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COMPUTERIZED DESIGN AND LIFE PREDICTION - BEARINGS

CRAWFORD MEEKS AND ELIAS POLENDO

AVCON - ADVANCED CONTROLS TECHNOLOGY, INC.
5210 LEWIS ROAD
AGOURA HILLS CA 91301

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Nonstructural Materials Branch
Nonmetallic Materials Division

KENT J. EISENTRAUT, Chief
Nonstructural Materials Branch
Nonmetallic Materials Division

CHARLES E. BROWNING, Chief
Nonmetallic Materials Division
Materials Directorate

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This report documents the computer study of bearing cage designs. The proposed cage designs possessed unsymmetrical geometry which differed considerably from conventional cage design. The ball bearing dynamics software, BABERDYN2, was modified to enable the analysis of this new geometry. Subsequently, an optimization study of the ball-to-pocket and land riding clearances was performed. The results of this study are contained herein.

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FOREWORD

This document is the final report covering an add-on project on a specific problem in bearing stability that originally was performed under U. S. Air Force Systems Command Contract F33615-92-C-5908. The project was sponsored by the Materials Directorate, Wright Laboratory, Air Force Systems Command, Wright Patterson AFB OH 45433-7750. The Advanced Research Projects Agency (ARPA), Arlington VA, was the original source of the funding. The Air Force Project Engineer was Karl R. Mecklenburg of Wright Laboratory.

STUDY OF GENERAL DYNAMICS BEARING CAGE DESIGNS

Summary

This report documents the study of bearing cage designs, proposed by General Dynamics Electric Boat Division (GDEB). The proposed cage designs possessed geometry which differed considerably from conventional cage designs. The ball bearing dynamics software, BABERDYN2, was modified to enable the analysis of this new geometry. Subsequently, an optimization study of the ball-to-pocket and land riding clearances was performed. The results of this study are contained herein.

1.0 Introduction

The proposed cage designs are shown in Figure 1. As can be seen from the figure, both Design "A" and Design "B" have an unconventional geometry for the ball cages. Typically, the left and right sides of the cage are symmetrical; however, in the present case, the ball cage design is new and unconventional.

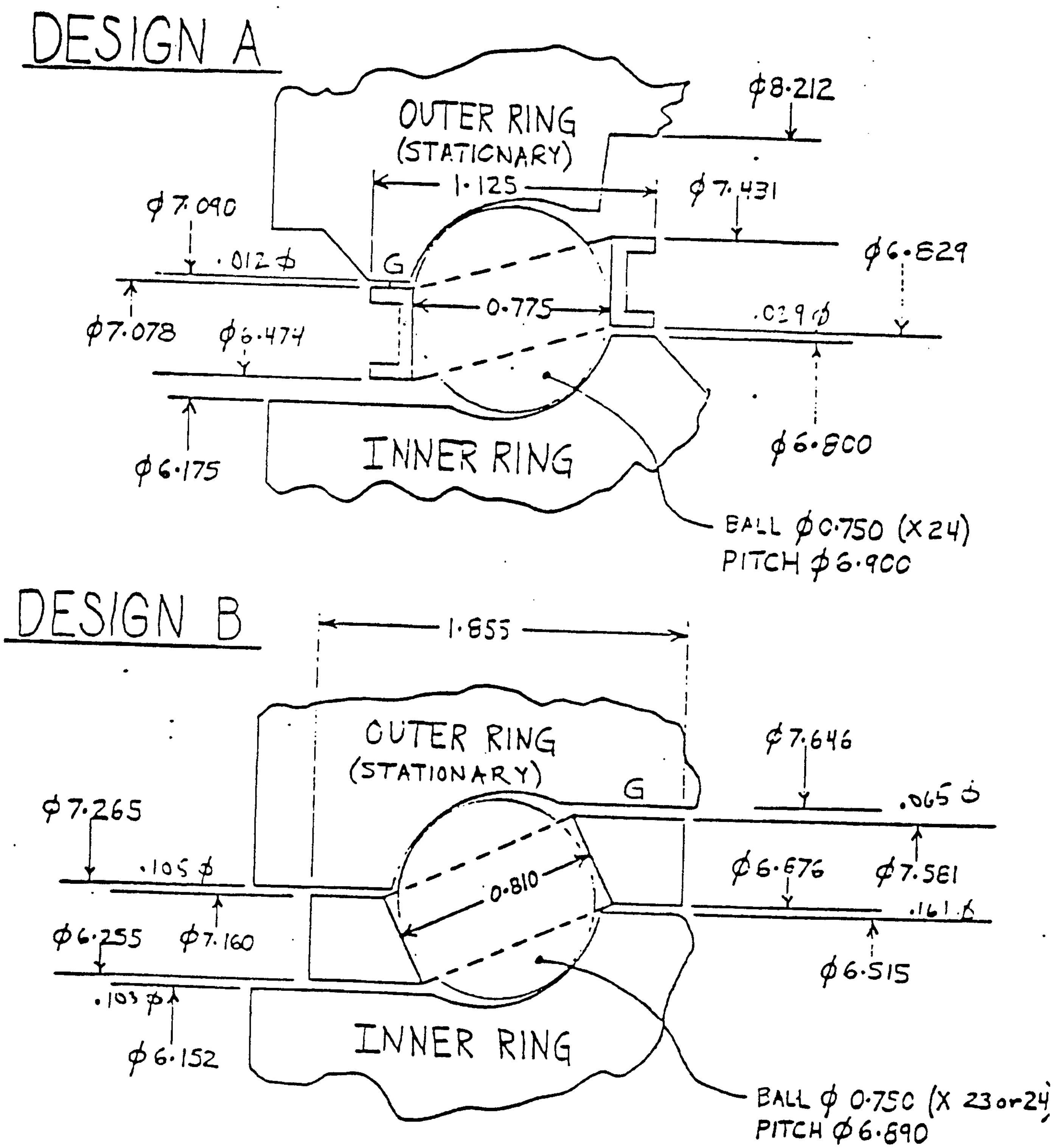

Fig 1 Bearing Design Specifics

2.0 Modification of the Bearing Dynamics Program BABERDYN

The existing bearing dynamics software BABERDYN2 is capable of handling cage designs which come into contact with either the outer race or inner race of the bearing. In either of these cases, the impact forces between guiding race and cage are symmetrical from the symmetry of the race geometry. Hence, no torques are exerted on the cage due to the symmetry condition.

In the present designs, the symmetry condition does not hold, thus necessitating an extension of the current model to handle these "skew guided" designs. The details of the modeling are explained in Sections 2.1 through 2.3.

2.1 Collision Forces

When collisions between race and cage occur, the normal and tangential forces are calculated as follows:

$$F_{b/cT} = \mu F_{b/cN}$$

$$F_{b/cN} = K_{c/r} * (\delta\text{-gap})^{1.11}$$

where

F_b = cage/race collision force, lbs, (Normal and Tangential)

$K_{c/r}$ = effective cage/race stiffness, $lb/in^{1.11}$

δ = displacement of cage fixed coordinate, in.

gap = cage/guiding race radial clearance, in.

μ = Coulomb friction coefficient between cage and race

If both bottom and top portions of the cage can contact the guiding race, the effective stiffness is equal to the input stiffness $K_{c/r}$. If only one side can contact the guiding race, then it is assumed the effective stiffness is 1/2 $K_{c/r}$.

2.2 Collision Moments

When both bottom and top portions of the cage can possibly contact the guiding races, it is assumed that the collision forces between the top and bottom portions of the cage and the guiding race are equal in magnitude. Next, it is assumed that the moment arms from the collision point and the cage center line (see Figure 2.) will be the same.

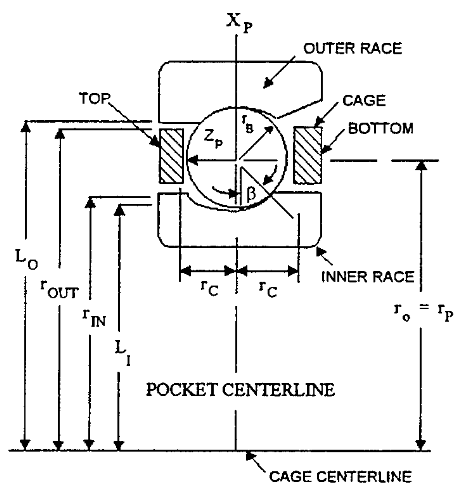

Fig 2 Race-Guided Cage Cross Section

Therefore, no moment will be transferred into the cage. Only when the top or bottom portion of the cage contacts the guiding land will the collision force on one portion of the cage create an offset moment transferring into the cage. The off-set moment will have a tendency to tip the cage and virtually lock the cage in place for a while. The off-set moment is calculated as follows:

$$\Delta M = \begin{Bmatrix} r_c \\ o \\ r_c \end{Bmatrix} * [F_{b/cN}\ 0\ F_{b/cT}]$$

where r_c = algebraic distance from the contact between guiding race and cage to the cage center line, in inches. r_c will be positive if the collision occurs on the top portion, negative if the collision occurs on the bottom portions, and zero if collision occurs on both portions of the cage. Then collision forces and moments are transformed back into the cage-fixed frame and added to the other ball-pocket forces as follows:

$$F = \Sigma[B_i]^T F_i$$

$$M = \Sigma[B_i]^T M_i$$

2.3 Cage Moment of Inertia and Center of Mass

The GDEB bearing cage is symmetric about the z-axis; therefore, the product of inertias are zero (i.e., Ixy, Ixz, Iyz). The center of mass of the cage is off-set from the geometrical center of the cage by a very small fraction. For the sake of simplicity, the center of mass of the cage is assumed to lie on the geometrical center.

3.0 Summary of Inputs

Table 1 Summary of Inputs, Cage

CAGE INPUTS	DESIGN A	DESIGN B
Outside Dia (in)	7.078	7.581
Inside Dia. (in)	6.829	6.2552
Width (in.)	1.125	1.855
X,Y, Z Inertia slug - in^2	0.0295, 0.0295, 0.0561	0.0991, 0.0991, 0.1883
Mass Slug	4.632 E-3	.0161

Table 2 Summary of Inputs, Bearing

BEARING INPUTS	DESIGN A	DESIGN B
Ball Dia (in)	0.75	0.75
Inner Race Land Dia (in	6.80	6.152
Outer Race Land Dia (in)	7.09	7.646
Inner Race Curvature	0.53	0.53
Outer Race Curvature	0.545	0.53
Pitch Dia (in)	6.9	6.89
Contact Angle	30°	30°

Table 3 Summary of Inputs, Friction and Lubricants

FRICTION & LUBRICANT INPUTS	DESIGN A	DESIGN B
C/L Damping $\frac{lb-s}{in}$	0.0285	0.0285
C/B Damping $\frac{lb-s}{in}$	0.0285	0.0285
C/B Stiffness $\frac{lb}{in}$	1800	10,400
C/L Stiffness $\frac{lb}{in}$	250	7,664
C/L Coulomb Friction	0.2	0.2
C/B Coulomb Friction	0.2	0.2
Lube Viscosity $\frac{lb-s}{in}$	2.53e-5	2.53e-5

Table 4 Summary of Inputs, Traction

Traction Data		
IN/SEC	LB/LB	
12.2	0.012	Rolling Speed 406 in/sec 41.7° C Contact Stress 150 Ksi
28.42	0.0184	
69.02	0.020	
121.8	0.020	

Table 5 Summary of Inputs, Cage Pocket Geometry

CAGE POCKET GEOMETRY	DESIGN A	DESIGN B
Cone Angle	90° for race guided cages	N/A
Cage/Ball	N/A	3.445
Pocket Dia (in)	0.775	0.810

Table 6 Summary of Inputs, Material Properties

PHYSICAL PROPERTIES	RING	BALLS	DESIGN A CAGE	DESIGN B CAGE
Young's Modulus (psi)	3.2×10^7	4.5×10^7	8.8×10^5	1×10^6
Poisson Ratio	0.32	0.26	0.4	0.26
Density (lb/in^3)	-	0.1156	0.015	0.050

Table 7 Summary of Inputs, Ball Contact Parameters

	Design A		Design B	
No.	B/IR Load (lb)	B/OR Load (lb)	B/IR Load (lb)	B/OR Load (lb)
1	141.362	141.563	121.324	121.998
2	140.441	140.628	120.244	120.918
3	139.862	140.043	119.567	120.240
4	139.666	139.843	119.335	120.010
5	139.763	140.044	119.568	120.241
6	140.441	140.628	120.244	120.919
7	141.361	141.561	121.325	121.997
8	142.566	142.782	122.737	123.408
9	143.973	144.205	124.389	125.058
10	145.489	145.739	126.170	126.839
11	147.009	147.275	127.960	128.626
12	148.432	148.715	129.635	130.300
13	149.657	149.952	131.077	131.143
14	150.600	150.905	132.190	132.854
15	151.193	151.504	132.890	133.554
16	151.396	151.709	133.130	133.794
17	151.193	151.504	132.890	133.554
18	150.600	150.905	132.190	132.853
19	149.657	149.952	131.078	131.744
20	148.432	148.715	129.634	130.300
21	147.010	147.276	127.959	128.626
22	145.489	145.738	126.169	126.838
23	143.973	144.205	124.388	125.059
24	142.566	142.782	122.737	123.407

Operating Conditions

B/IR Stiffness	3.6×10^7	No. IR Waves	3
B/OR Stiffness	3.7×10^7	Phase Shift	0
OR Waviness	1.0×10^{-5}	Minimum Ball Dia	0.75
IR Waviness	1.0×10^{-5}	Maximum Ball Dia	0.75
No. OR Waves	4	OR Speed	0
		IR Speed	1200

4.0 Conclusions

A summary of the simulation results is presented in Tables 8-19. The time histories of each of the cases simulated is included in the Appendix. Both Design A and Design B were simulated. For each design, the upper and lower bounds of the coulomb friction parameter were simulated. The coulomb friction parameters are under the Menu Item (of Baberdyn) "Friction and Lubricant Inputs" as C/L Coulomb Friction (cage to land) and C/B Coulomb Friction (cage to ball). The generally agreed upon practical lower bound is 0.2 and the upper bound is taken as 0.5. A review of the results presented in Tables 8-19 should be used to judge the qualitative behavior of the designs under consideration. The criteria used here for judging a "good" design is one which results in low (on the order of tenths of in-lbs) running torques. From the results presented in Tables 8-19 it appears that in general (for either high or low coulomb friction) larger retainer to land clearances (R) and larger retainer to ball clearances (B) will not result in unstable motion of the ball and retainer system. However, it is also the case that stable motion can also be obtained with smaller B/R values for the given conditions of lower coulomb friction.

Appendix Time Histories of All Simulations

The time histories of all simulations (except where noted below) are included herein. The following abbreviations are used on the plot labels:

BF = body fixed (i.e. coordinates fixed to the cage)

(x & y components are plotted on the same graph)

P_{xx} = x component of radial motion in inertial coordinates

(x & y components are plotted on the same graph)

Note: In Tables 8–19 the cases marked with an asterisk were not included because these cases required excessively long completion times (on the order of 24 hours of continuous execution on a 33 MHz PC 486 computer). Cases which require excessive run times can be safely assumed to be indicative of an unstable system.

Table 8 Design A with Low Friction, Retainer Pocket Diameter

DESIGN A WITH LOW COULOMB FRICTION (0.2)

RETAINER POCKET DIA. [IN.]	RETAINER INSIDE DIA [IN]		
	6.81	**6.82**	**6.83**
0.76	0101	0201	0301
0.77	0102	0202	0302
0.78	0103	0203	0303

Nominal retainer inside diameter = 6.829 Nominal retainer pocket diameter = 0.775

Table 9 Design A with Low Friction, Retainer to Ball Clearance

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.01	**0.02**	**0.03**
0.01	0101	0201	0301
0.02	0102	0202	0302
0.03	0103	0203	0303

Nominal R - 0.029 Nominal B - 0.025

Table 10 RMS Torque for Design A, Retainer to Ball Clearance

RMS TORQUE FOR DESIGN A SERIES (IN-LB)

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.01	**0.02**	**0.03**
0.01	UNSTABLE*	UNSTABLE	UNSTABLE
0.02	0.08	0.08	0.08
0.03	0.08	0.08	0.08

TABLE 1. SUMMARY OF GDEB BEARING DESIGN A RESULTS (LOW COULOMB FRICTION)

*See Note in Section 5

Table 11 Design A with High Friction, Retainer Pocket Diameter

DESIGN A WITH HIGH COULOMB FRICTION (.5)

RETAINER POCKET DIA. [IN.]	RETAINER INSIDE DIA [IN]		
	6.81	**6.82**	**6.83**
0.76	0101	0201	0301
0.77	0102	0202	0302
0.78	0103	0203	0303

Nominal retainer inside diameter = 6.829 Nominal retainer pocket diameter = 0.775

Table 12 Design A with High Friction, Retainer to Ball Clearance

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.01	**0.02**	**0.03**
0.01	0101	0201	0301
0.02	0102	0202	0302
0.03	0103	0203	0303

Nominal R - 0.029 Nominal B - 0.025

Table 13 RMS Torque for Design A, Retainer to Ball Clearance

RMS TORQUE FOR DESIGN A SERIES (IN-LB)

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.01	**0.02**	**0.03**
0.01	UNSTABLE	UNSTABLE	UNSTABLE
0.02	0.11	UNSTABLE	UNSTABLE
0.03	0.1	0.09	0.09

Table 14 Design B with Low Friction, Retainer Pocket Diameter

DESIGN B WITH LOW COULOMB FRICTION (.2)

RETAINER POCKET DIA. [IN.]	RETAINER INSIDE DIA [IN]		
	6.175	6.225	6.275
.76	0101	0201	0301
.78	0102	0202	0302
.80	0103	0203	0303

Nominal retainer inside diameter = 6.2552 Nominal retainer pocket diameter = 0.810

Table 15 Design B with Low Friction, Retainer to Ball Clearance

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.023	0.073	0.123
0.01	0101	0201	0301
0.03	0102	0202	0302
0.05	0103	0203	0303

Nominal R - 0.103 Nominal B - 0.06

Table 16 RMS Torque for Design B, Retainer to Ball Clearance

RMS TORQUE FOR DESIGN B SERIES LOW COULOMB FRICTION (IN-LB)

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]					
	0.023		0.073		0.123	
	AVG.	RMS	AVG.	RMS	AVG.	RMS
0.01	0.17	0.09	0.17	0.09	0.17	0.09
0.03	0.18	0.2	0.18	0.21	0.18	0.21
0.05	0.22	0.24	0.22	0.24	0.22	0.24

Table 17 Design B with High Friction, Retainer Pocket Diameter

DESIGN B WITH HIGH COULOMB FRICTION (.5)

RETAINER POCKET DIA. [IN.]	RETAINER INSIDE DIA [IN]		
	6.175	**6.225**	**6.275**
.76	0101	0201	0301
.78	0102	0202	0302
.80	0103	0203	0303

Nominal retainer inside diameter = 6.2552 Nominal retainer pocket diameter = 0.810

Table 18 Design B with High Friction, Retainer to Ball Clearance

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]		
	0.023	**0.073**	**0.123**
0.01	0101	0201	0301
0.03	0102	0202	0302
0.05	0103	0203	0303

Nominal R - 0.103 Nominal B - 0.06

Table 19 RMS Torque for Design B, Retainer to Ball Clearance

RMS TORQUE FOR DESIGN B SERIES HIGH COULOMB FRICTION (IN-LB)

B - RETAINER TO BALL CLEARANCE [IN.]	R - RETAINER TO LAND CLEARANCE [IN.]					
	0.023		**0.073**		**0.123**	
	AVG.	RMS	AVG.	RMS	AVG.	RMS
0.01		*		*		*
0.03		UNSTABLE		*		*
0.05	0.5	0.5		UNSTABLE		UNSTABLE

