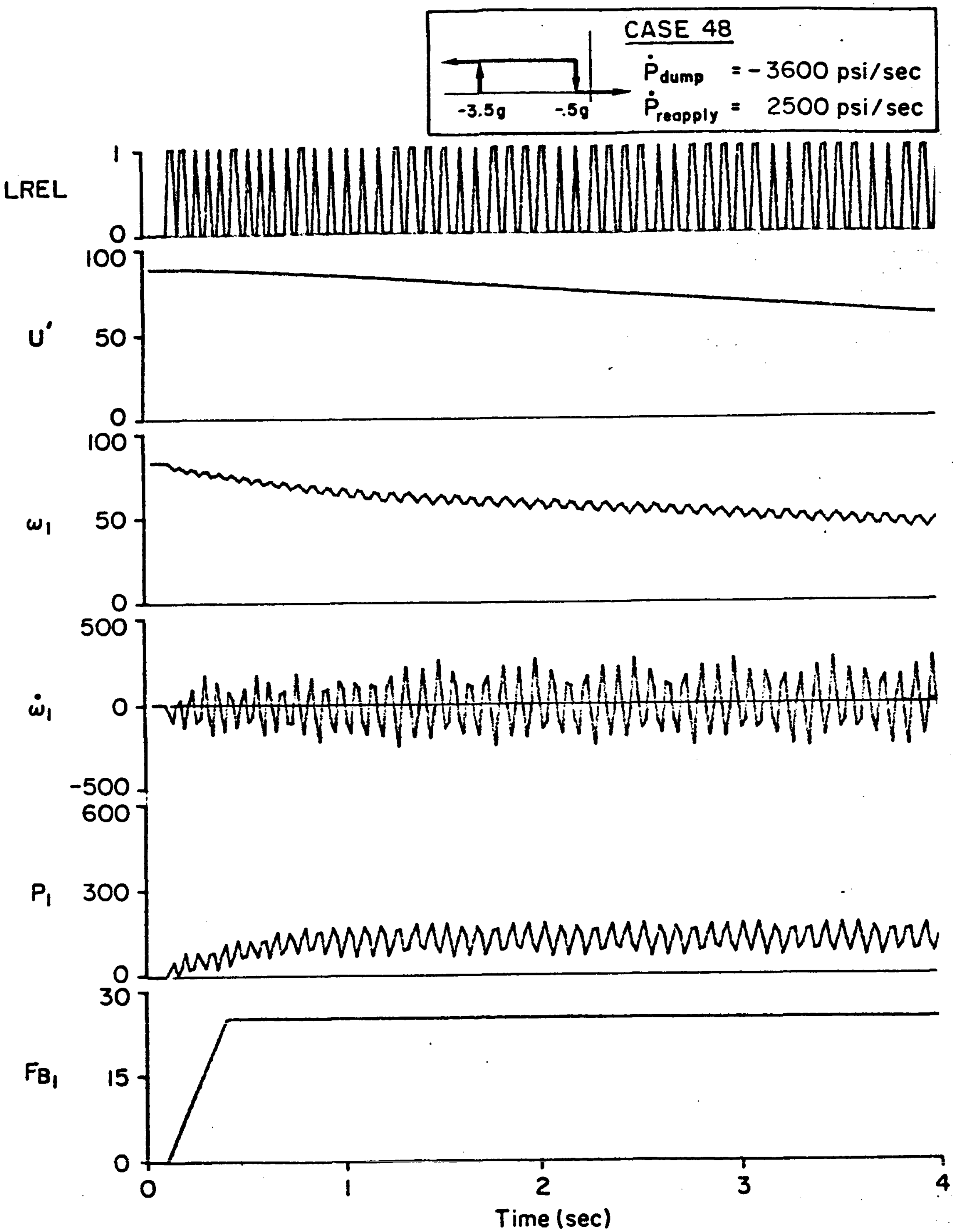

Figure A-27. Time History Showing the Effect of Increased Reapply Rate, Low Mu