*See note in Section 5

DESIGN "A" LOW COULOMB FRICTION SIMULATION PLOTS

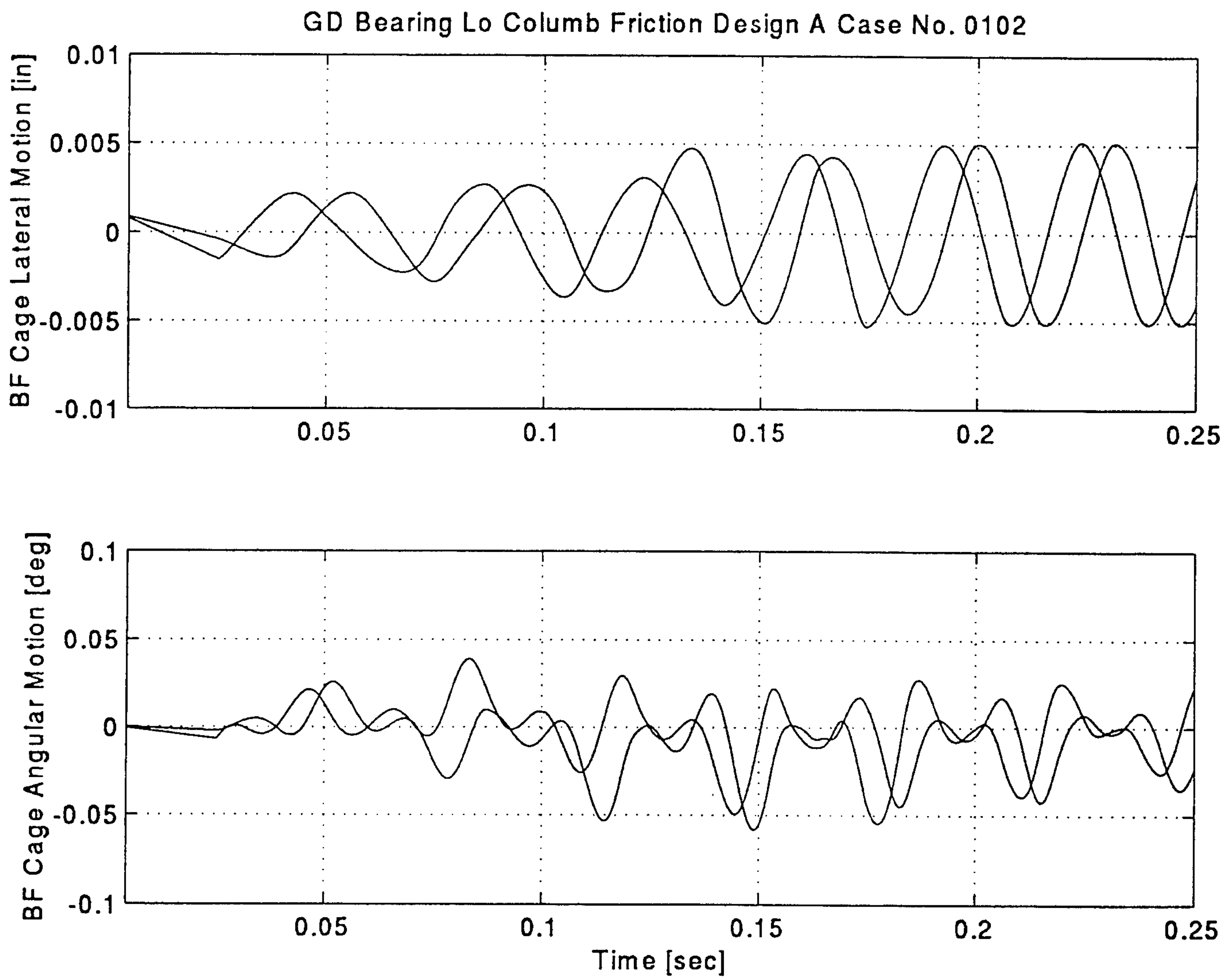

Fig 3 Design "A" Low Friction Plots, Case 0102, Motions

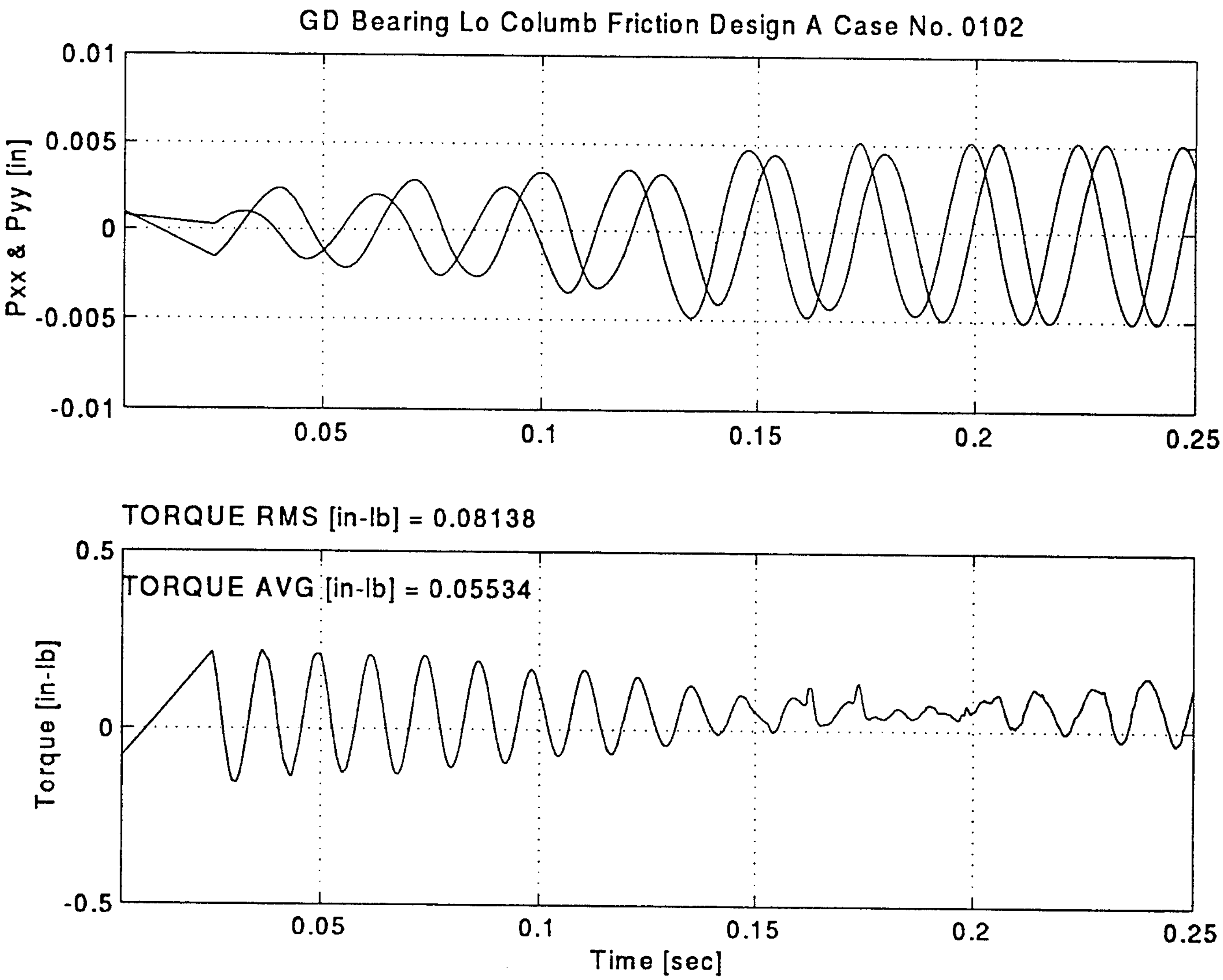

Fig 4 Design "A" Low Friction Plots, Case 0102, Torque

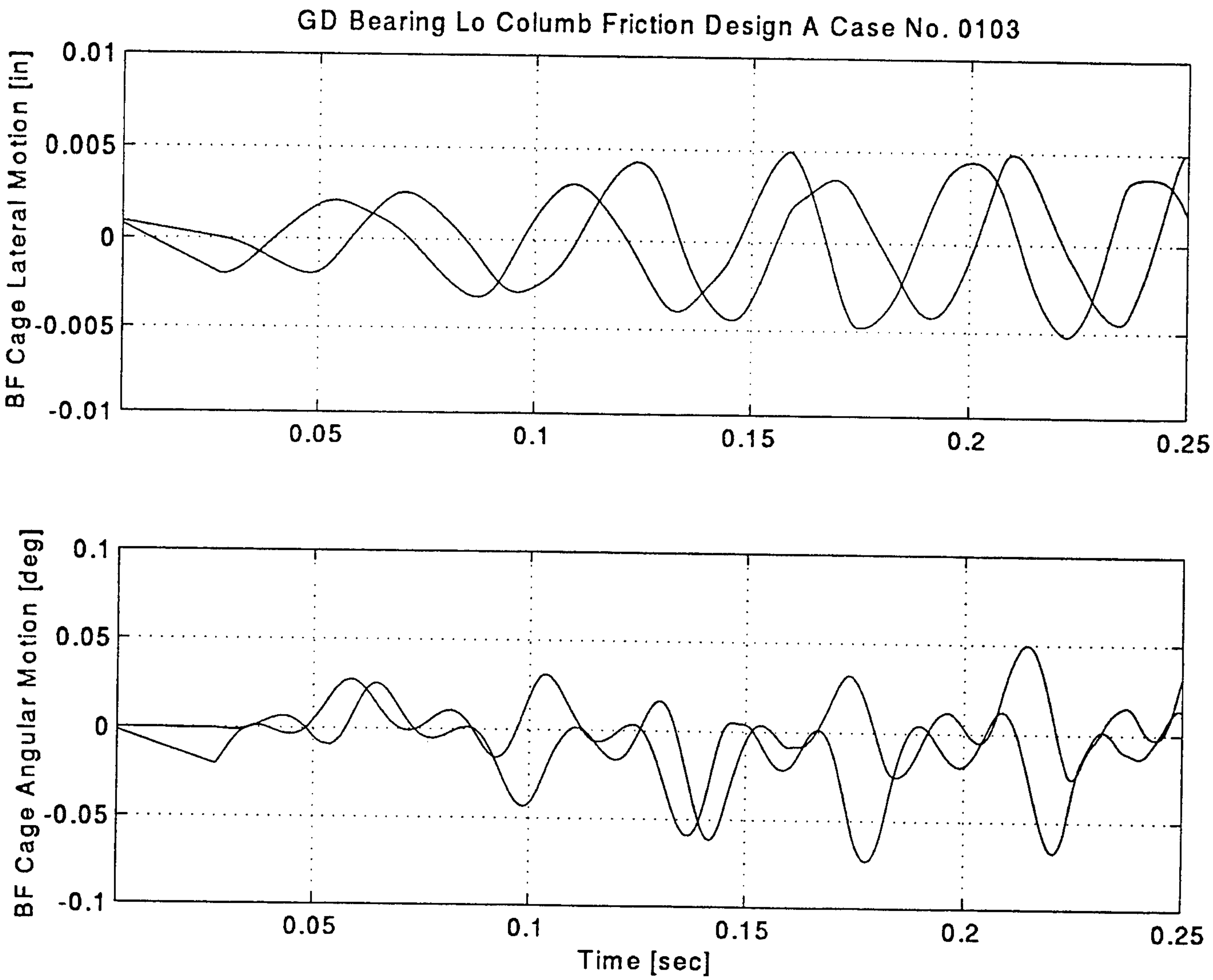

Fig 5 Design "A" Low Friction Plots, Case 0103, Motions

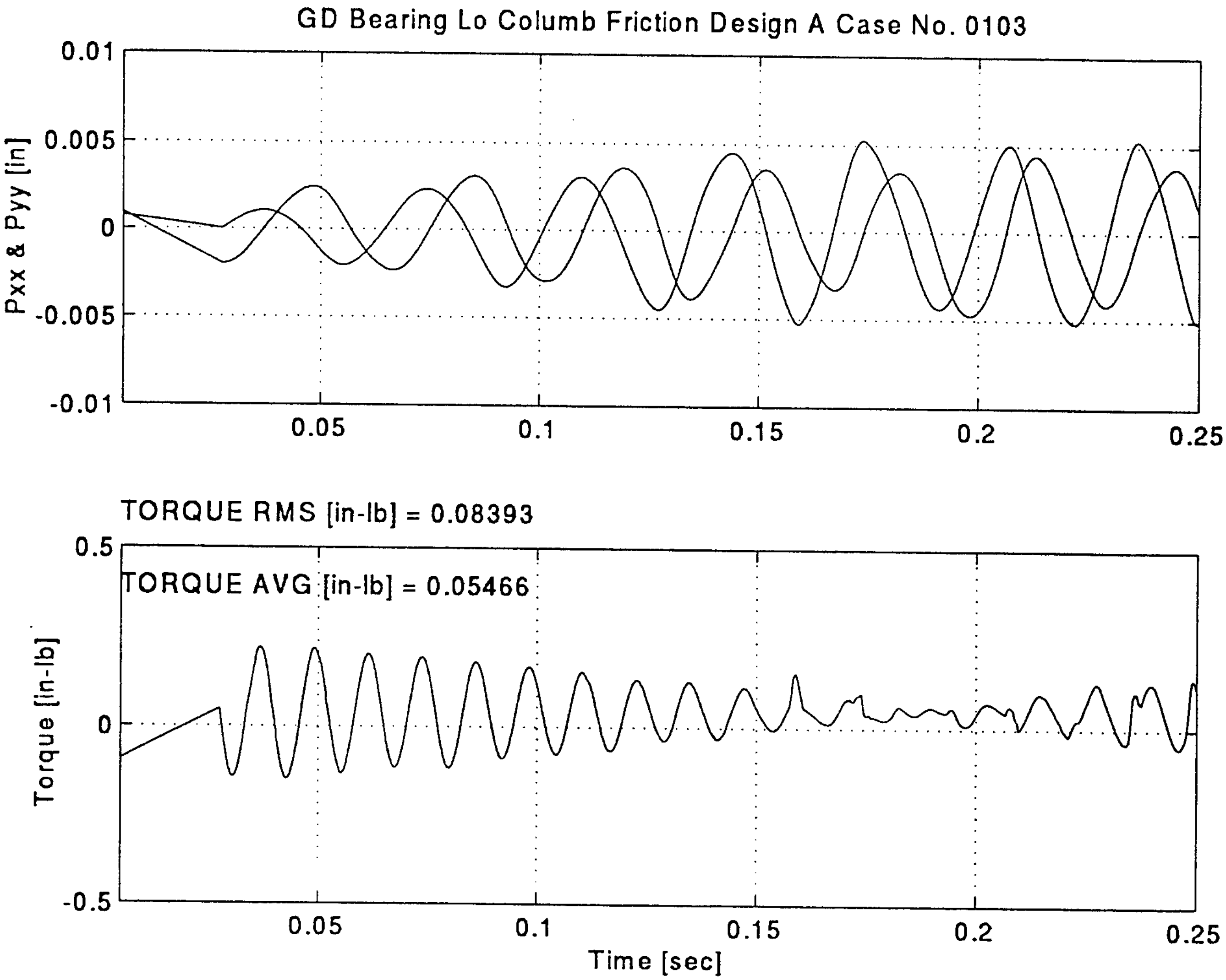

Fig 6 Design "A" Low Friction Plots, Case 0103, Torque

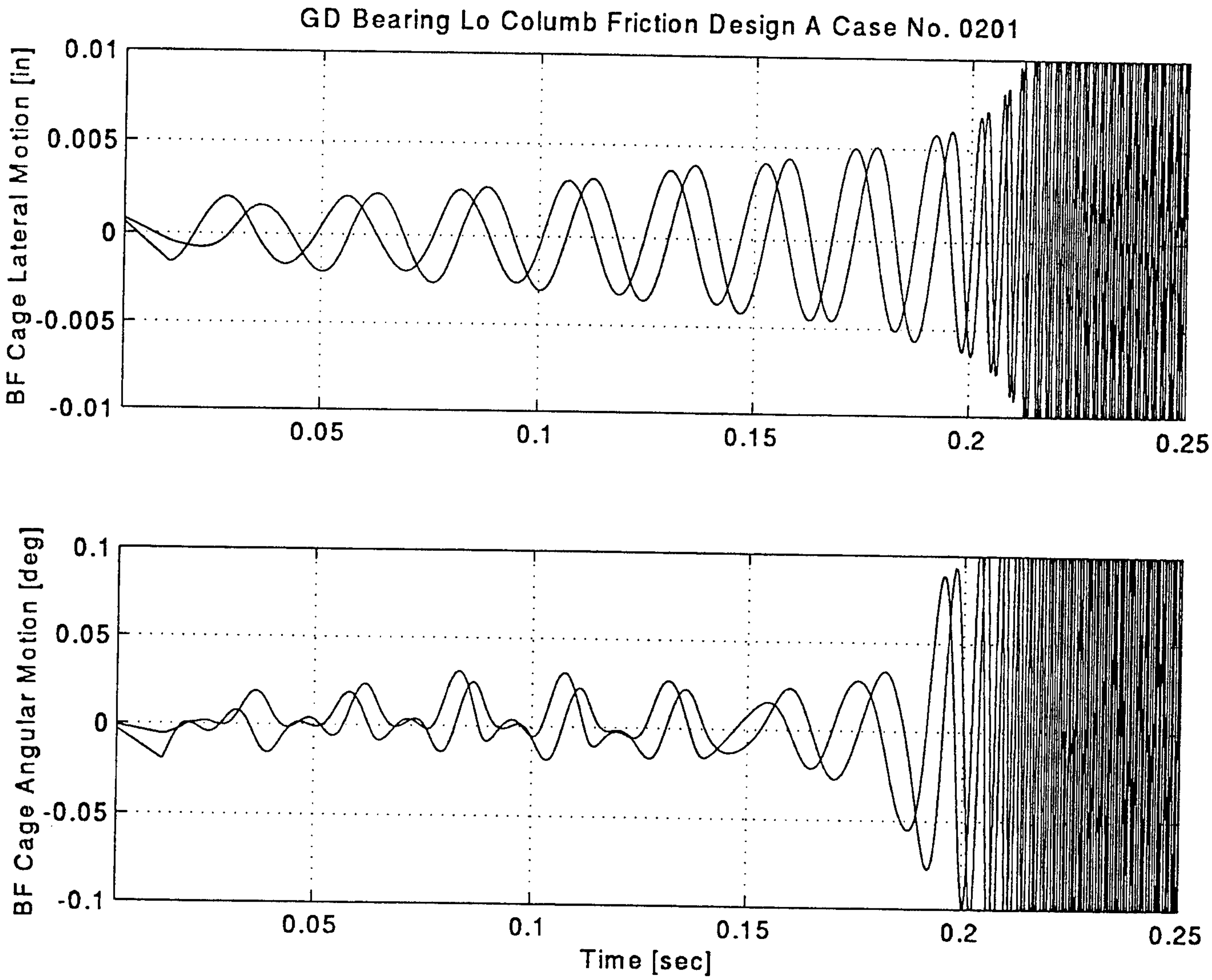

Fig 7 Design "A" Low Friction Plots, Case 0201, Motions