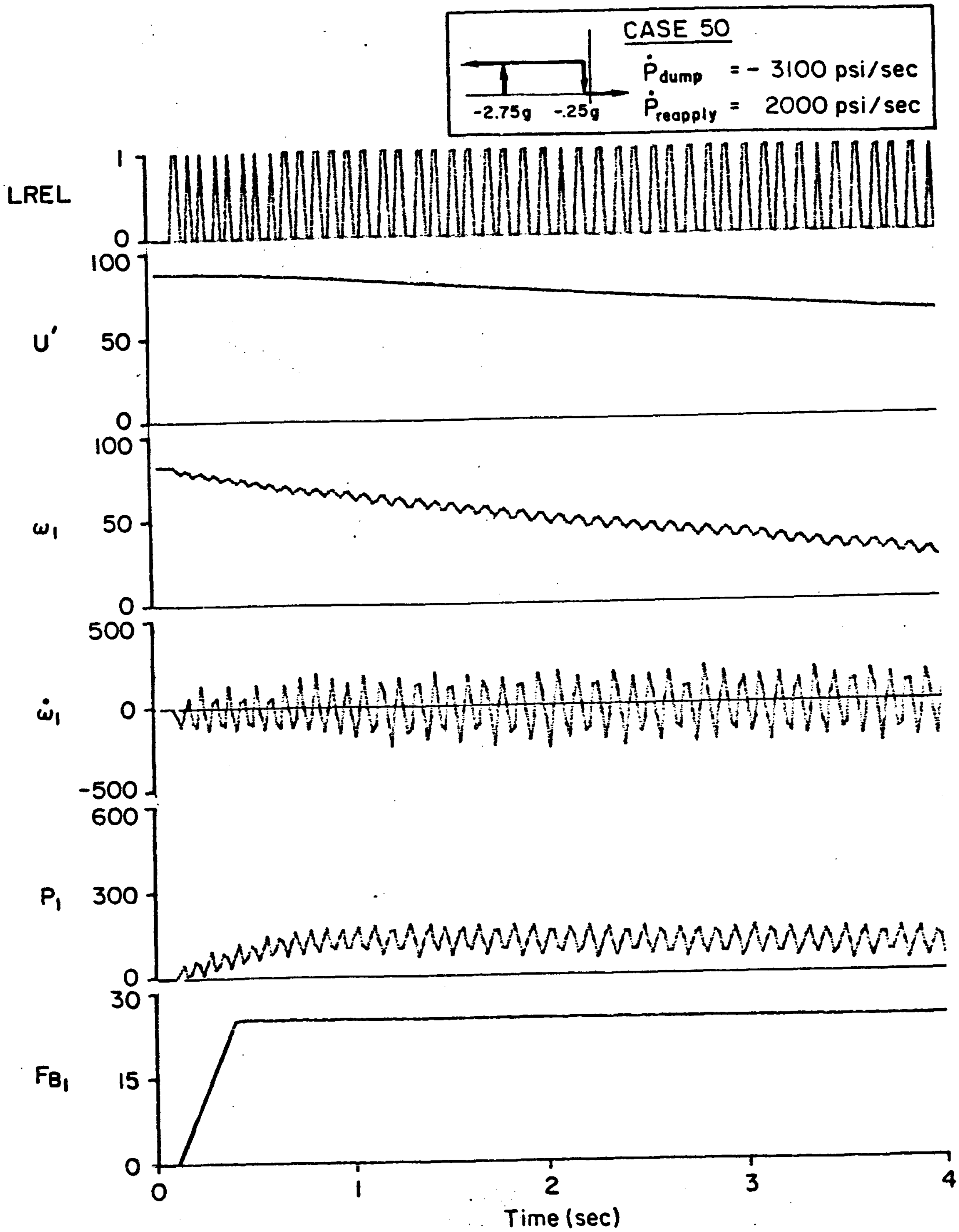

Figure A-28. Time History Showing the Effect of Reduced Dump Rate, Low Mu