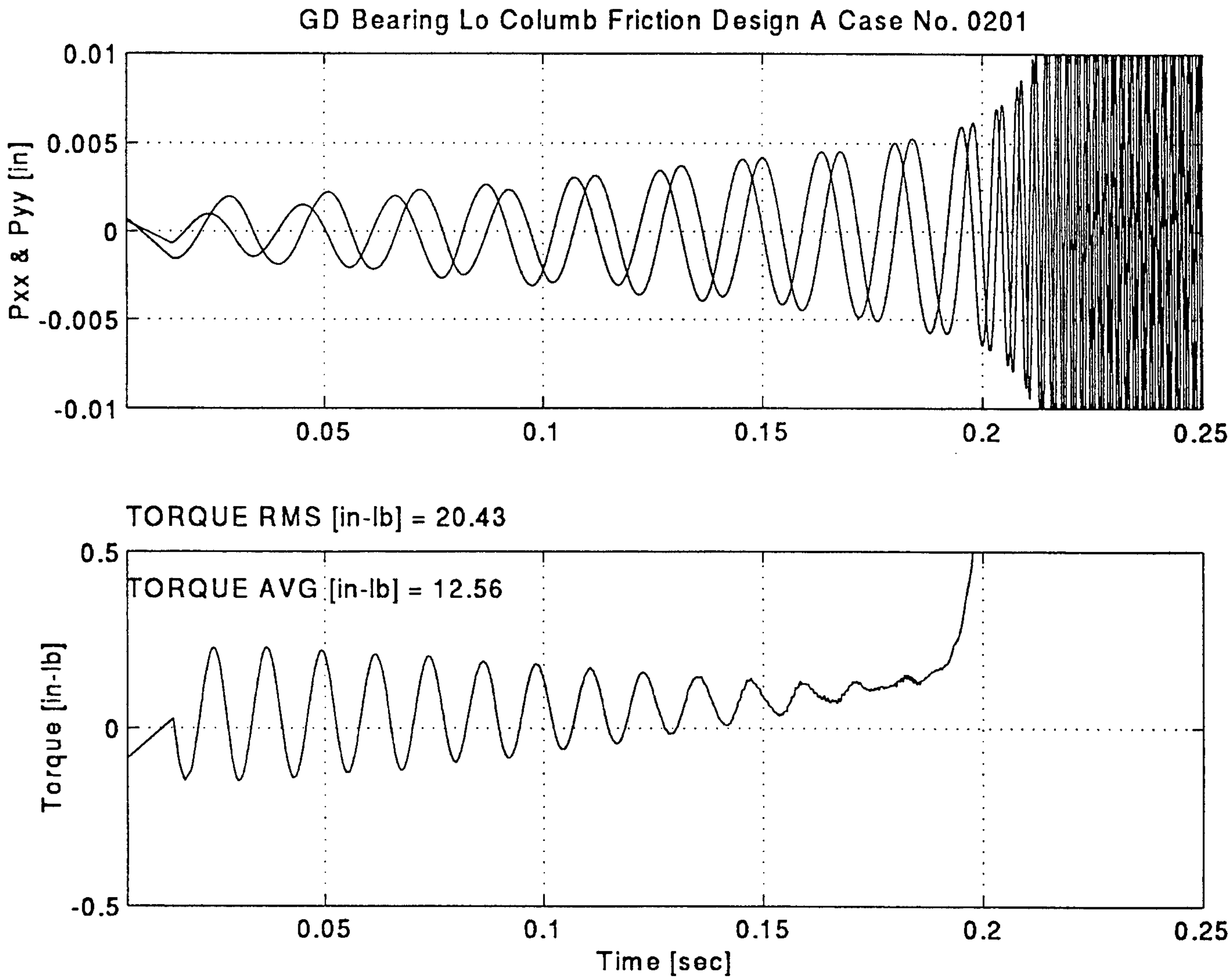

Fig 8 Design "A" Low Friction Plots, Case 0201, Torque

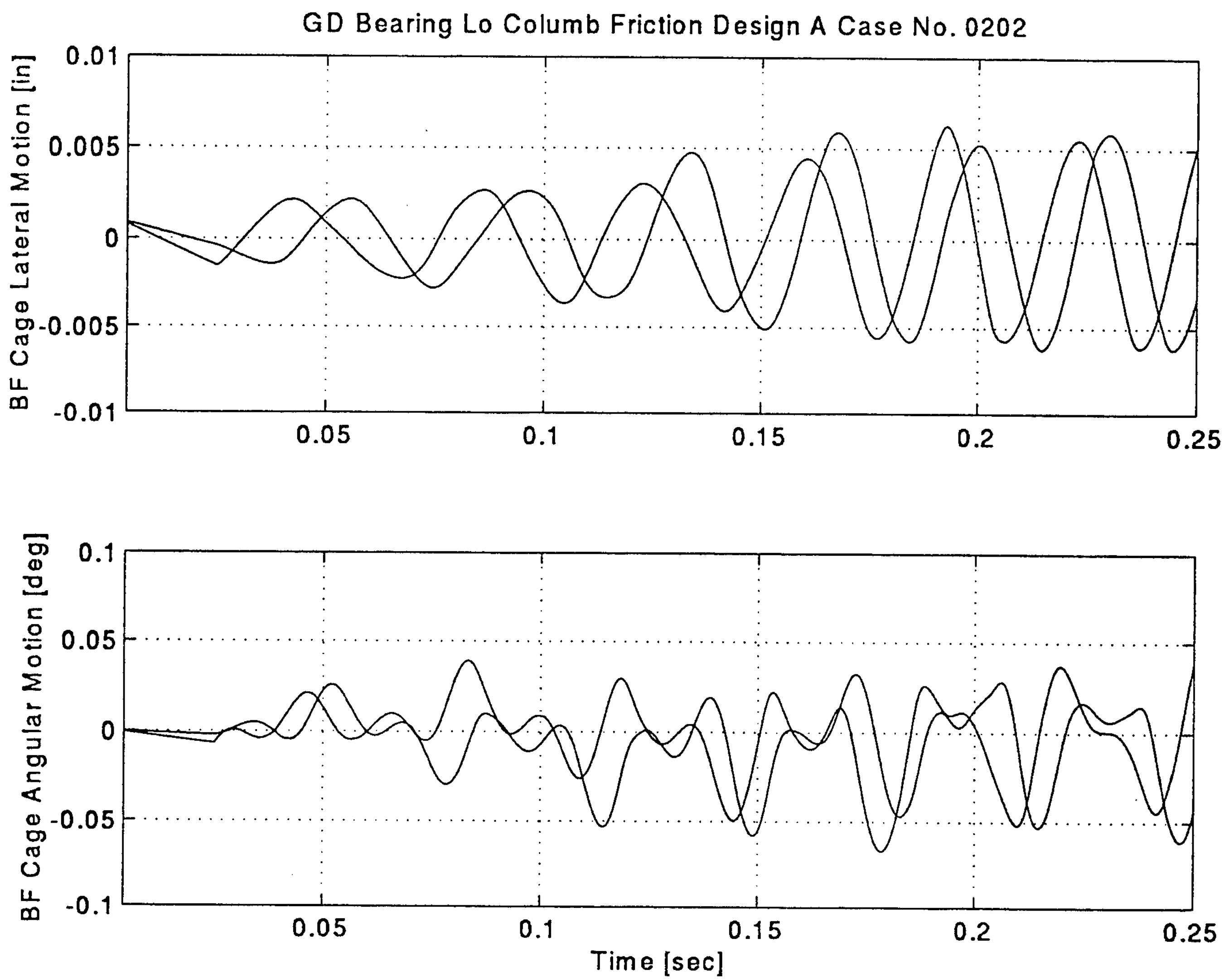

Fig 9 Design "A" Low Friction Plots, Case 0202, Motions

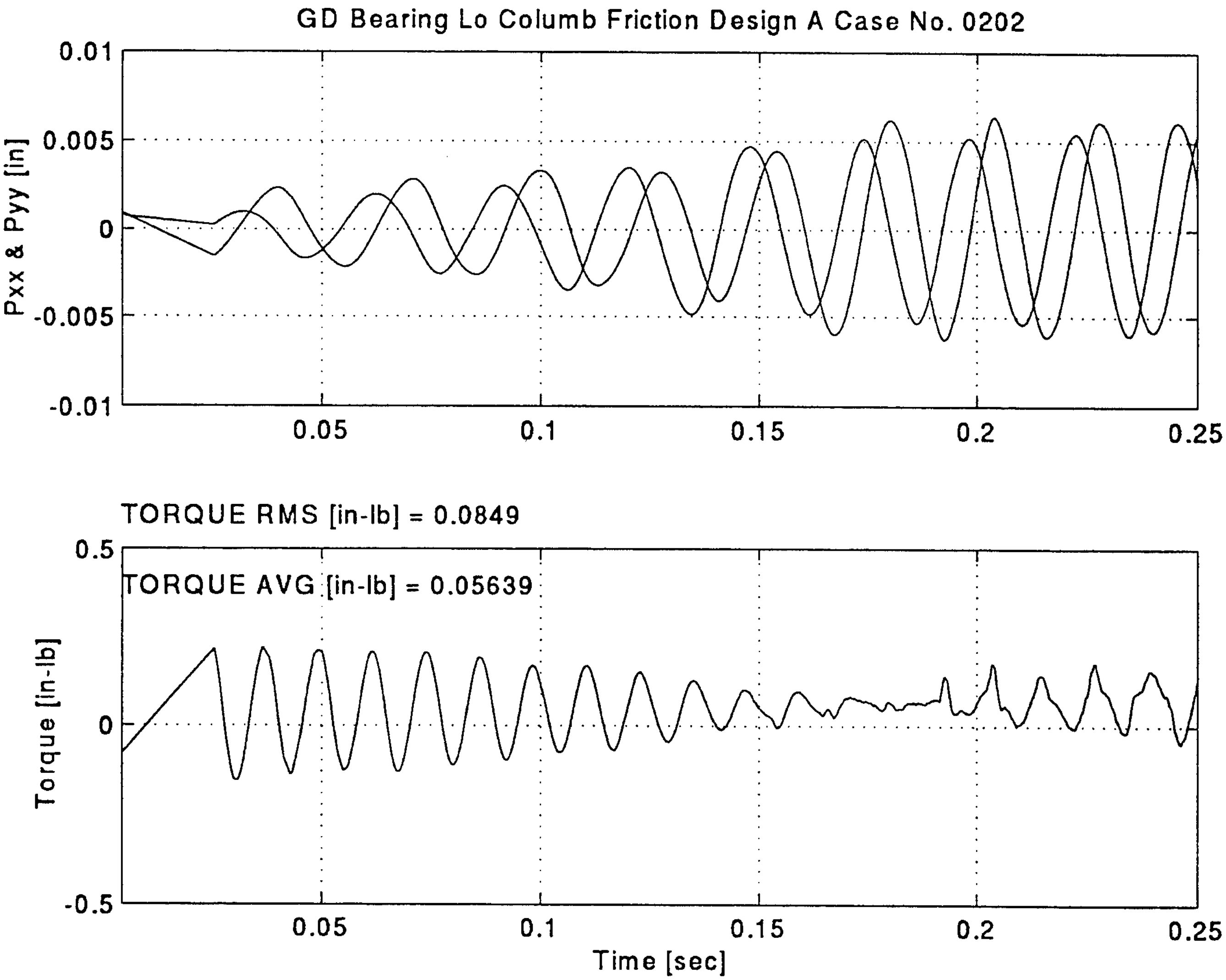

Fig 10 Design "A" Low Friction Plots, Case 0202, Torque

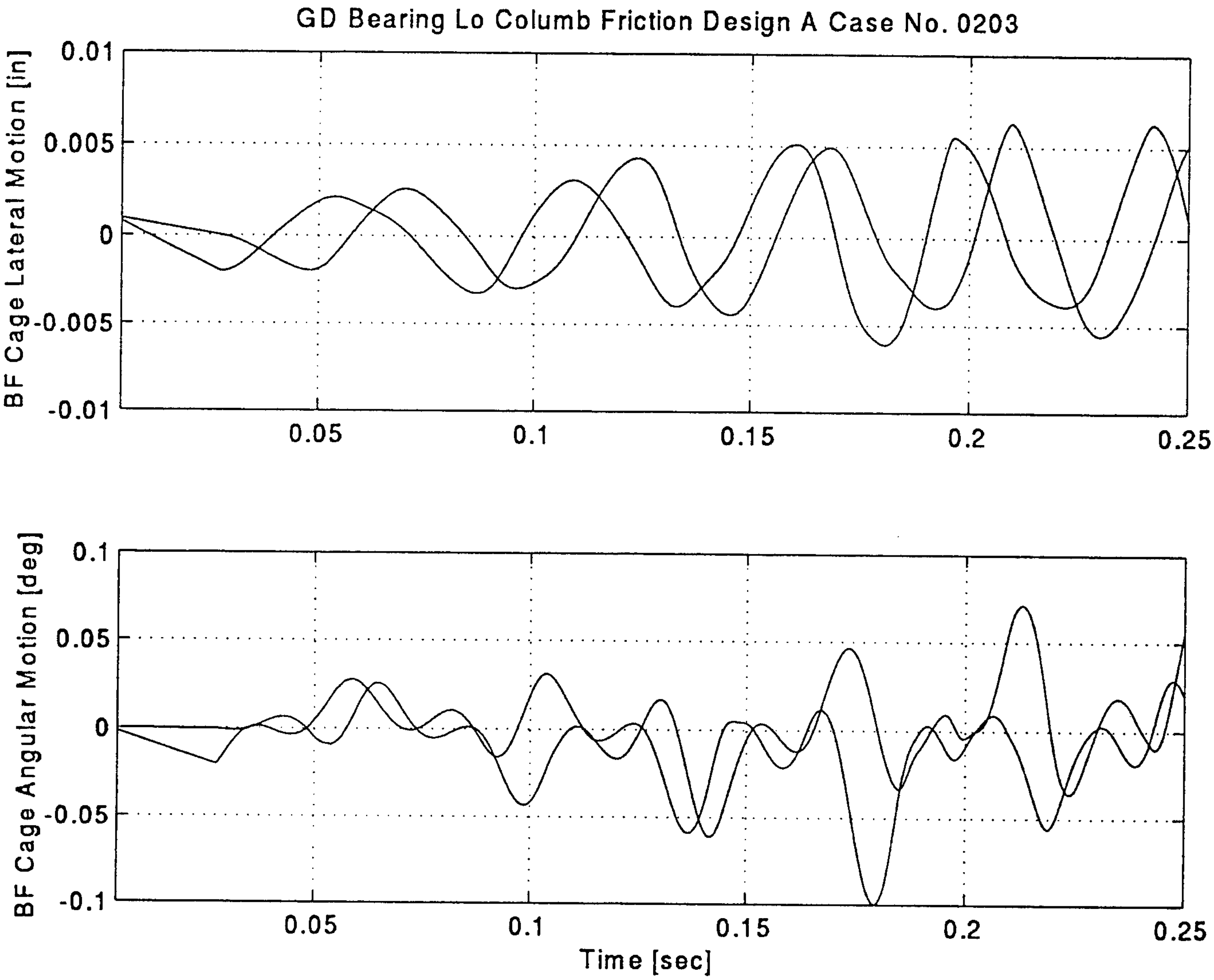

Fig 11 Design "A" Low Friction Plots, Case 0203, Motions

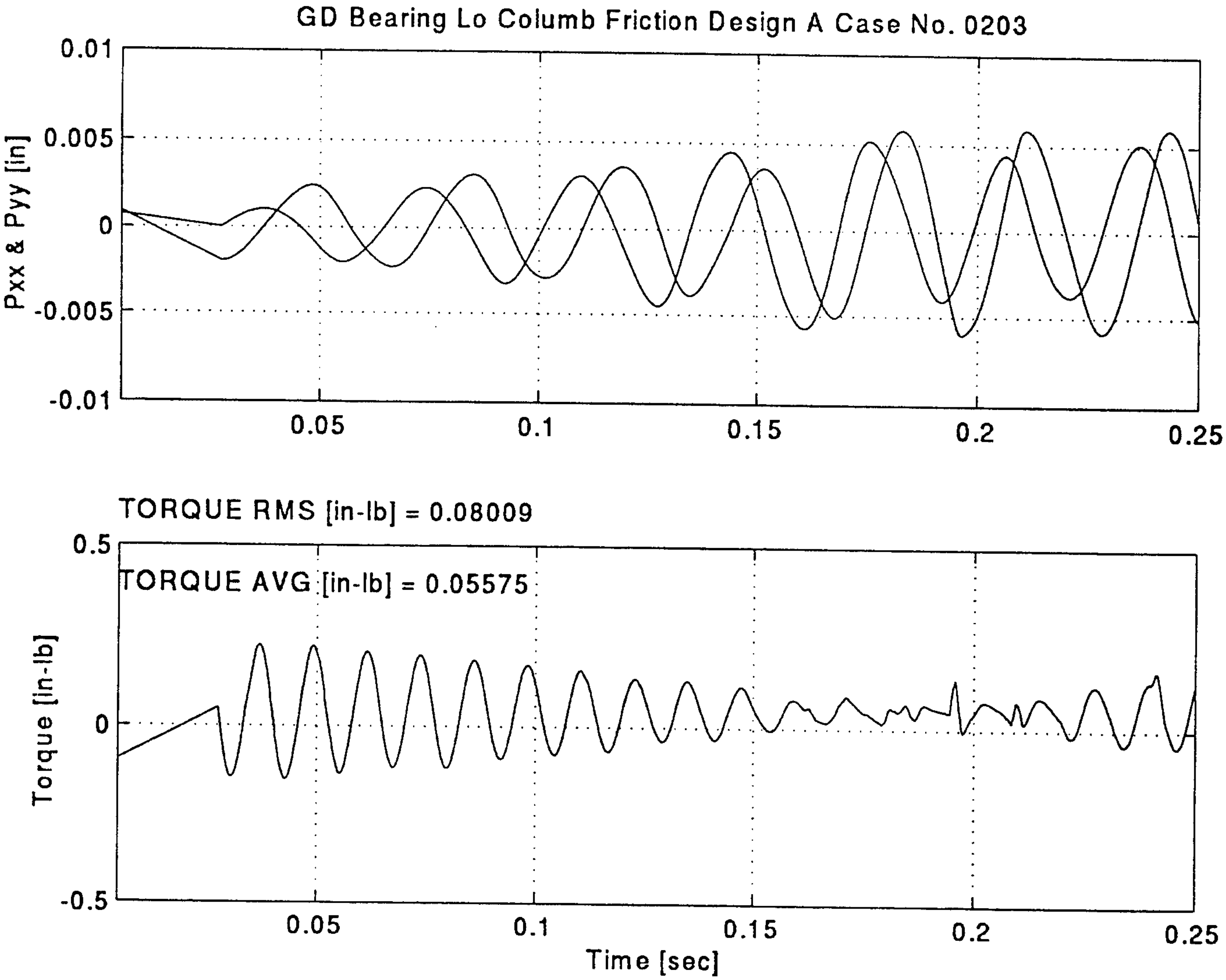

Fig 12 Design "A" Low Friction Plots, Case 0203, Torque

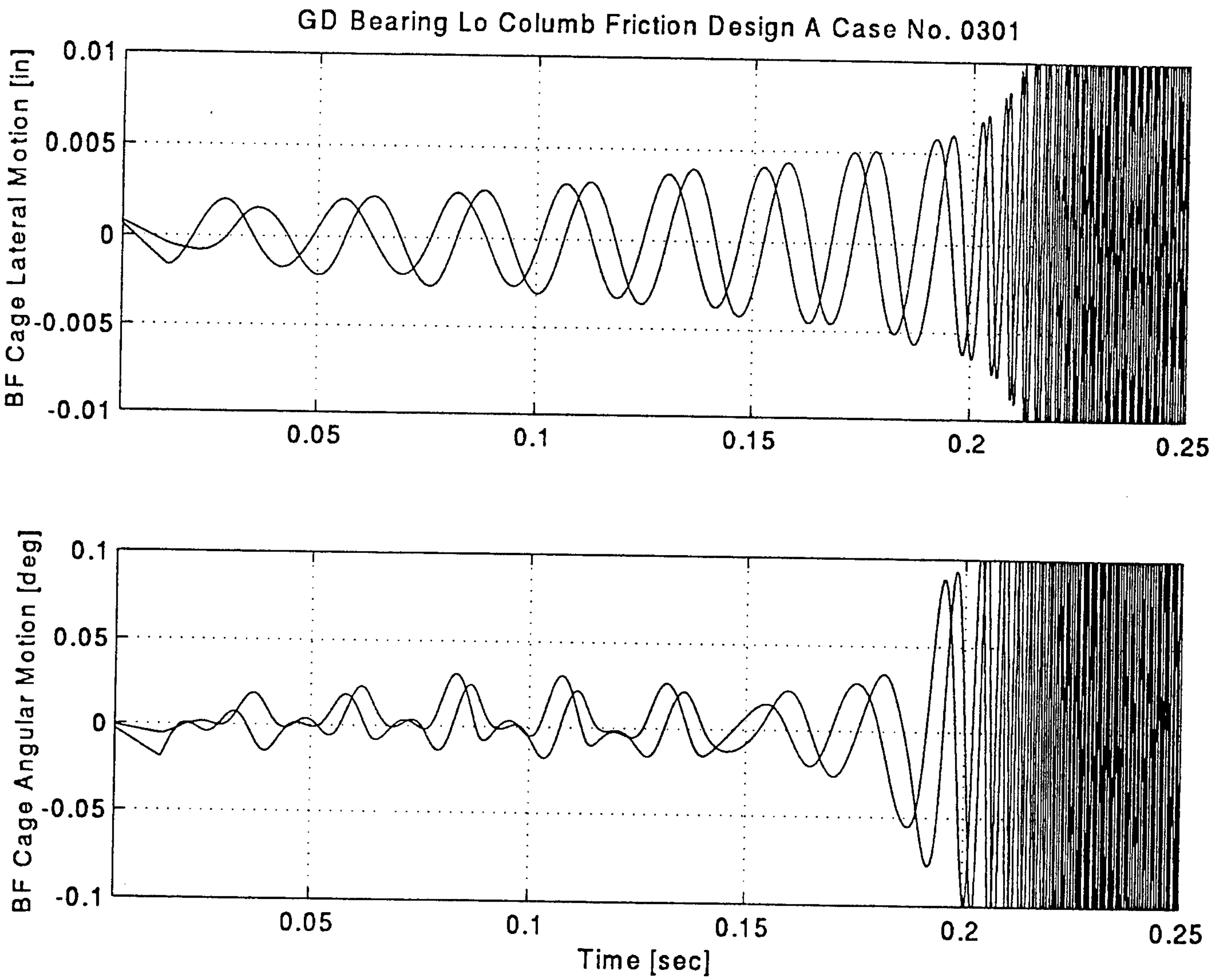