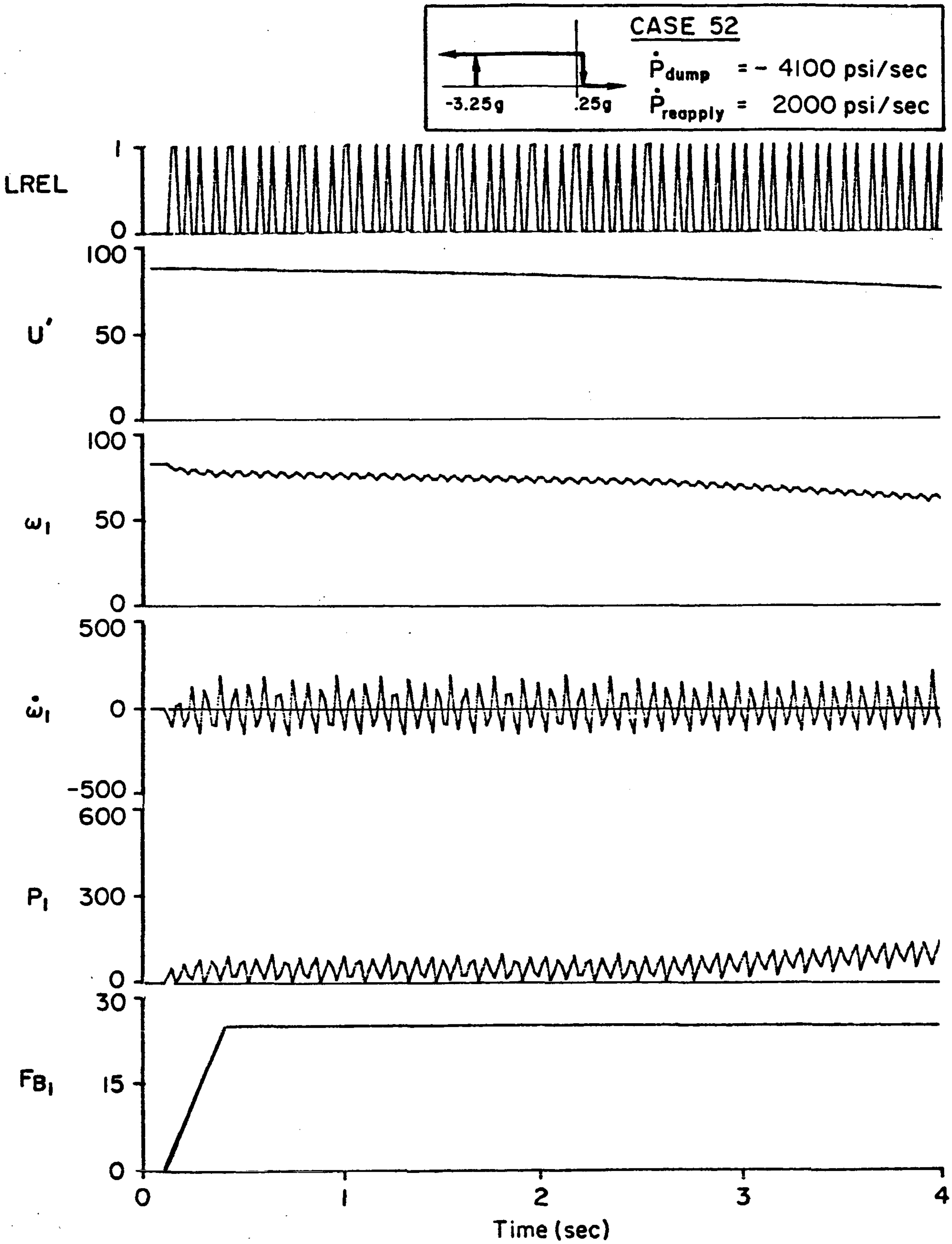

Figure A-29. Time History Showing the Effect of Increased Dump Rate, Low Mu