Fig 13 Design "A" Low Friction Plots, Case 0301, Motions

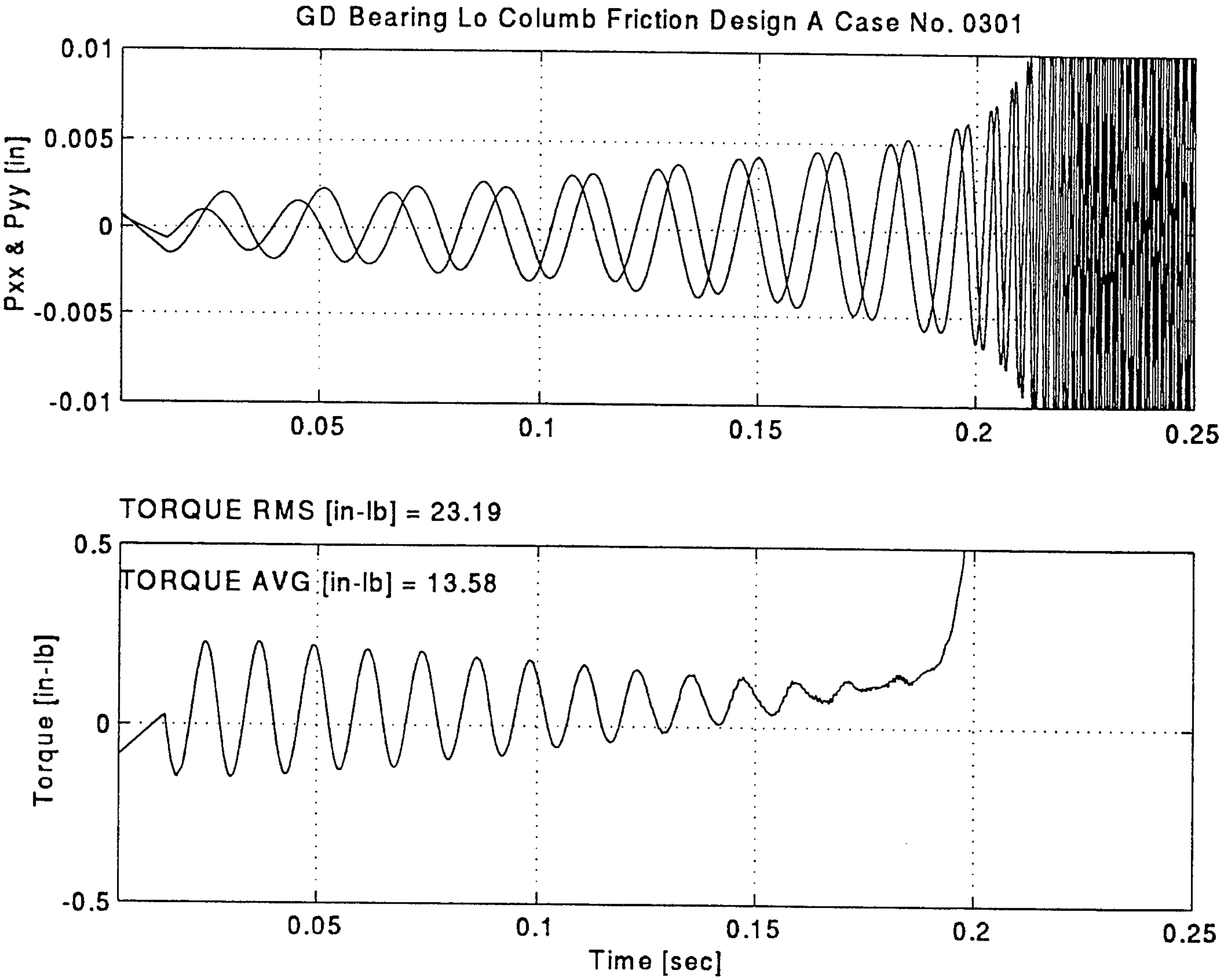

Fig 14 Design "A" Low Friction Plots, Case 0301, Torque

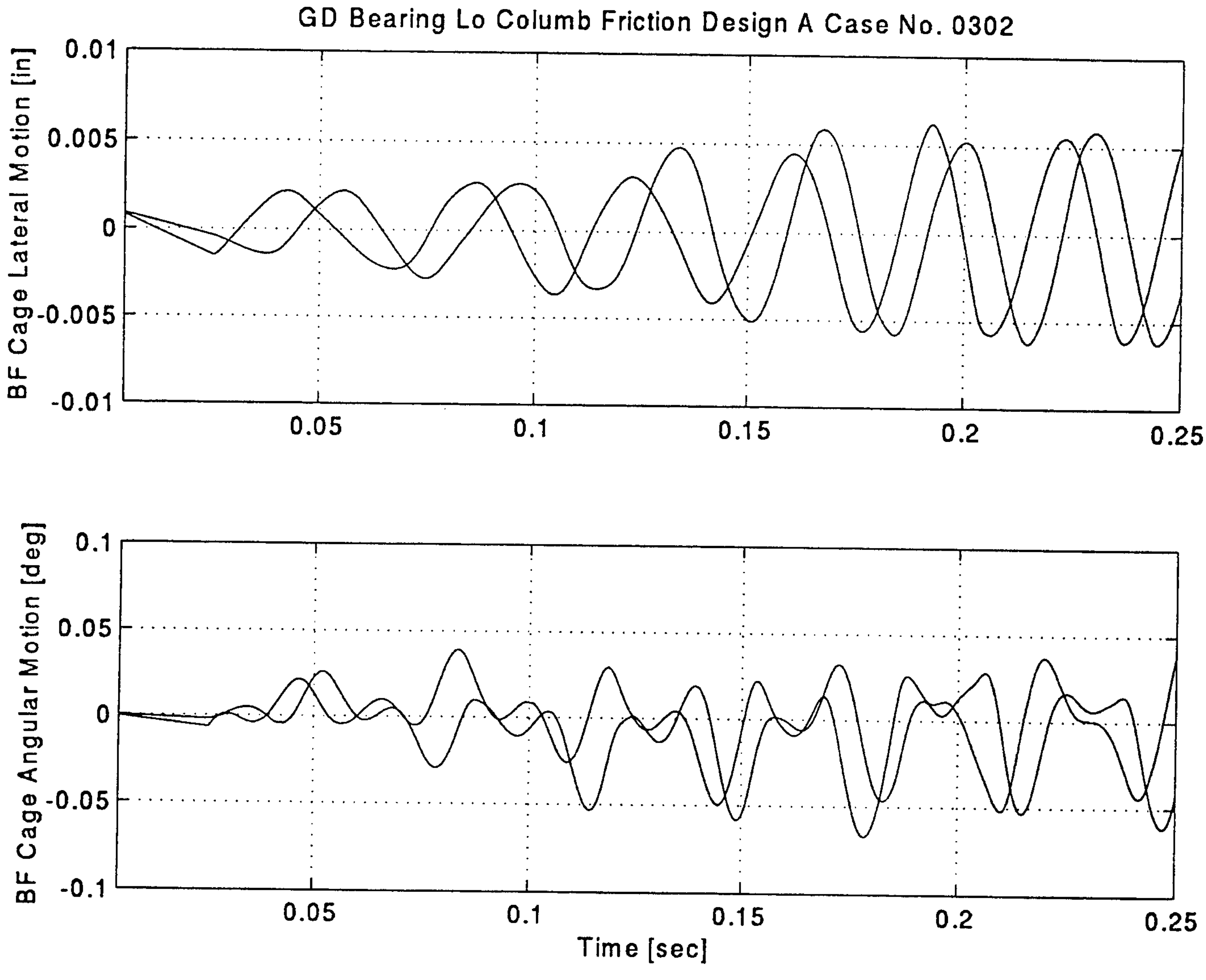

Fig 15 Design "A" Low Friction Plots, Case 0302, Motions

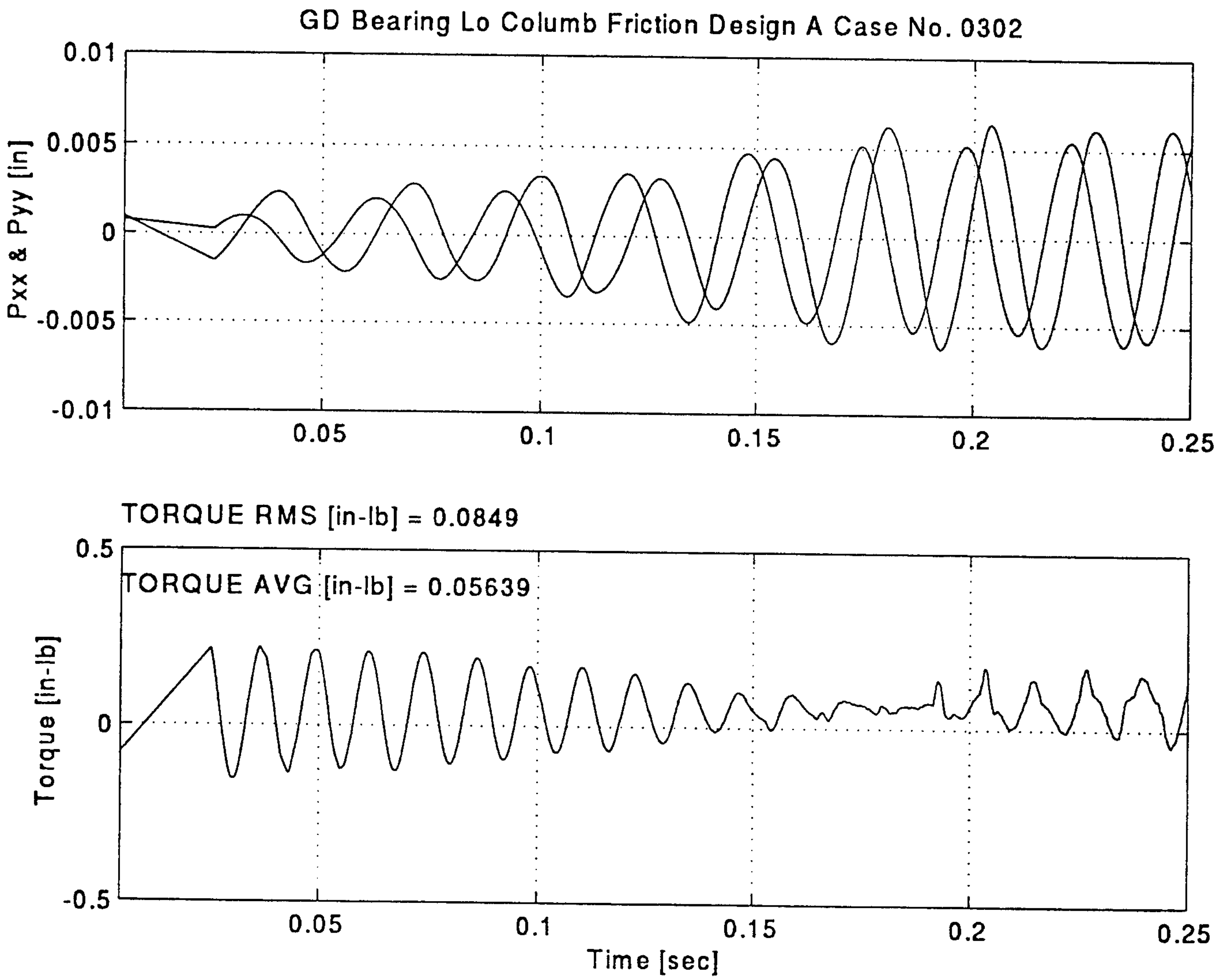

Fig 16 Design "A" Low Friction Plots, Case 0302, Torque

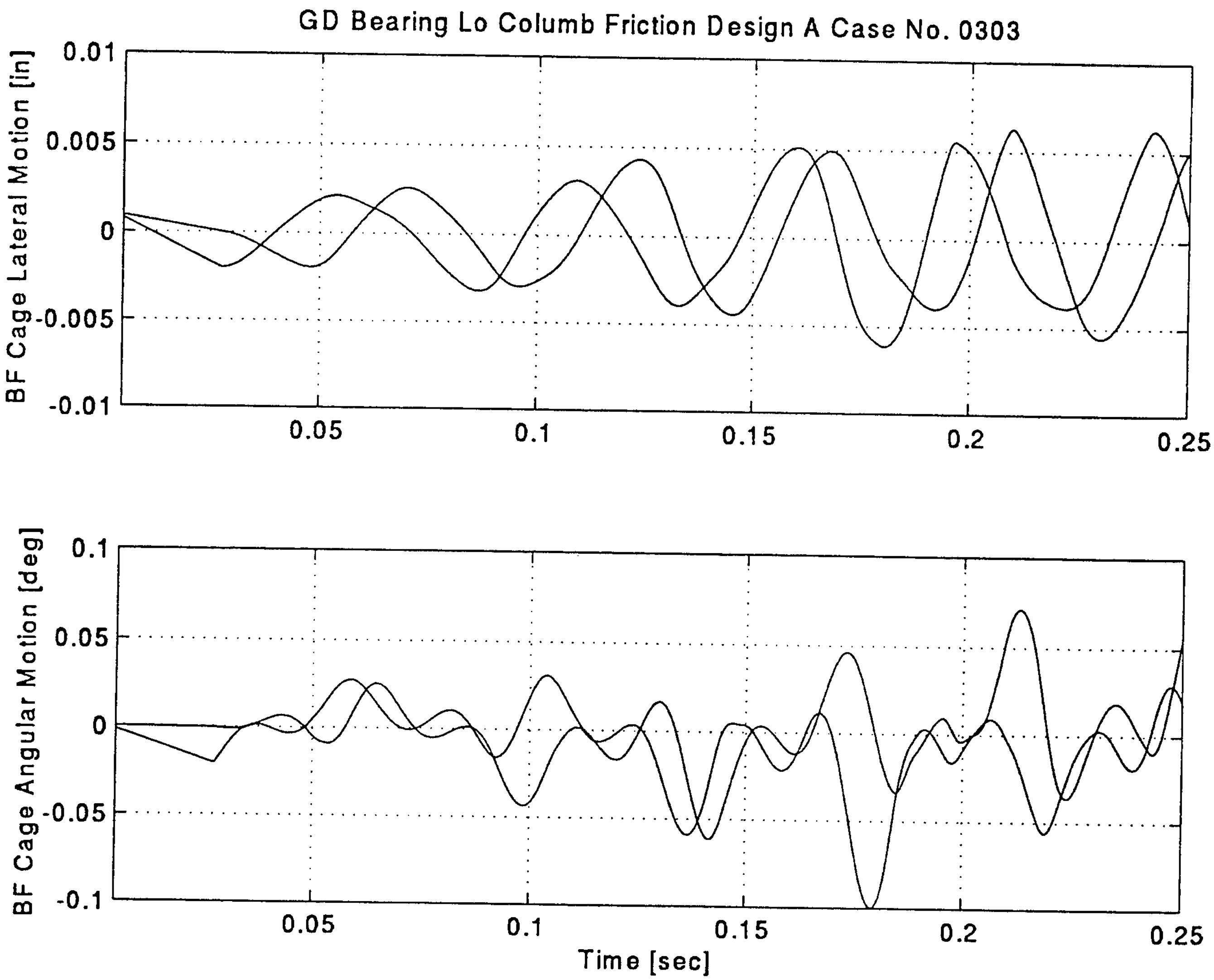

Fig 17 Design "A" Low Friction Plots, Case 0303, Motions

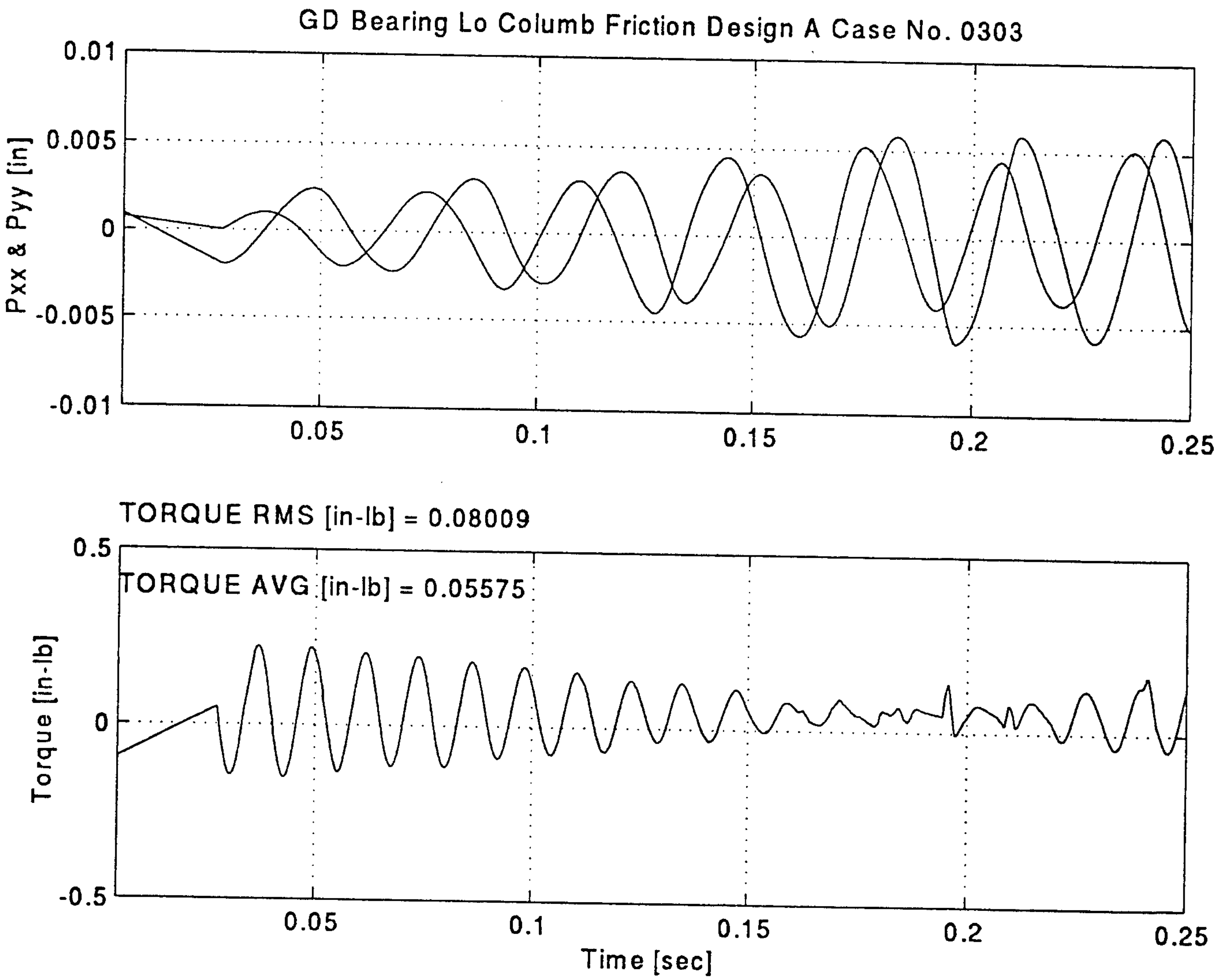

Fig 18 Design "A" Low Friction Plots, Case 0303, Torque

DESIGN "A" HIGH COULOMB FRICTION SIMULATION PLOTS

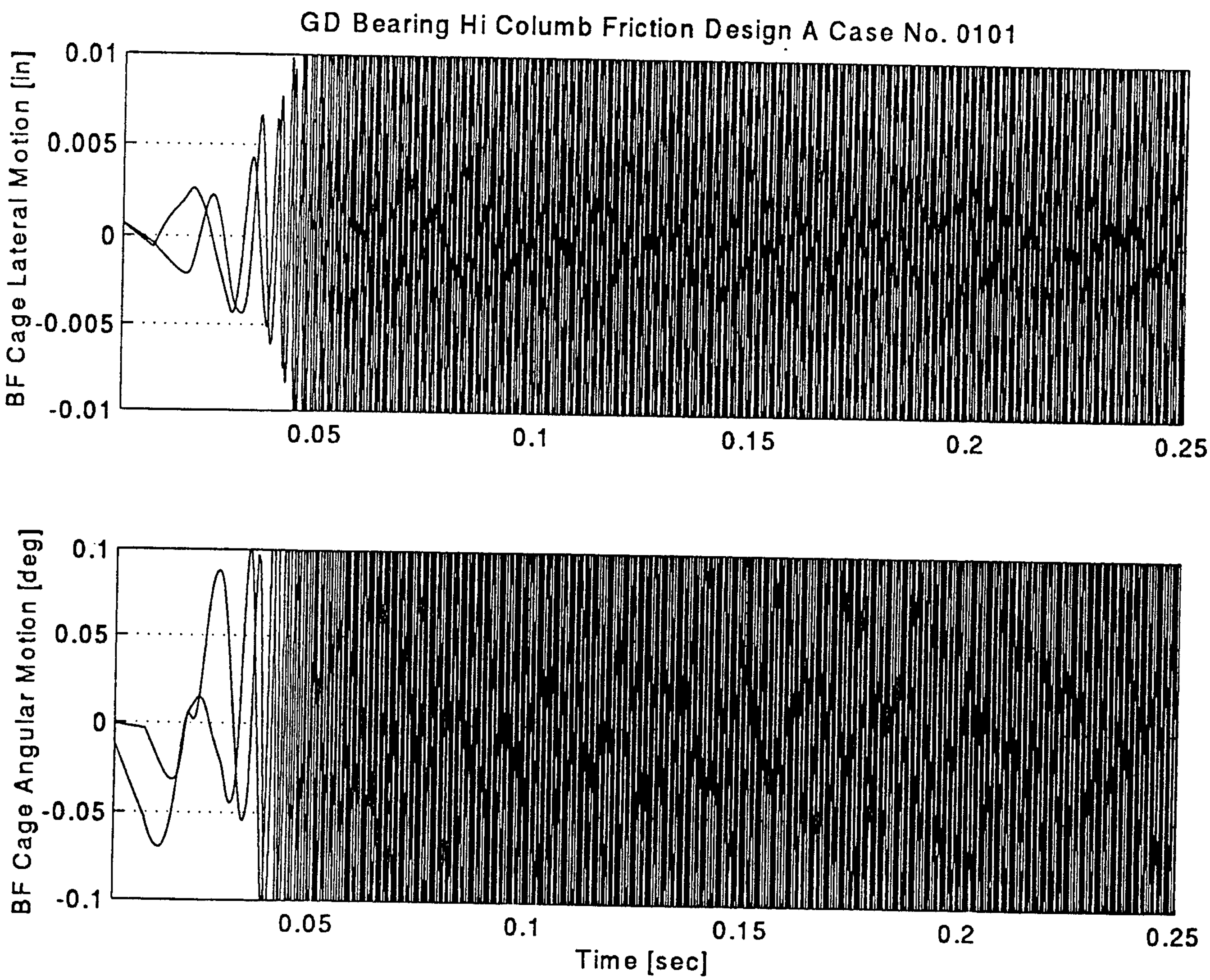

Fig 19 Design "A" High Friction Plots, Case 0101, Motions

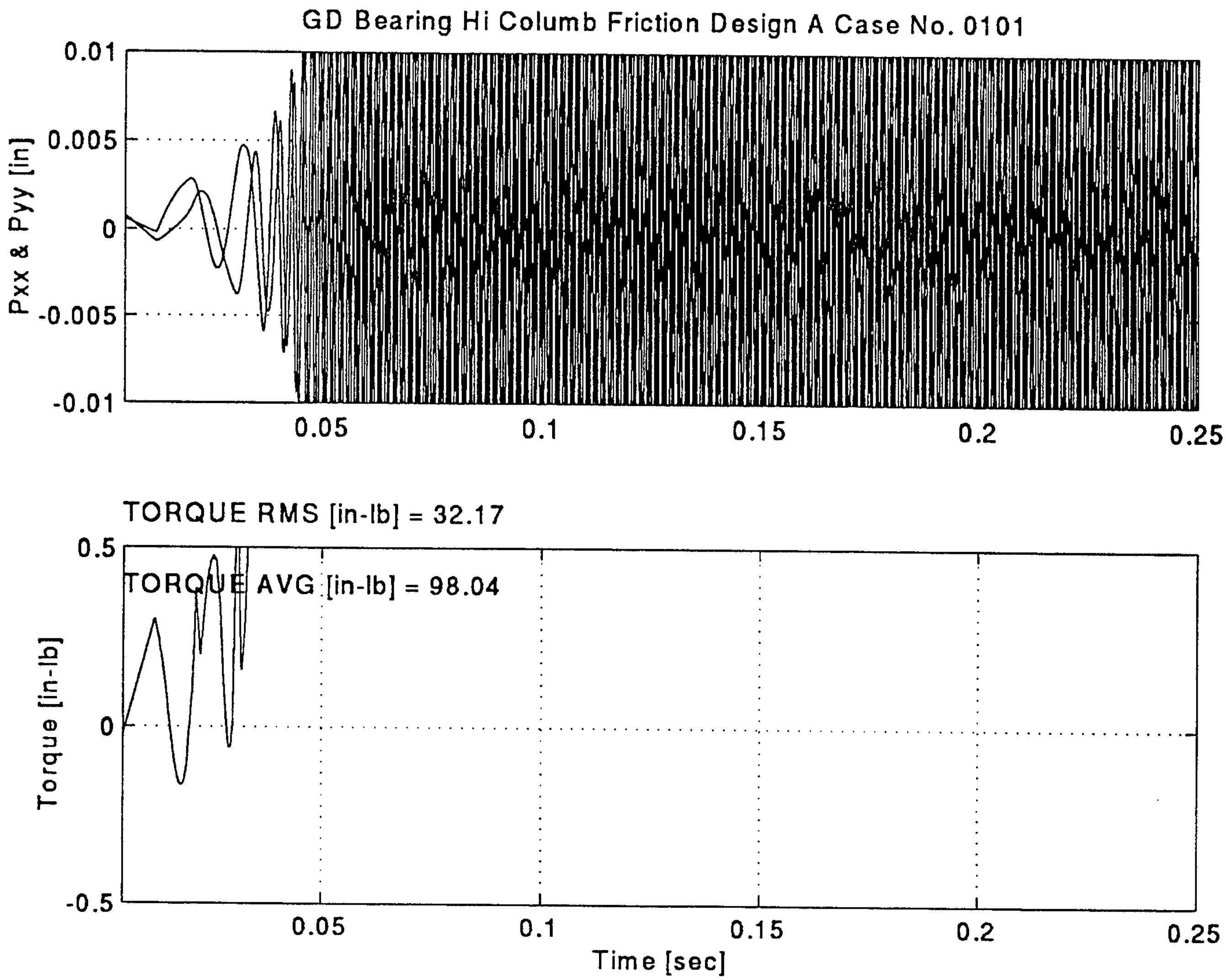

Fig 20 Design "A" High Friction Plots, Case 0101, Torque

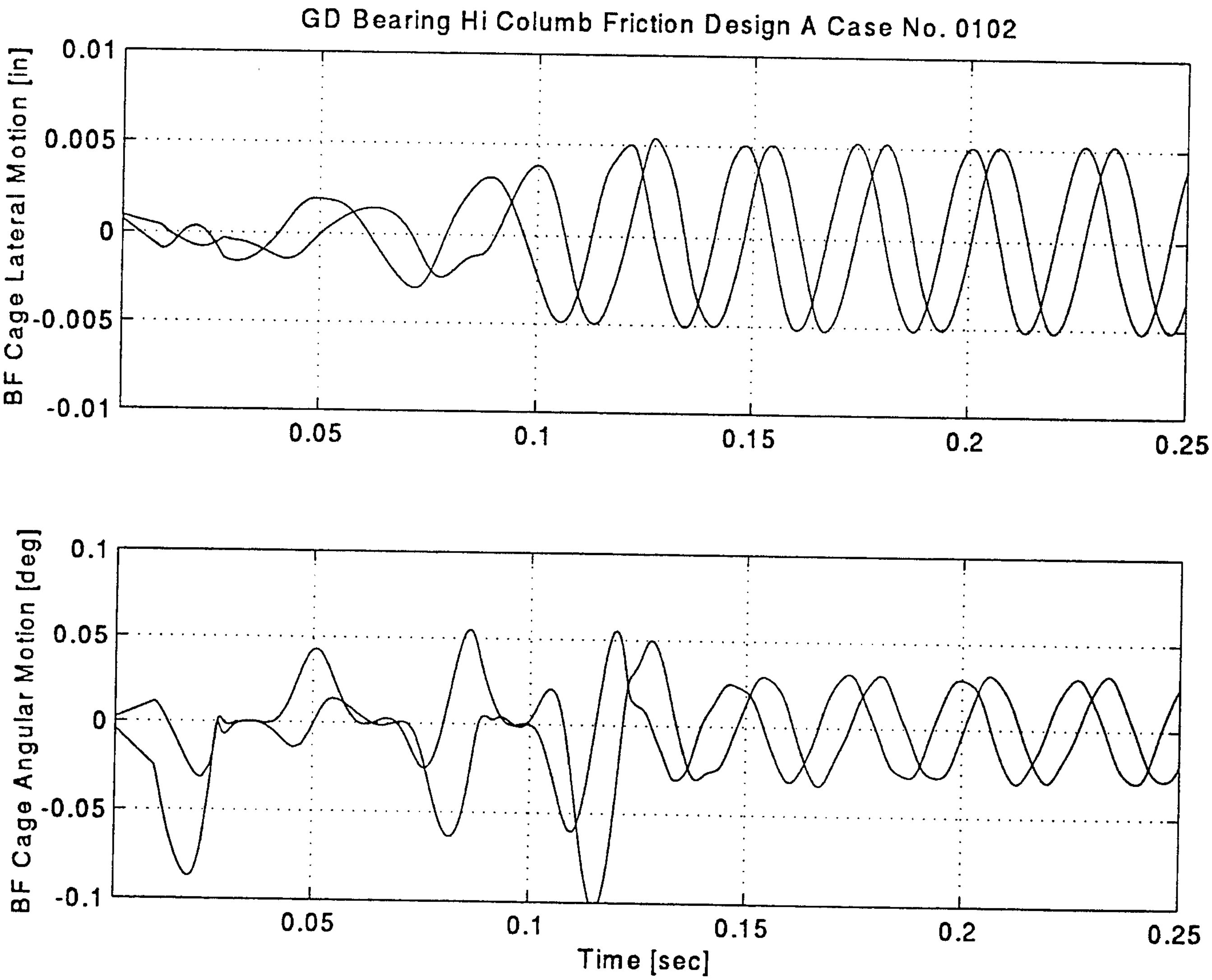

Fig 21 Design "A" High Friction Plots, Case 0102, Motions

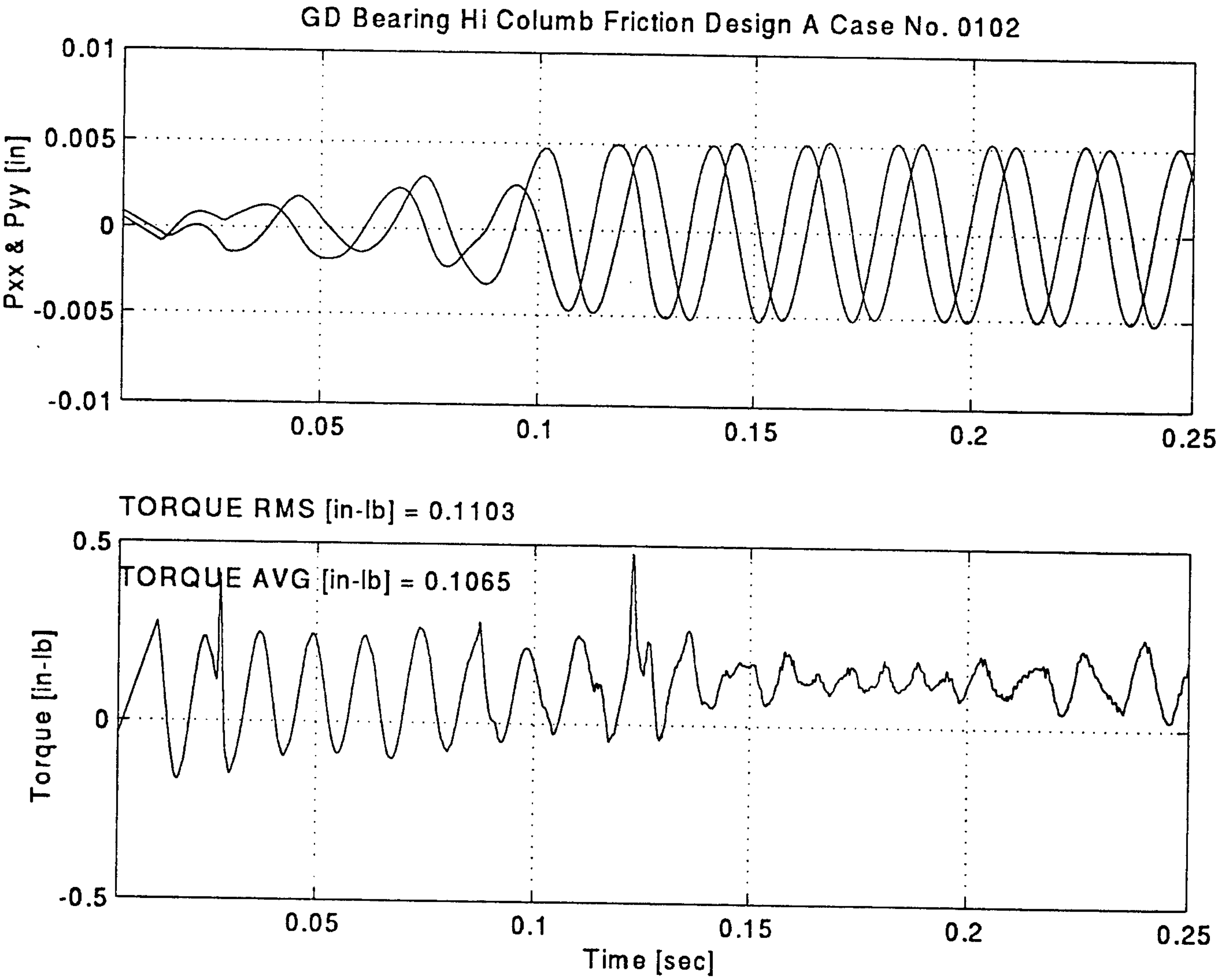

Fig 22 Design "A" High Friction Plots, Case 0102, Torque

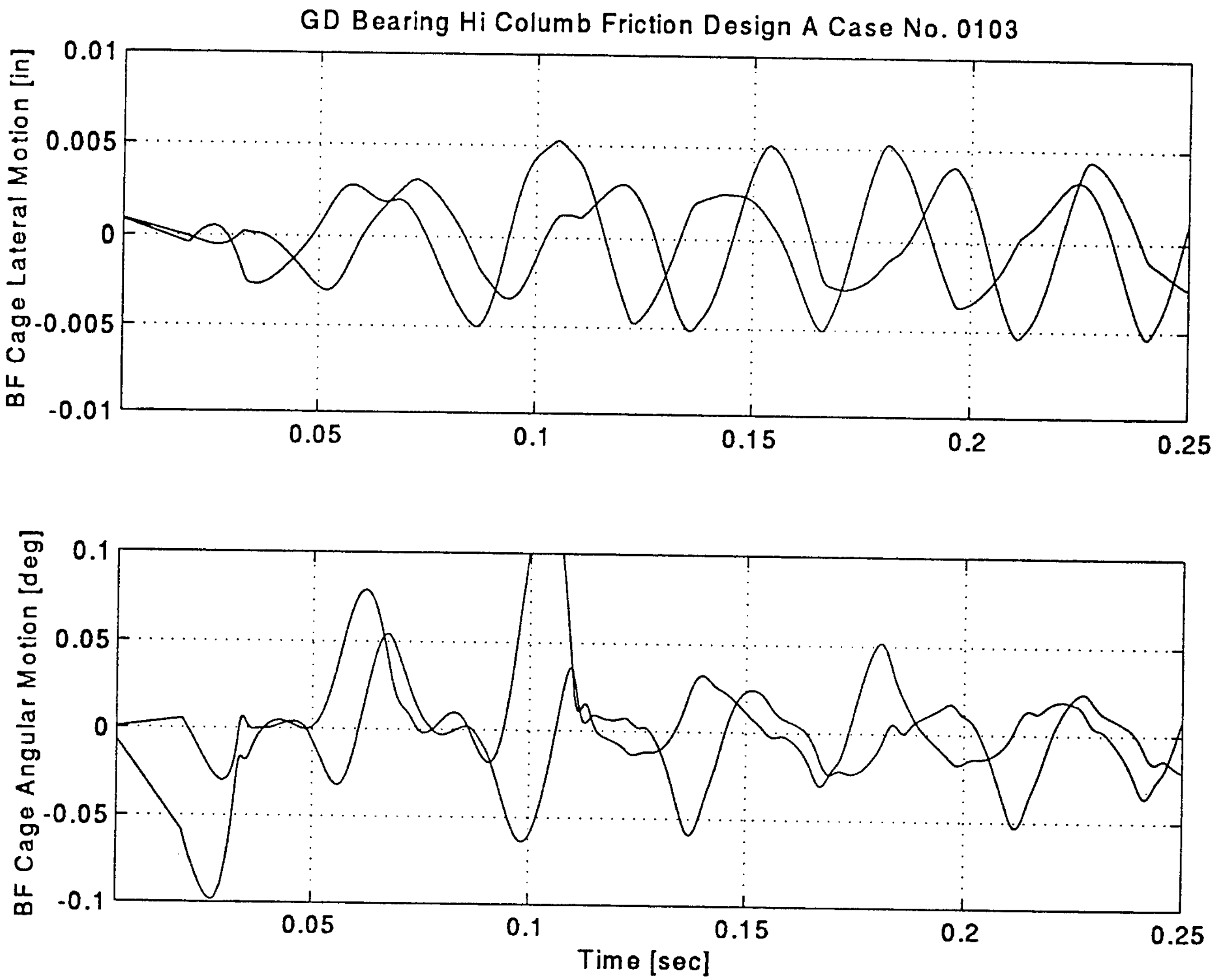

Fig 23 Design "A" High Friction Plots, Case 0103, Motions