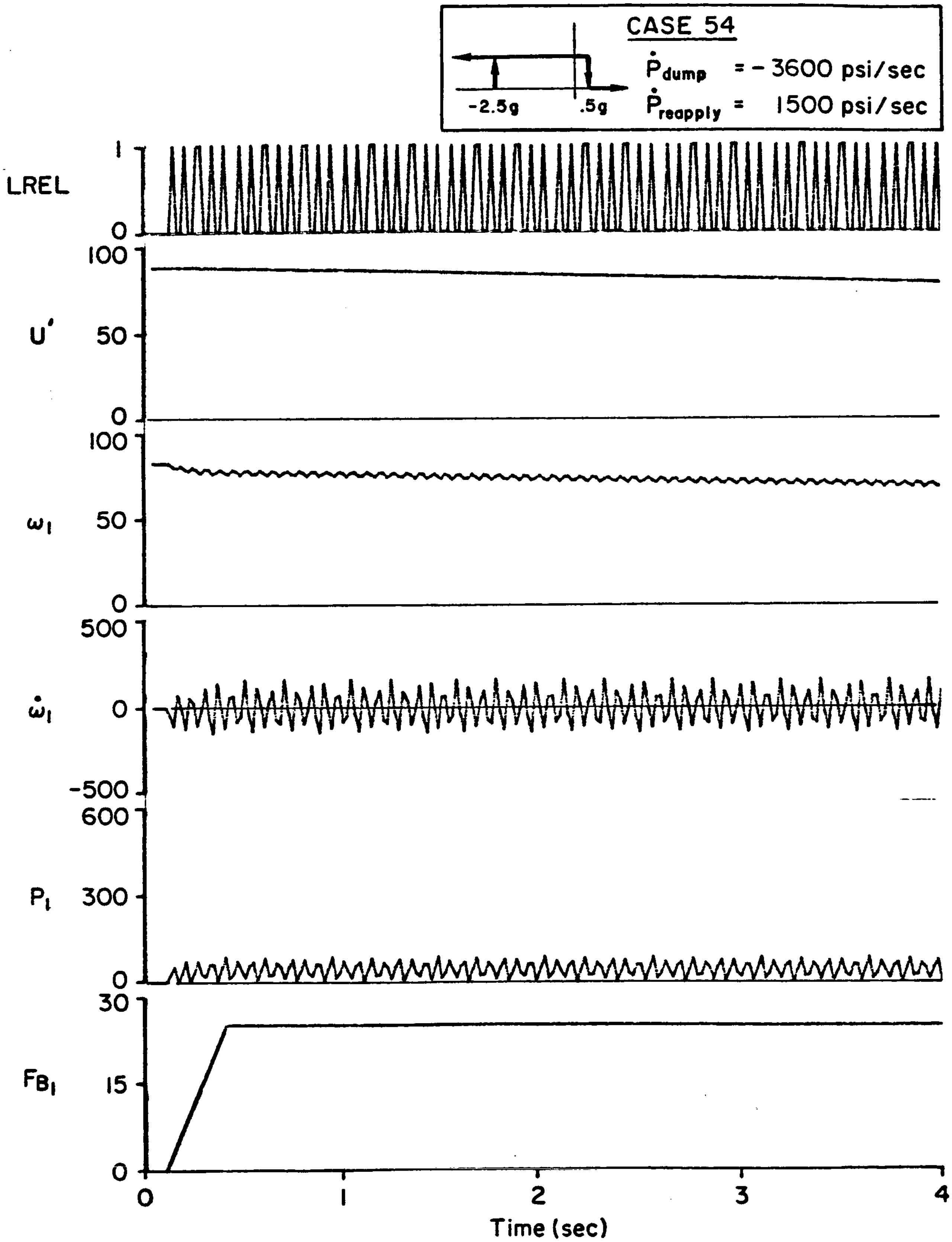

Figure A-30. Time History Showing the Effect of Less Negative Toggle Bias, Low Mu

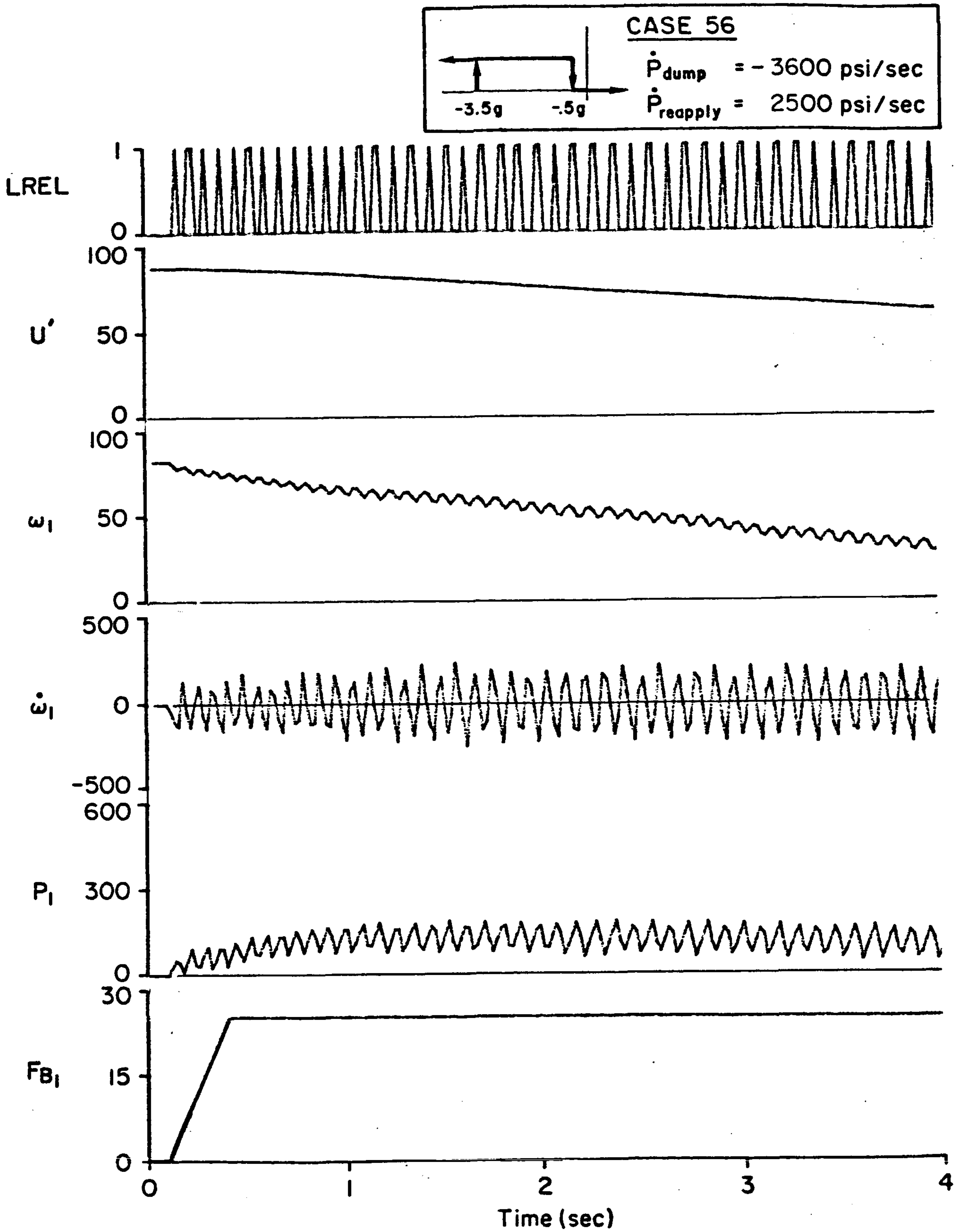

Figure A-31. Time History Showing the Effect of More Negative Toggle Bias, Low Mu