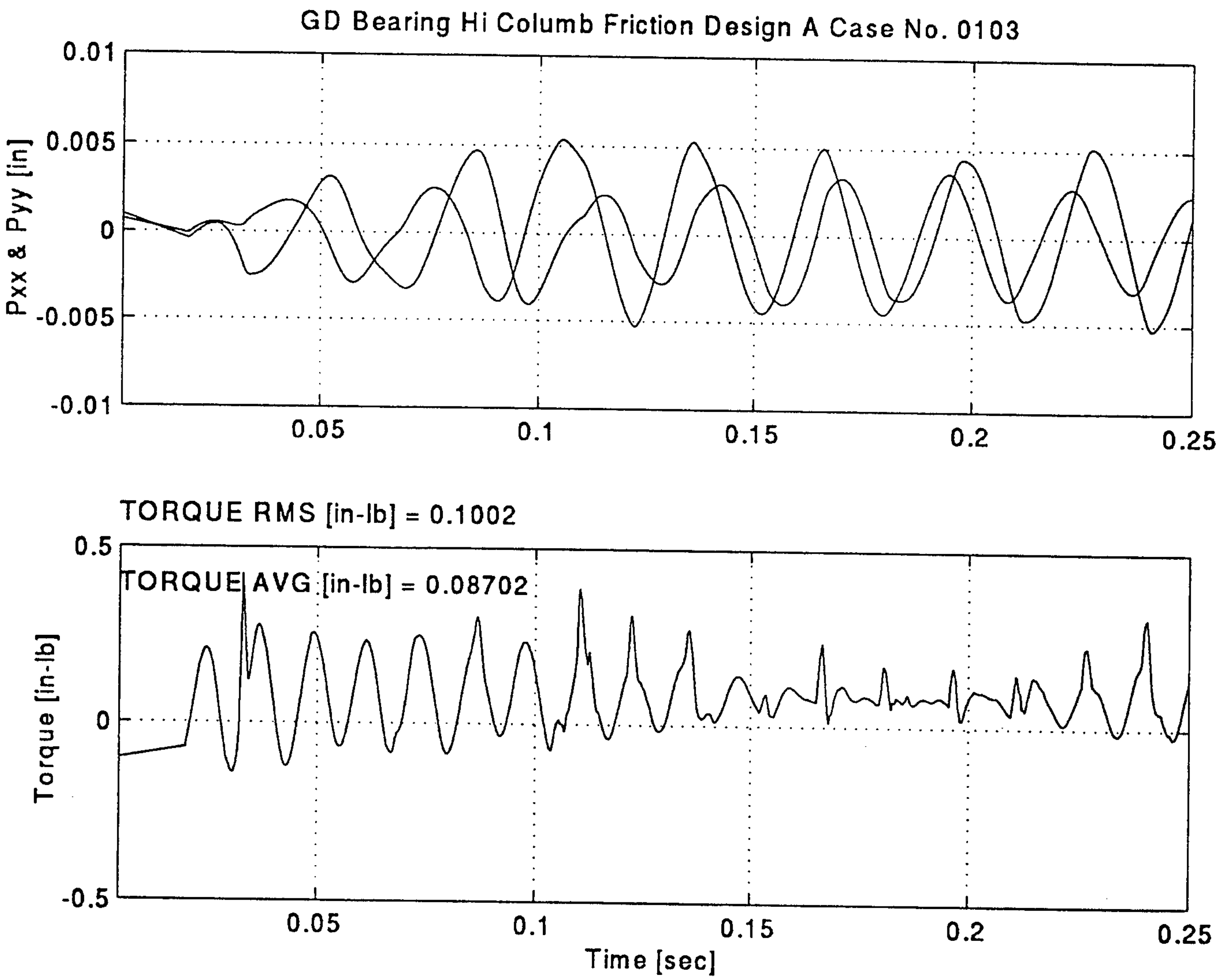

Fig 24 Design "A" High Friction Plots, Case 0103, Torque

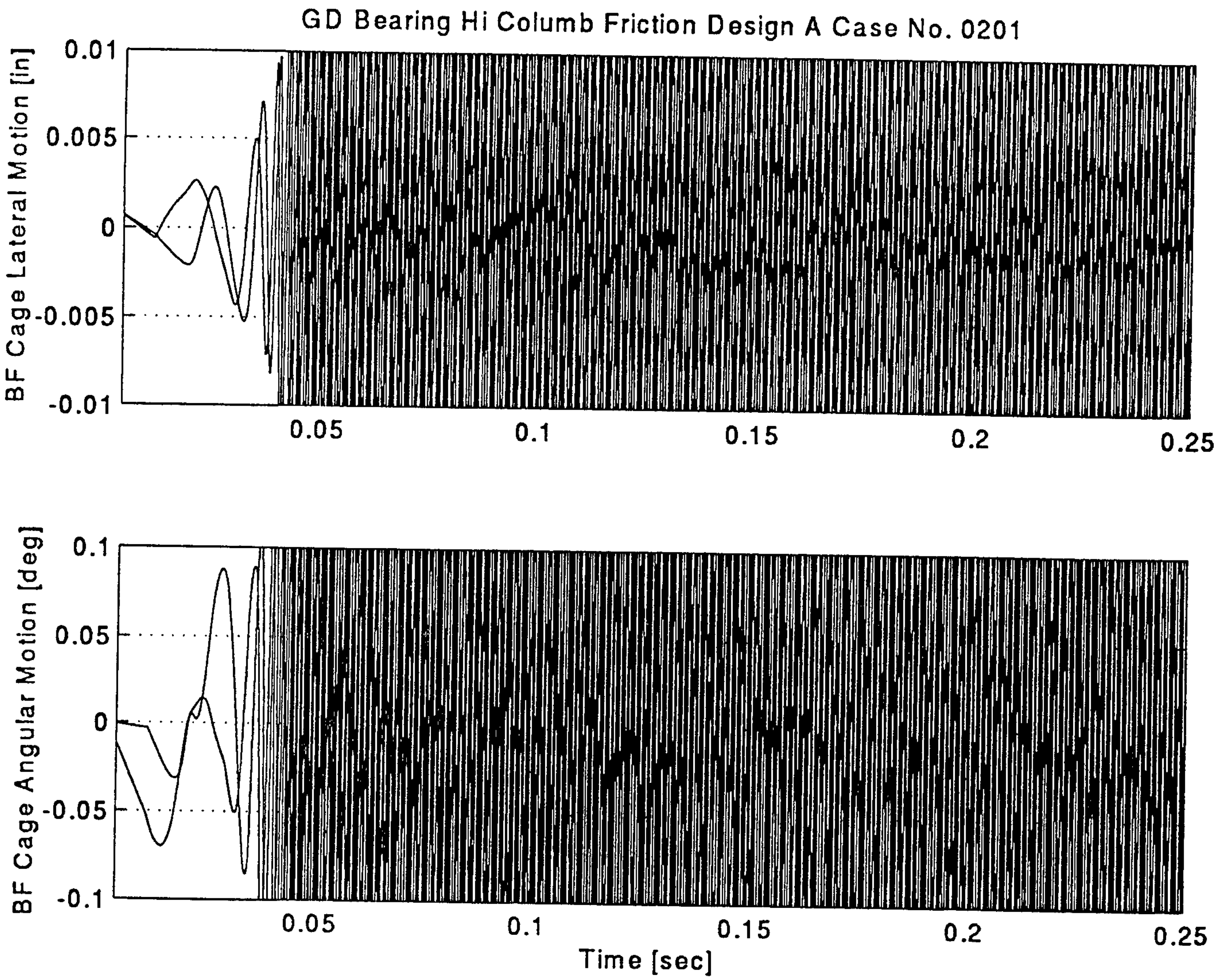

Fig 25 Design "A" High Friction Plots, Case 0201, Motions

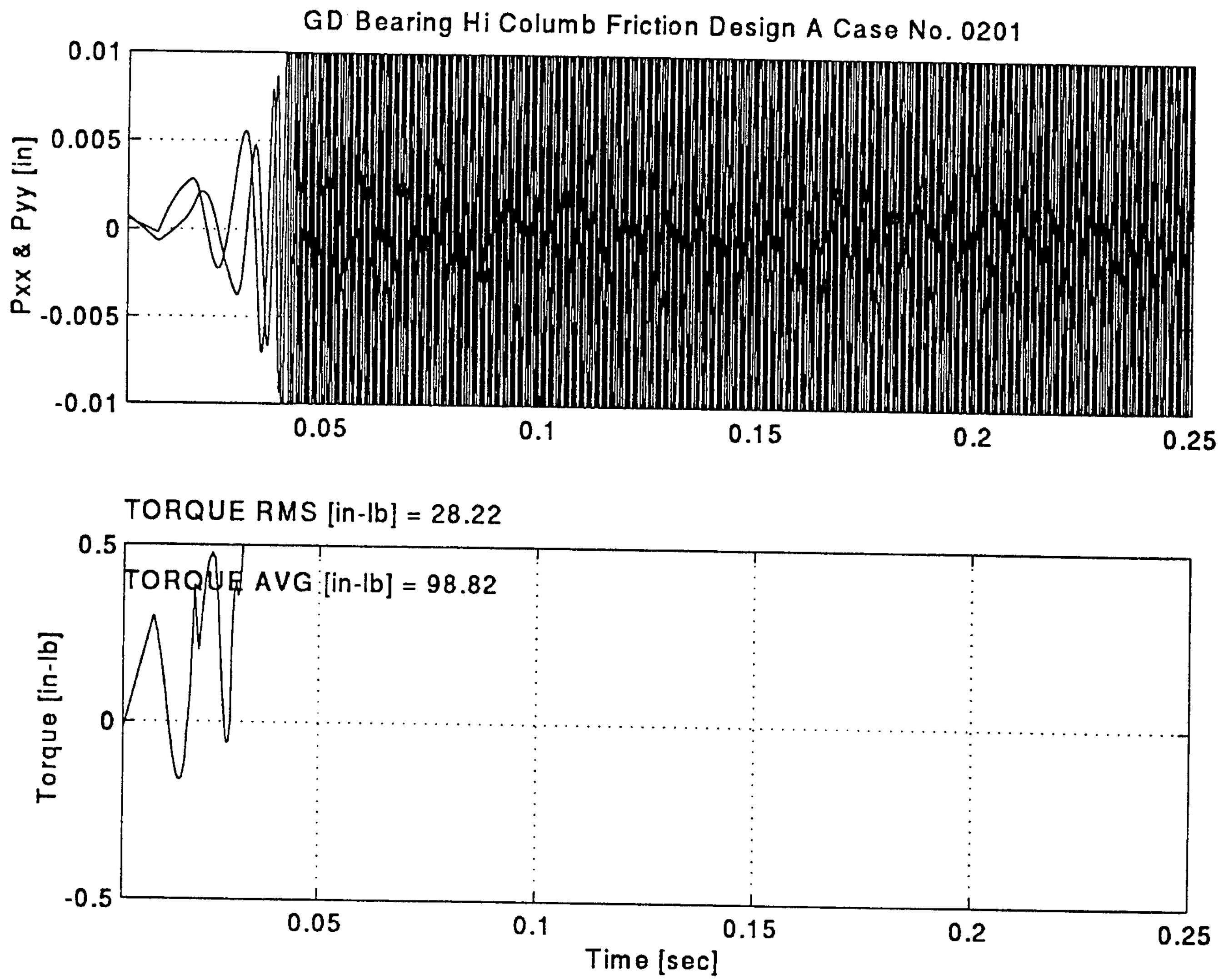

Fig 26 Design "A" High Friction Plots, Case 0201, Torque

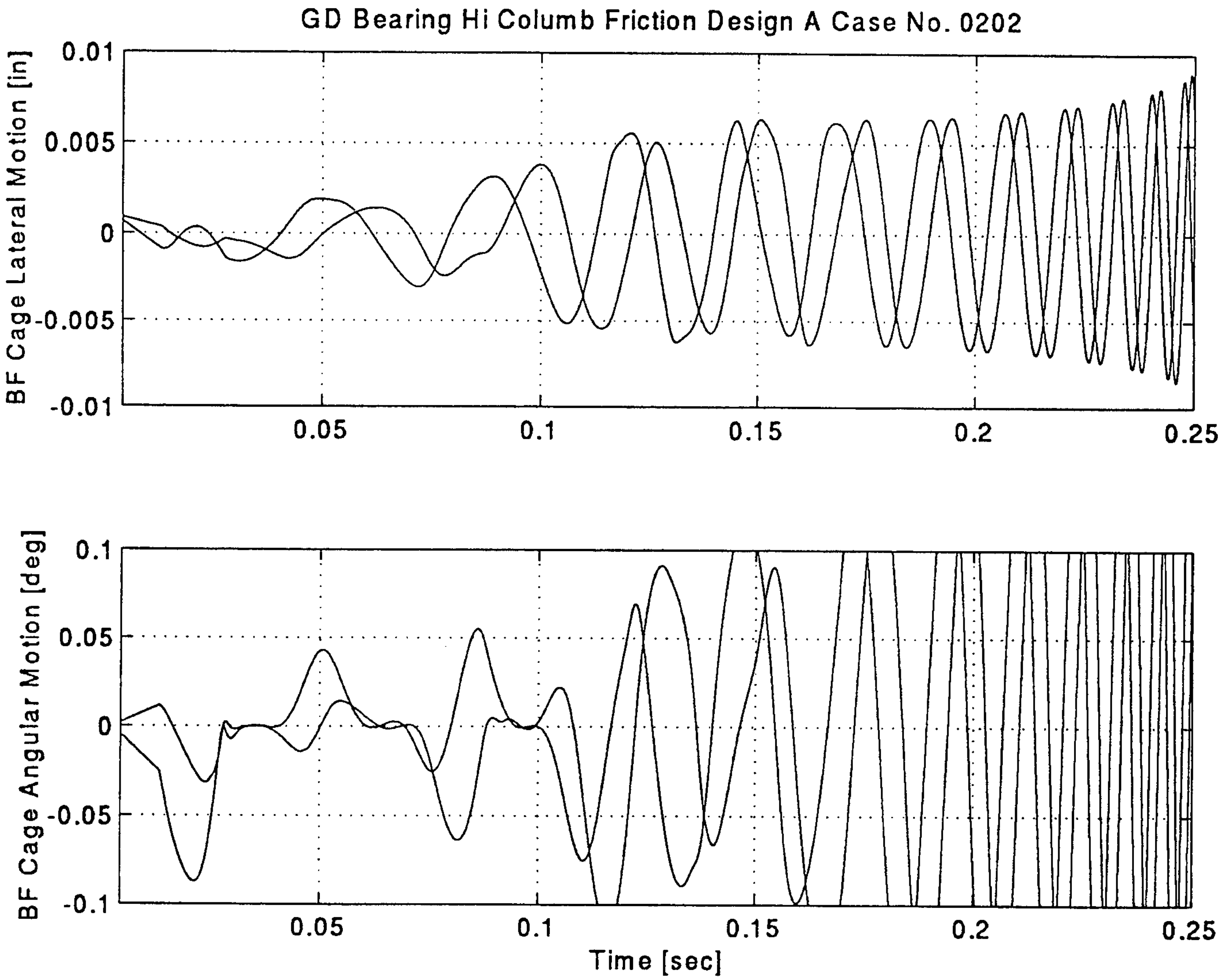

Fig 27 Design "A" High Friction Plots, Case 0202, Motions

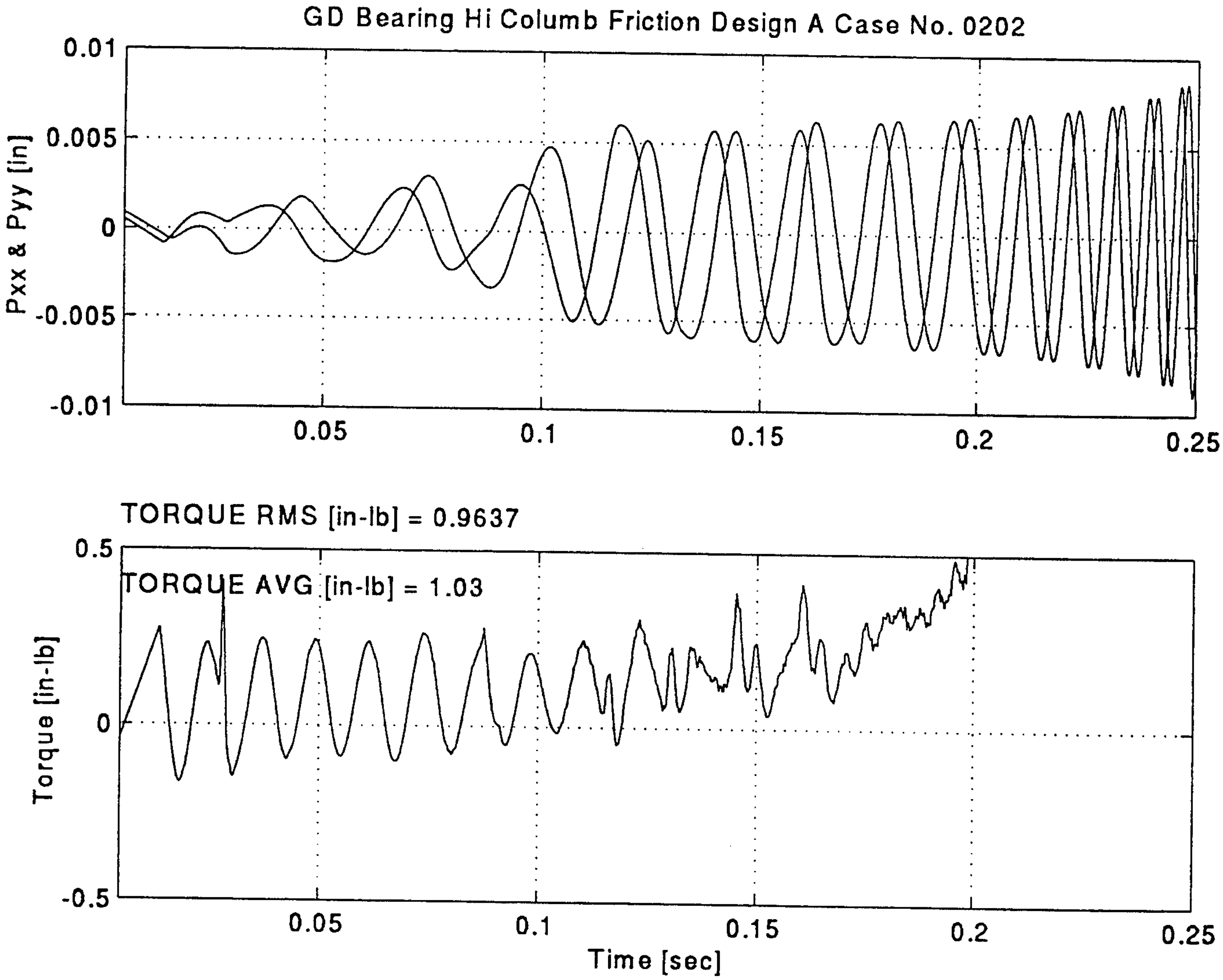

Fig 28 Design "A" High Friction Plots, Case 0202, Torque

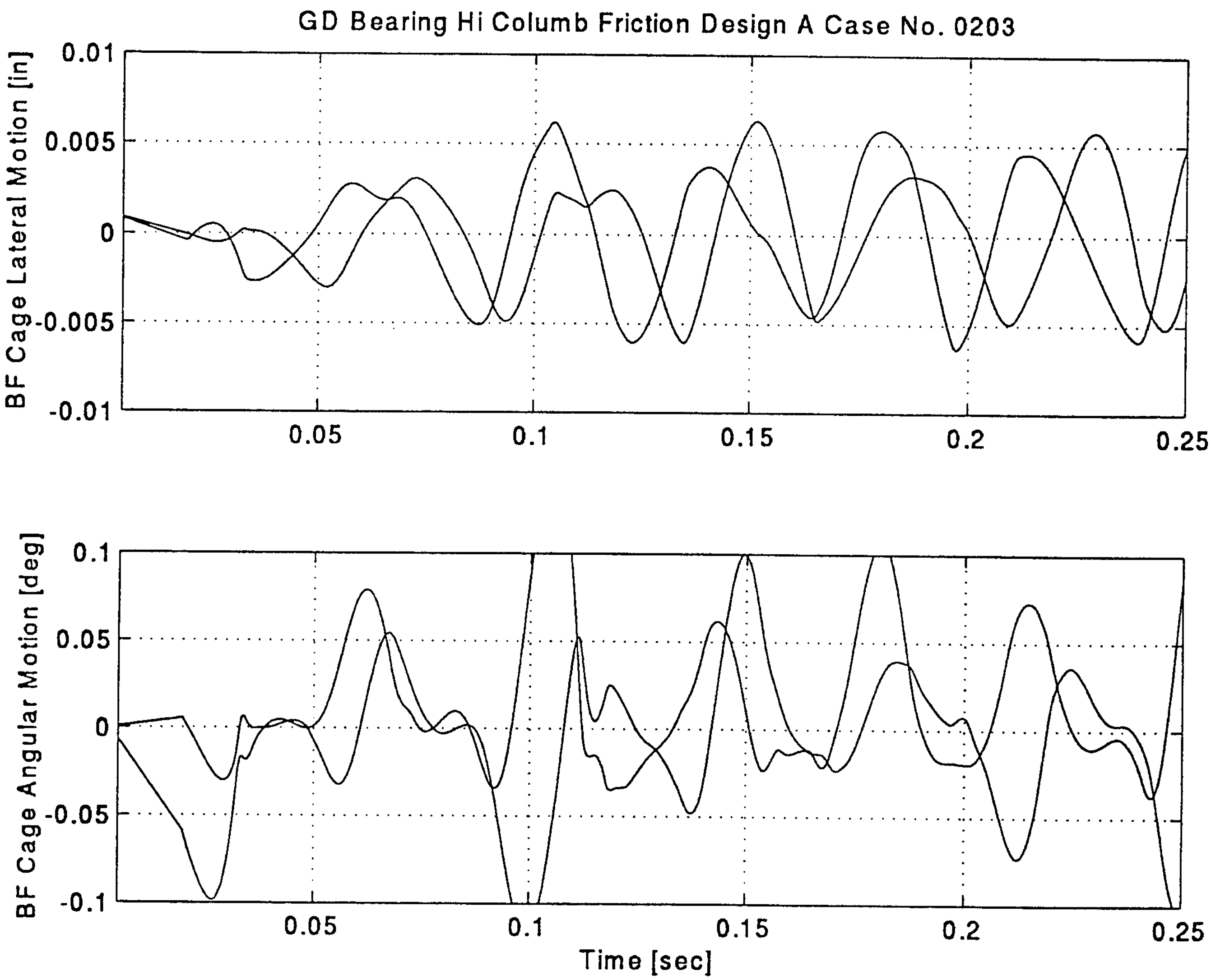