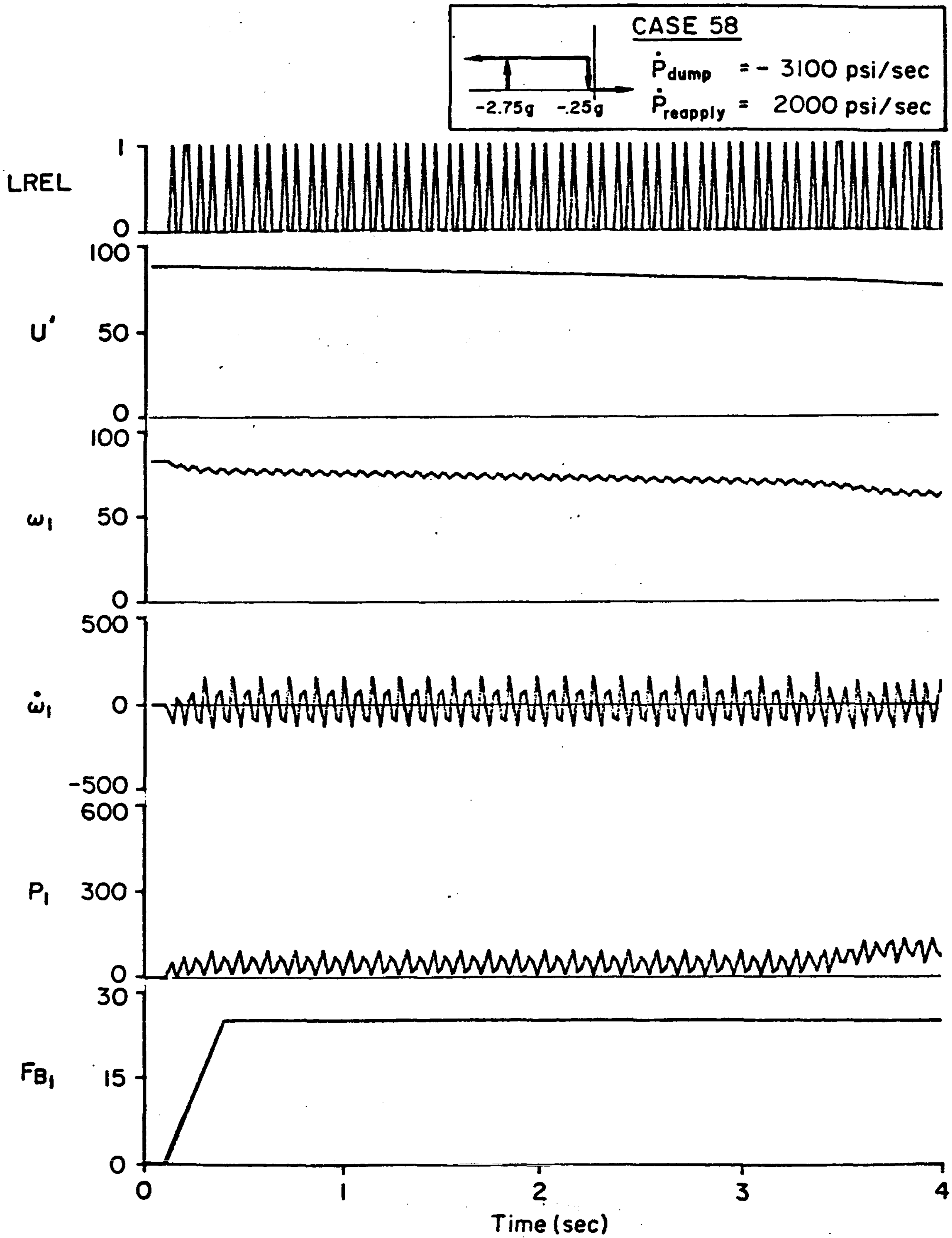

Figure A-32. Time History Showing the Effect of Narrower Toggle Width, Low Mu

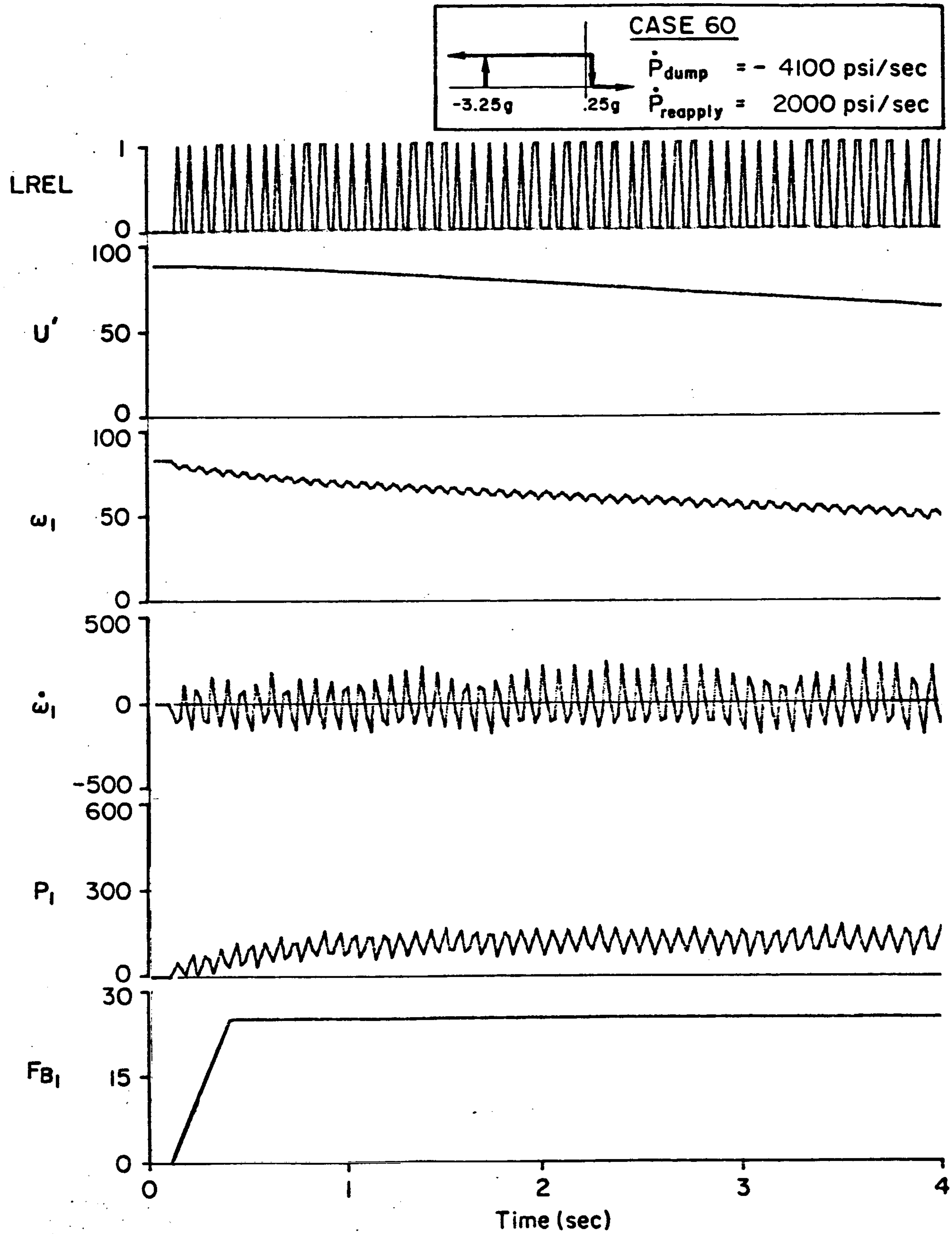

Figure A-33. Time History Showing the Effect of Wider Toggle Width, Low Mu

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3. "Critical Review of Report DOT-HS-802-288, Towards a Low Cost Highly Reliable Anti-Lock Brake System for Small Motorcycles," Dynamic Research, Inc. Technical Memorandum 82-7, Sept., 1982.

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8. <u>Test Report on Motorcycle with Antiskid Brake System</u>, Japan Automobile Manufacturers Association, Inc., Motorcycle Brake Working Group, Jan., 1978.

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APPENDIX

GENERIC MODULATOR SUBROUTINE LISTING