Fig 29 Design "A" High Friction Plots, Case 0203, Motions

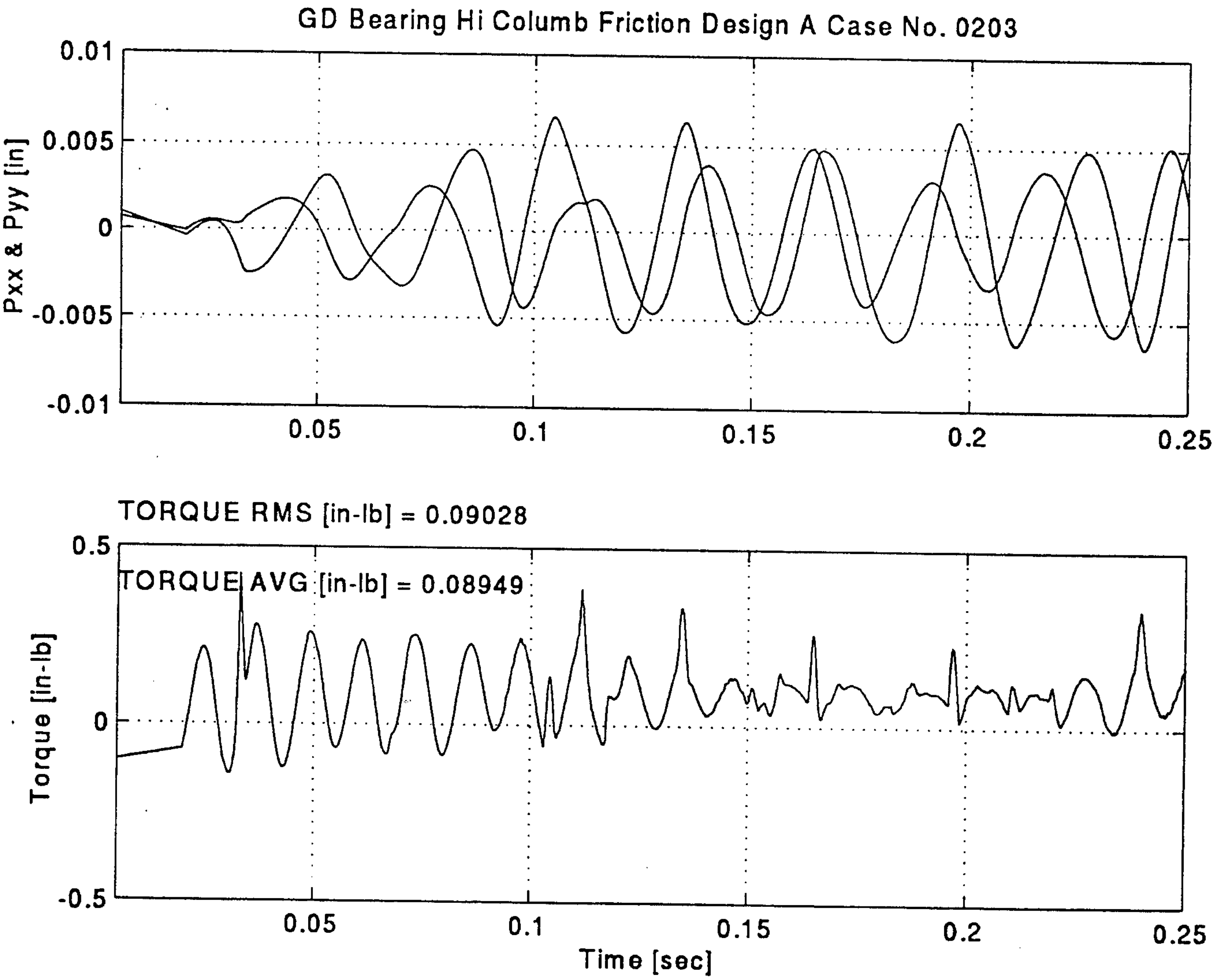

Fig 30 Design "A" High Friction Plots, Case 0203, Torque

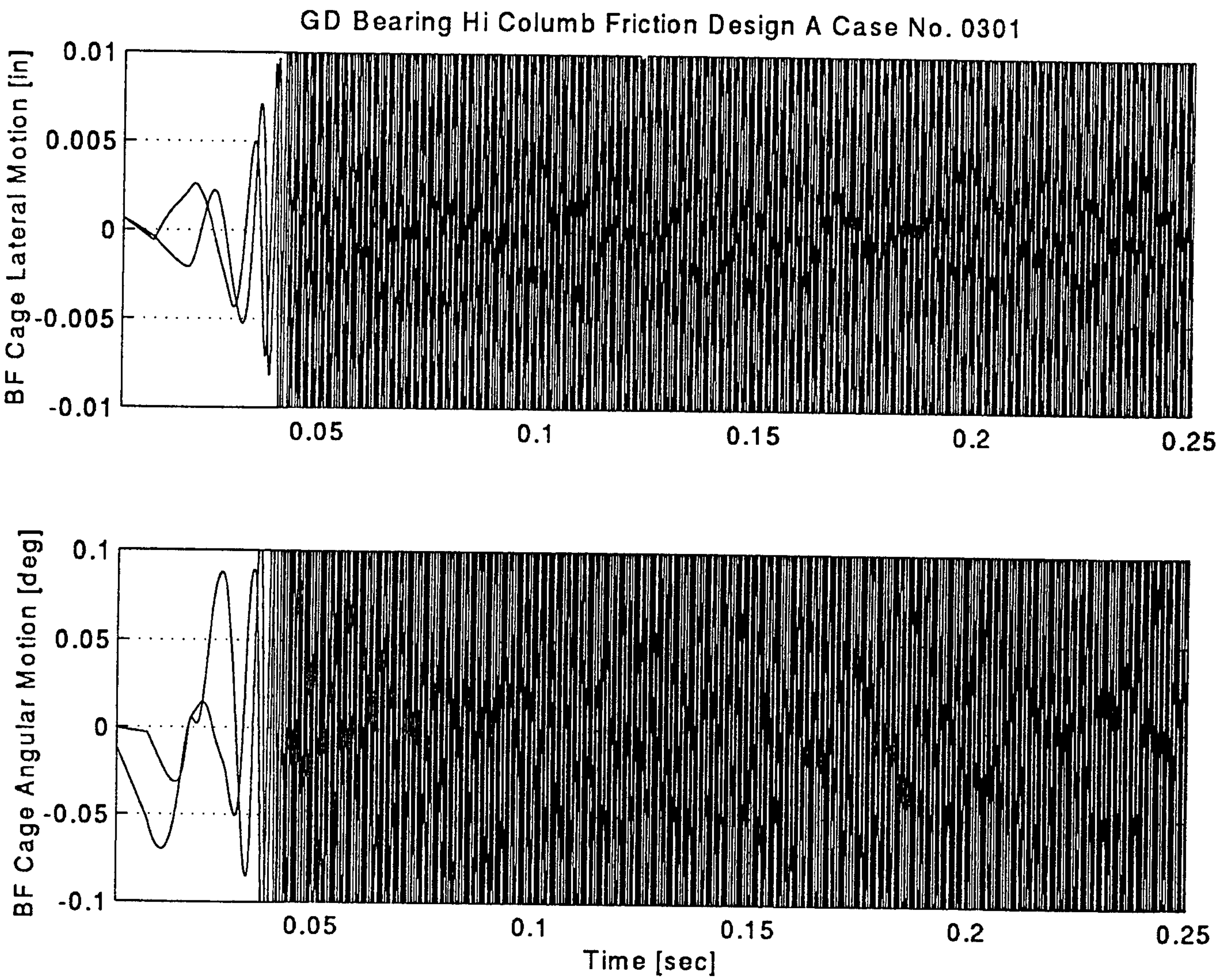

Fig 31 Design "A" High Friction Plots, Case 0301, Motions

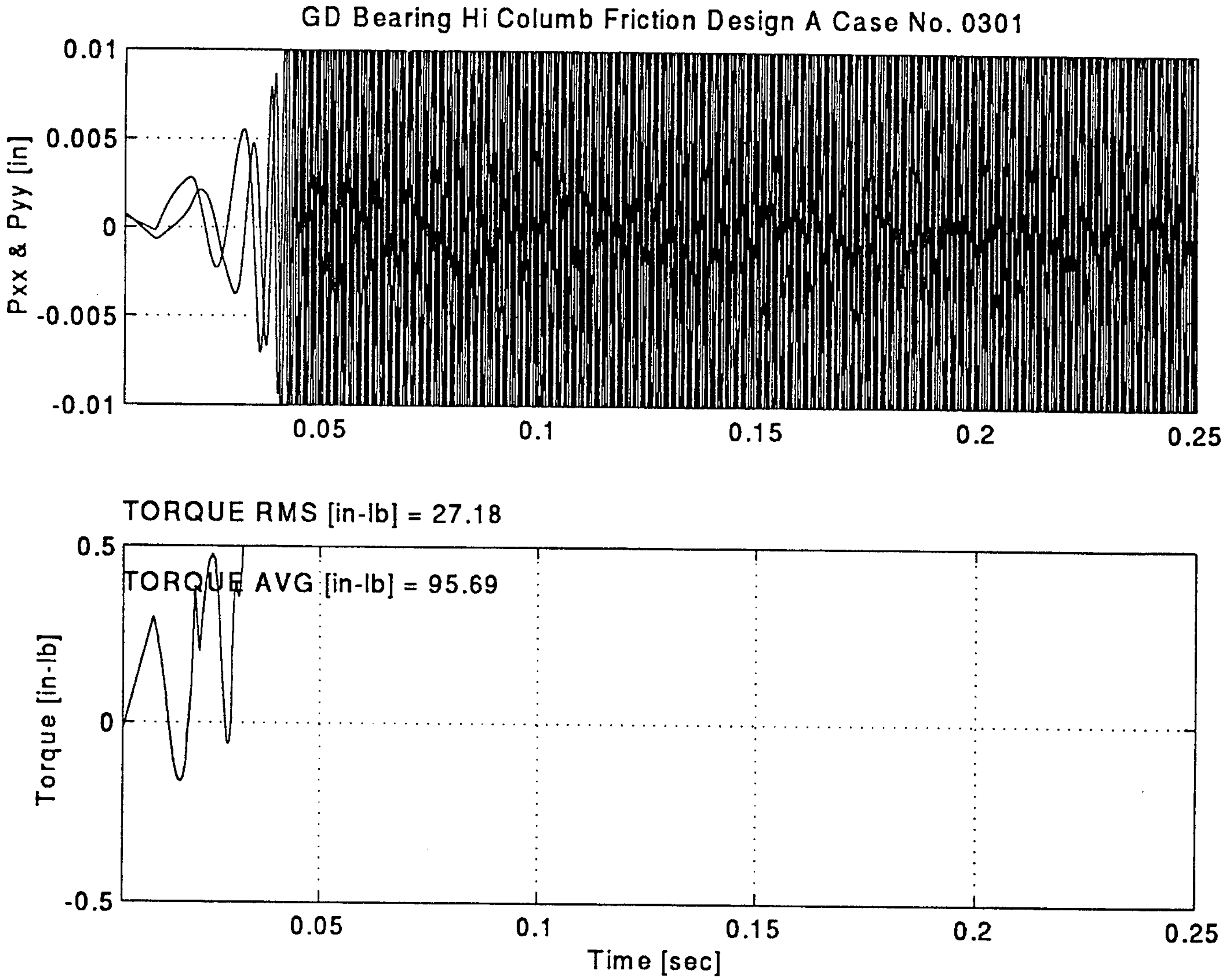

Fig 32 Design "A" High Friction Plots, Case 0301, Torque

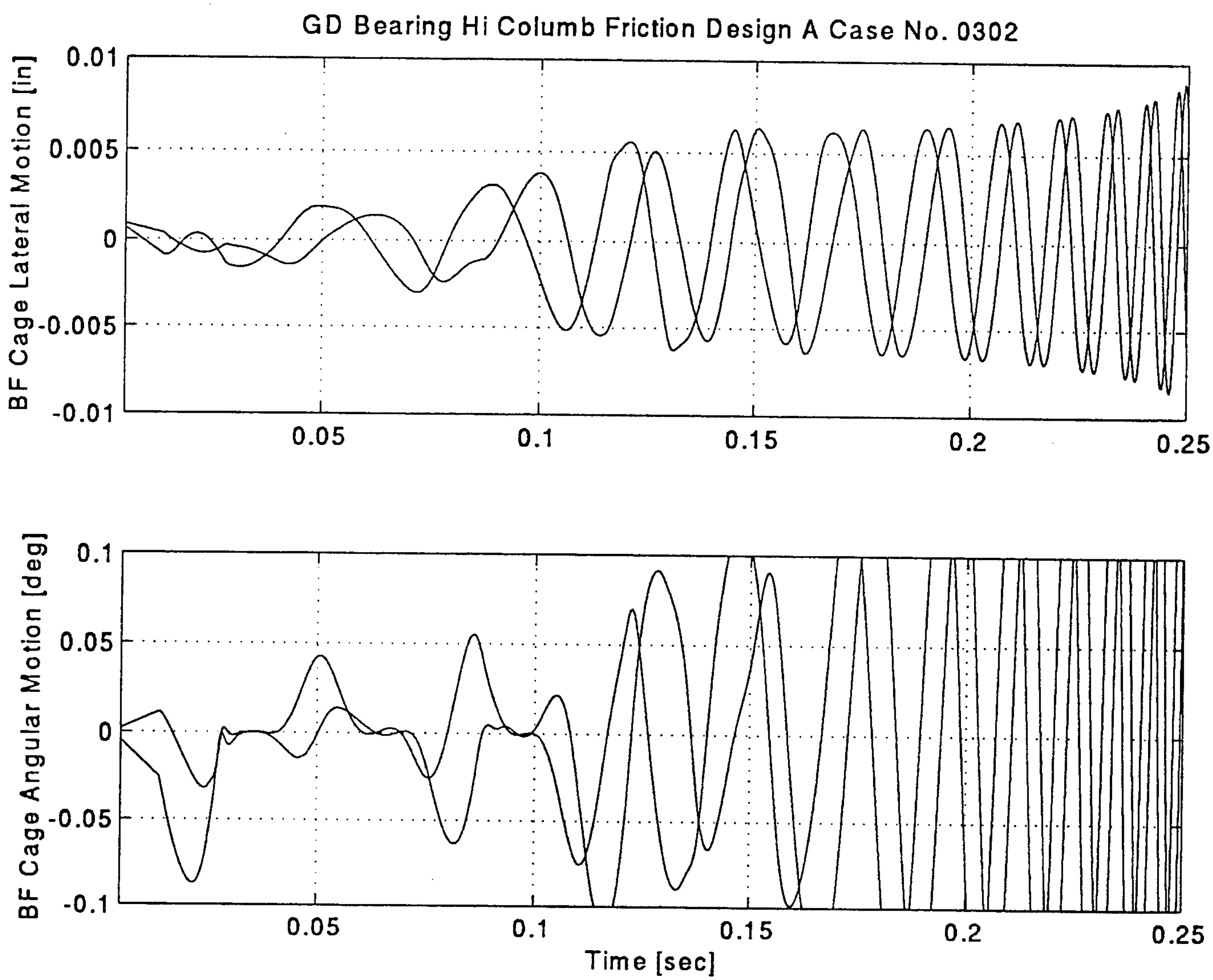

Fig 33 Design "A" High Friction Plots, Case 0302, Motions

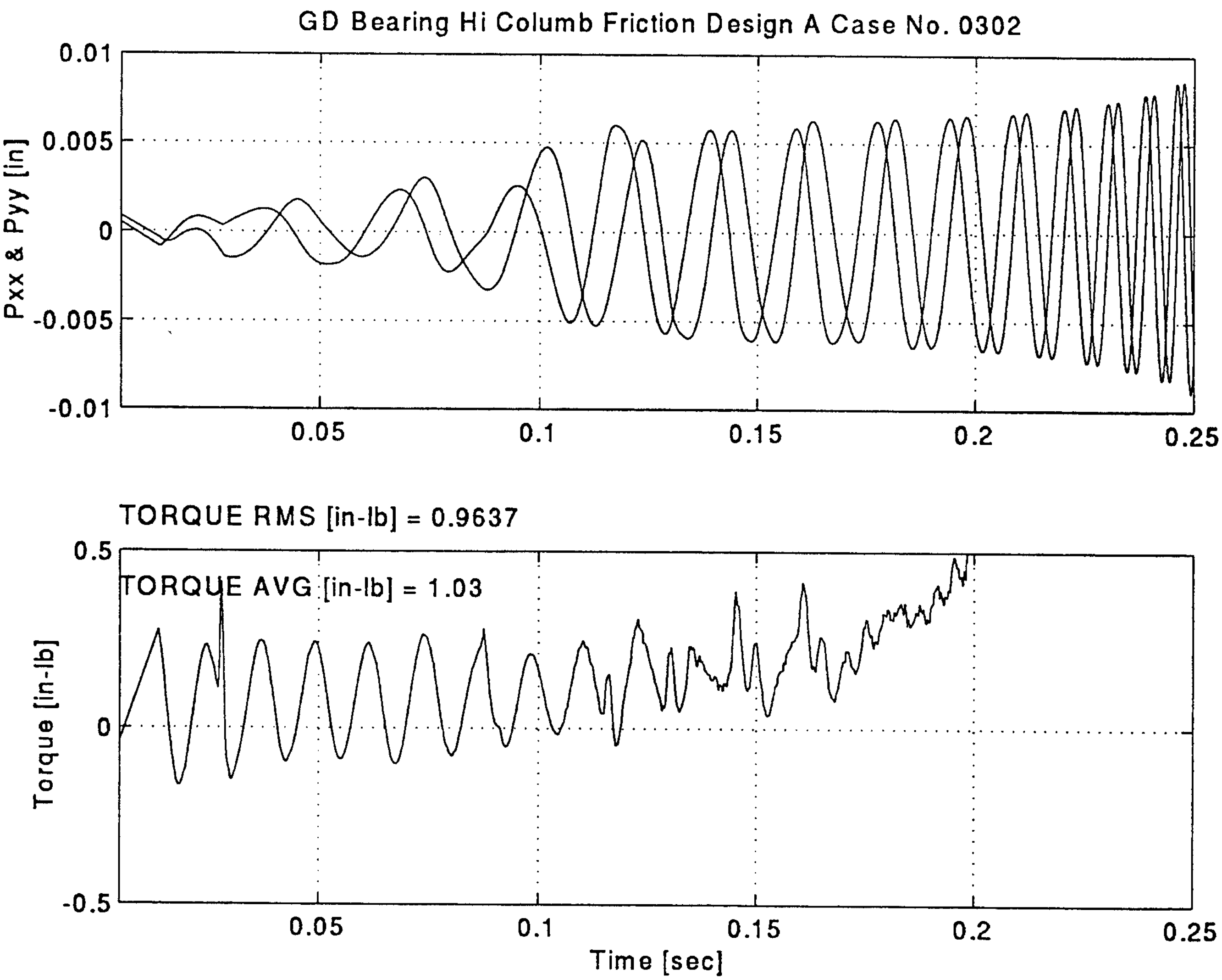

Fig 34 Design "A" High Friction Plots, Case 0302, Torque