This appendix presents the listing of the FORTRAN source code for the subroutine 'MOD.' This provides for linear pressure dump and reapply rates, trigerred by the appropriate signal from the toggle. It also provides for upper and lower limits on pressure (namely, applied pressure and zero pressure). As shown, the listing is self documenting, and is meant to replace the corresponding subroutine describing the Mitsubishi modulator in the digital simulation program, 'CYCLE2.'

```
      SUBROUTINE MOD(P1)
C
      LOGICAL LREL,LBL,LVALR,LVALB,LFLAG
      LOGICAL LSVALR(30),LSVALB(30)
      INTEGER KK
C
C     ROUTINE WILL DETERMINE THE MODULATED PRESSURE
C     TO THE WHEEL CYLINDER IF ANTI-LOCK IS NEEDED
C
C     INPUT/OUTPUT COMMONS:
C
      COMMON/CTRL/LREL,LBL,IREL,IBL
      COMMON/ALBVAR/PD(2)
      COMMON/DELVAR/TD1,XT,TD2
      COMMON/VAR/V(14)
C
      EQUIVALENCE(PSI1,V(13))
C
C     LSVALR=STORAGE LOGIC VARIABLE OF RELEASE VALVE
C     LSVALB=STORAGE LOGIC VARIABLE OF BUILD VALVE
C     LVALR=DELAYED LOGIC VARIABLE OF RELEASE VALVE
C     LVALB=DELAYED LOGIC VARIABLE OF BUILD VALVE
C
C-----------------------------------------------------
C
C     CHECK MODULATOR STATE
C
      IREL = 0
      IBL = 0
      IF (LREL) IREL=1
      IF(LBL) IBL = 1
C
C     DELAY OF CONTROLLER COMMANDS TO VALVES
C
      TD2=0.01
      KK=INT(30.-(TD2/XT))
C
      LSVALR(30)=LREL
      LSVALB(30)=LBL
C
      DO 2110 I=1,29
      LSVALR(I)=LSVALR(I+1)
      LSVALB(I)=LSVALB(I+1)
 2110 CONTINUE
C
      LVALR=LSVALR(KK)
      LVALB=LSVALB(KK)
C
C     DETERMINE RELEASE OR BUILT RATE
C
      PDI = 0.0
      IF(LVALR) PDI = PD(1)
      IF(LVALB) PDI = PD(2)
C
      IF((.NOT.LVALR).AND.(.NOT.LVALB)) GO TO 2900
C
```

```
C       CALCULATE MODULATED PRESSURE
C
        PSI1 = PSI1 + (PDI*XT)
        IF(PSI1 .GT. P1) PSI1 = P1
        IF(PSI1 .LT. 0.) PSI1 = 0.
        GO TO 2999
C
 2900   PSI1 = P1
C
 2999   WRITE(6,500) KK,IREL,IBL,PDI,P1,PSI1
  500   FORMAT(1X,3I2,3F12.4)
C
        RETURN
        END
```