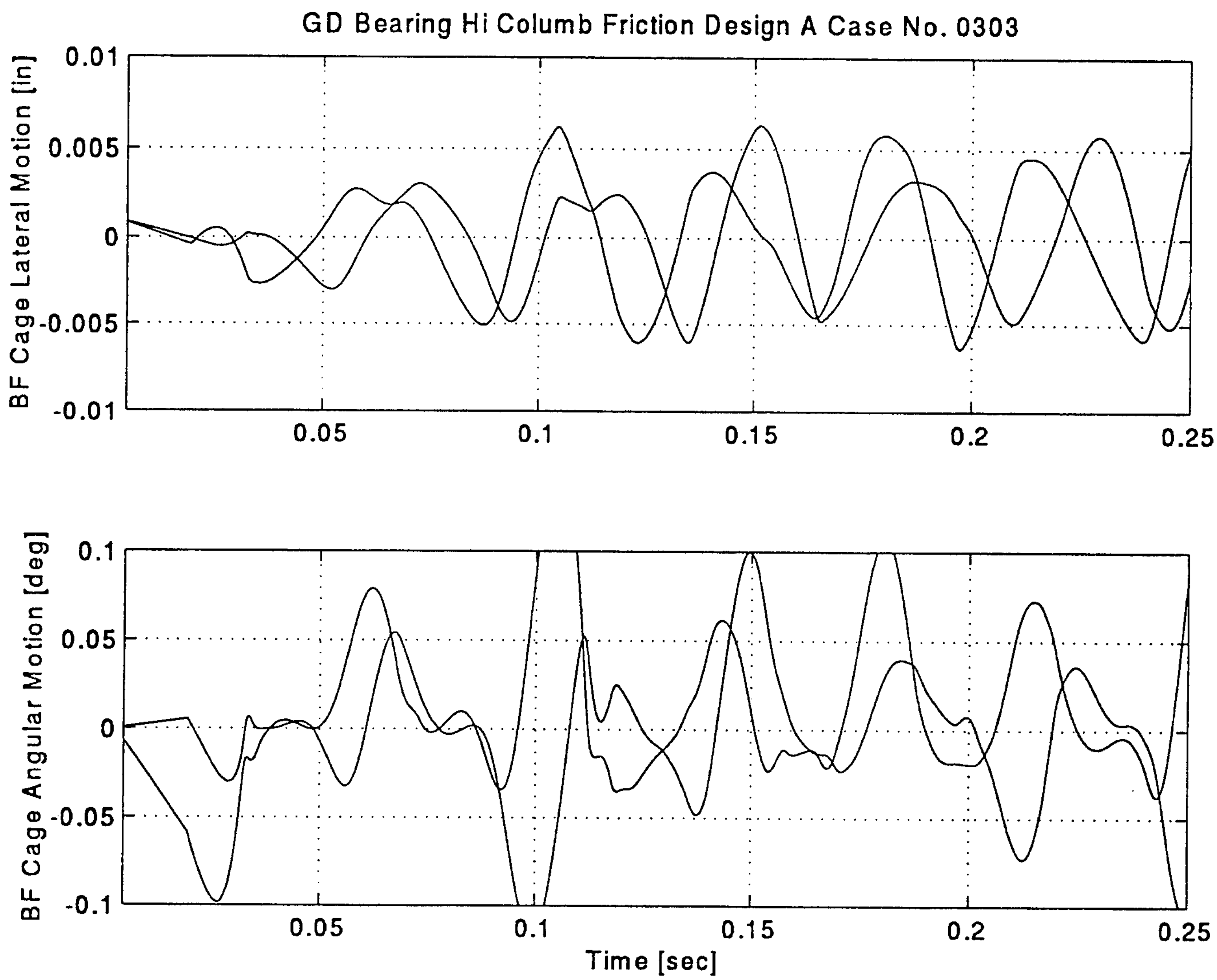

Fig 35 Design "A" High Friction Plots, Case 0303, Motions

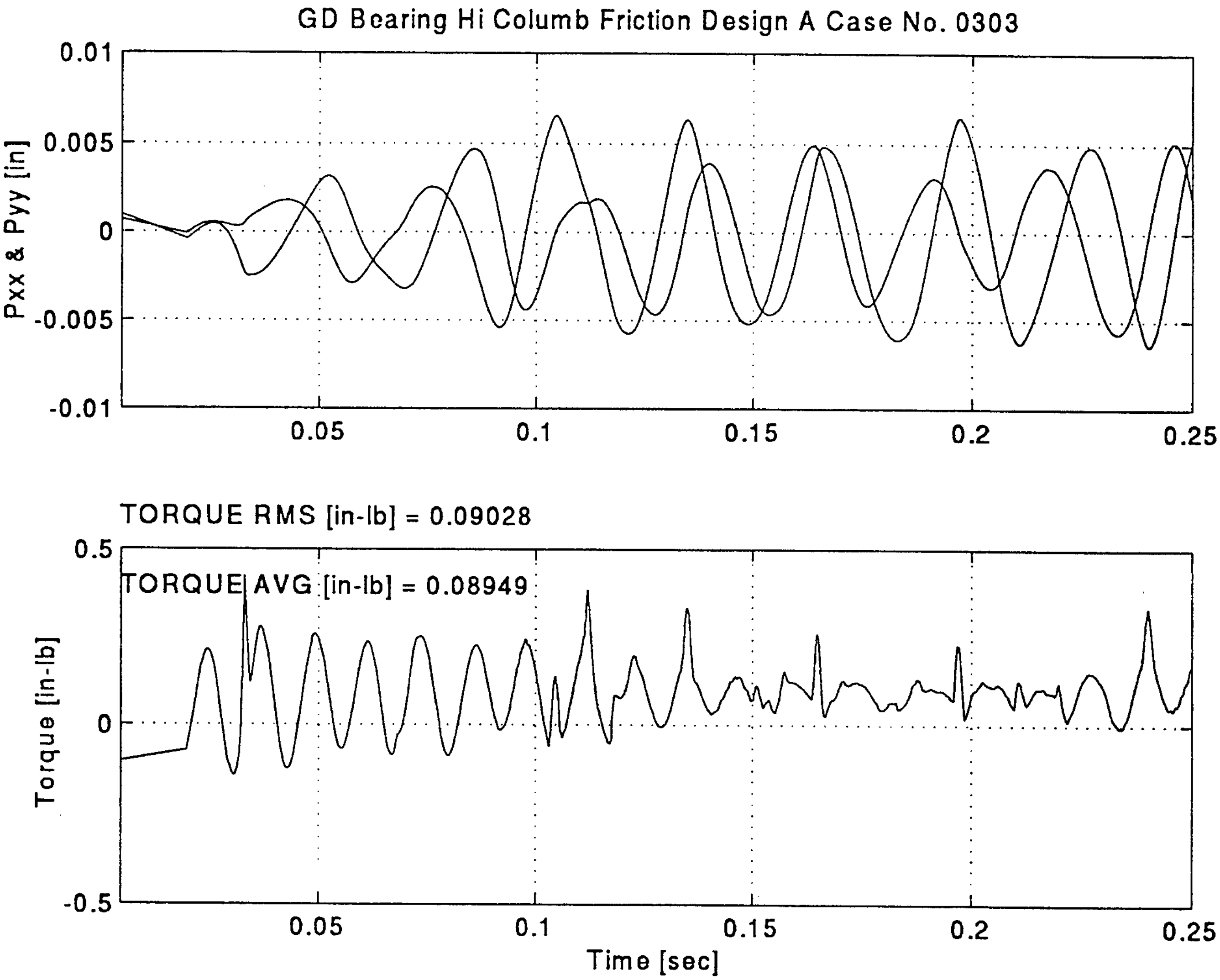

Fig 36 Design "A" High Friction Plots, Case 0303, Torque

DESIGN "B" HIGH COULOMB FRICTION SIMULATION PLOTS

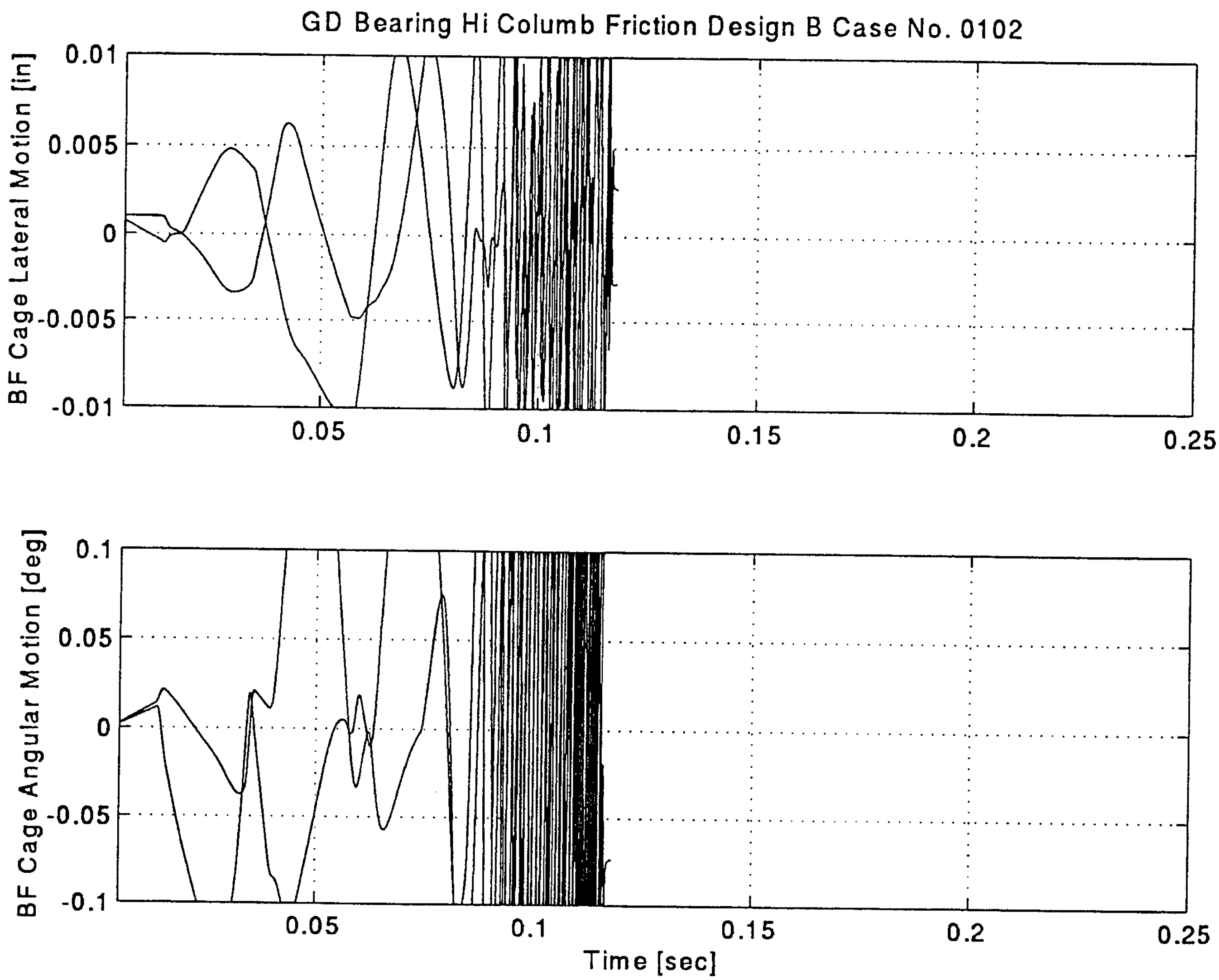

Fig 37 Design "B" High Friction Plots, Case 0102, Motions

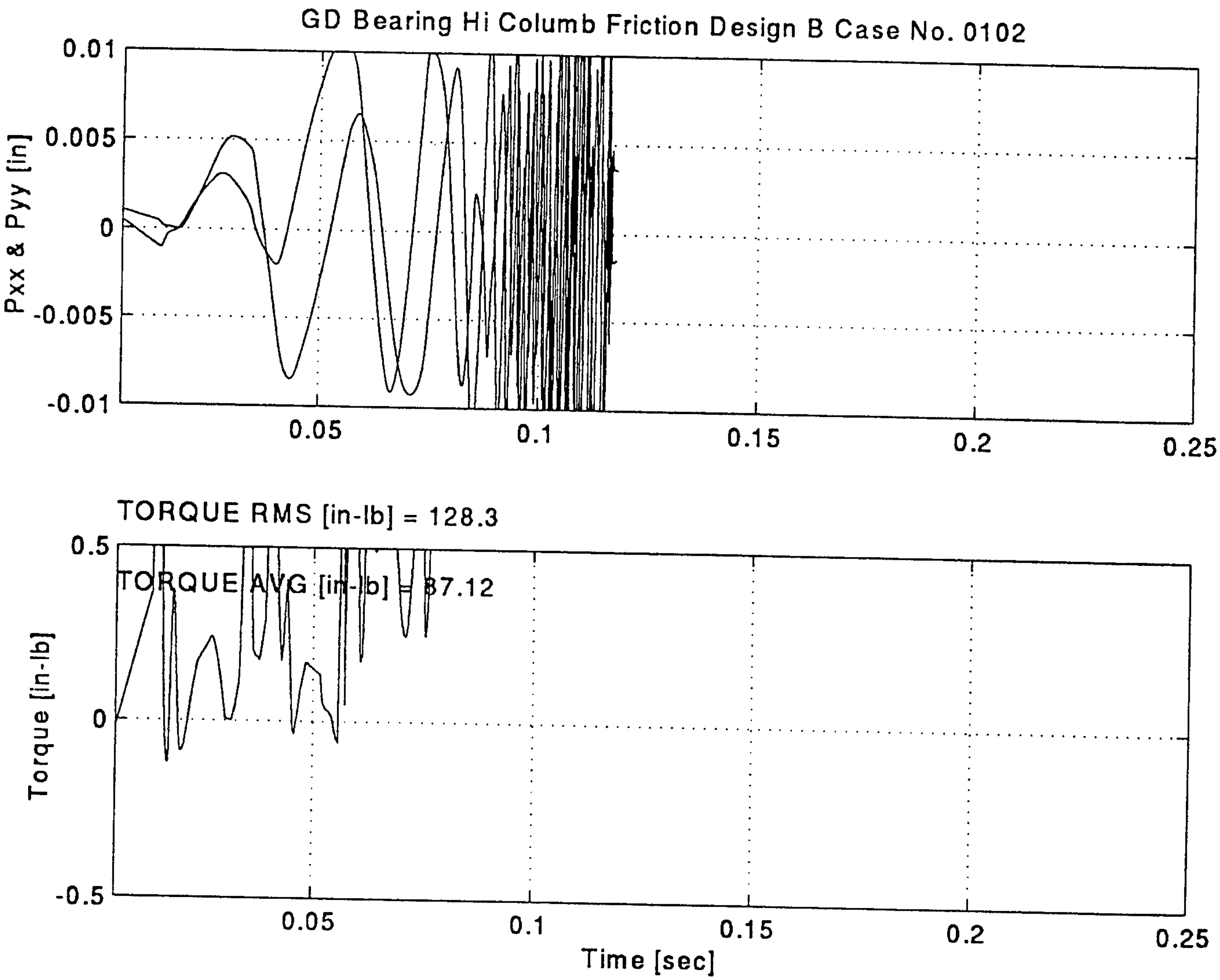

Fig 38 Design "B" High Friction Plots, Case 0102, Torque

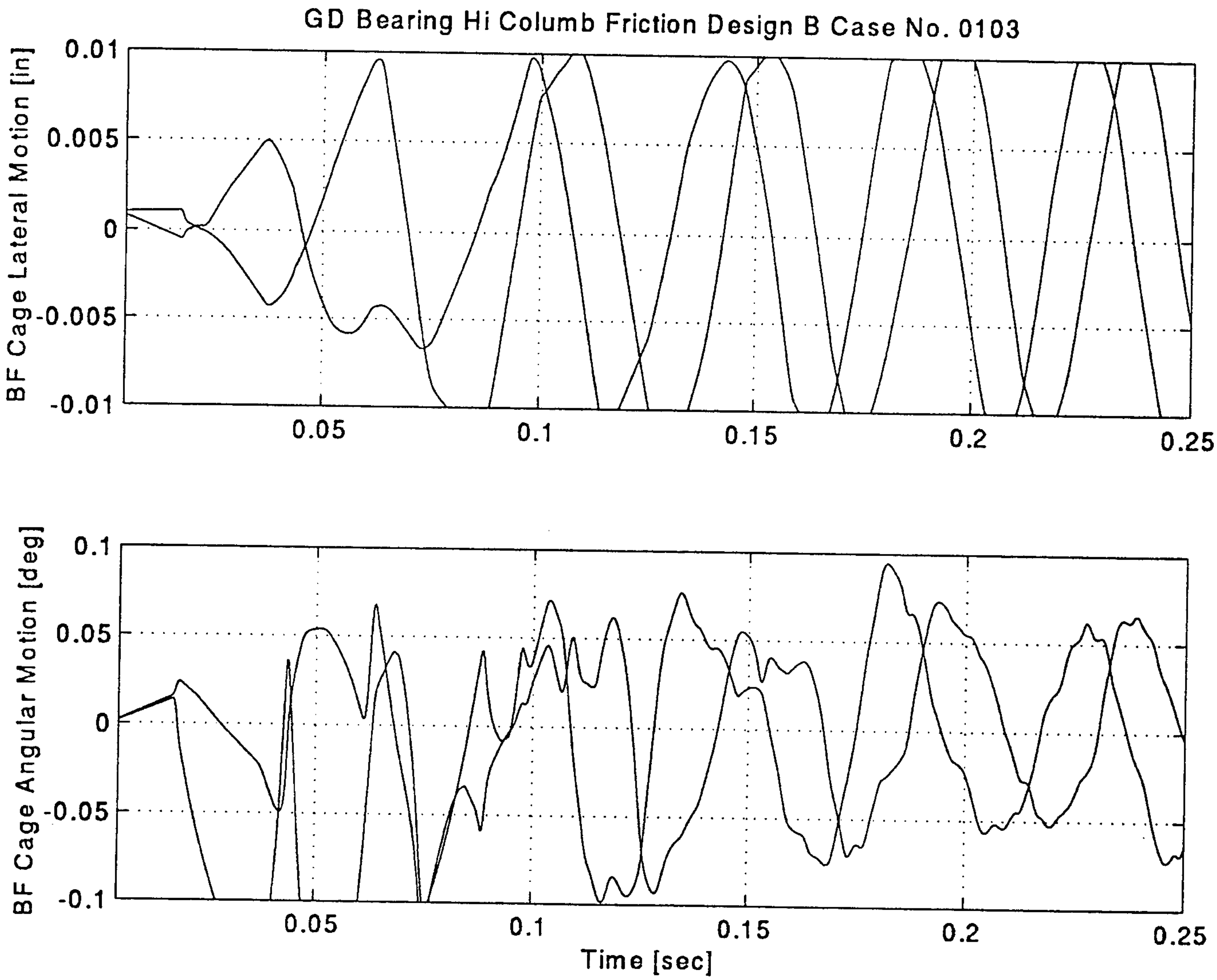

Fig 39 Design "B" High Friction Plots, Case 0103, Motions

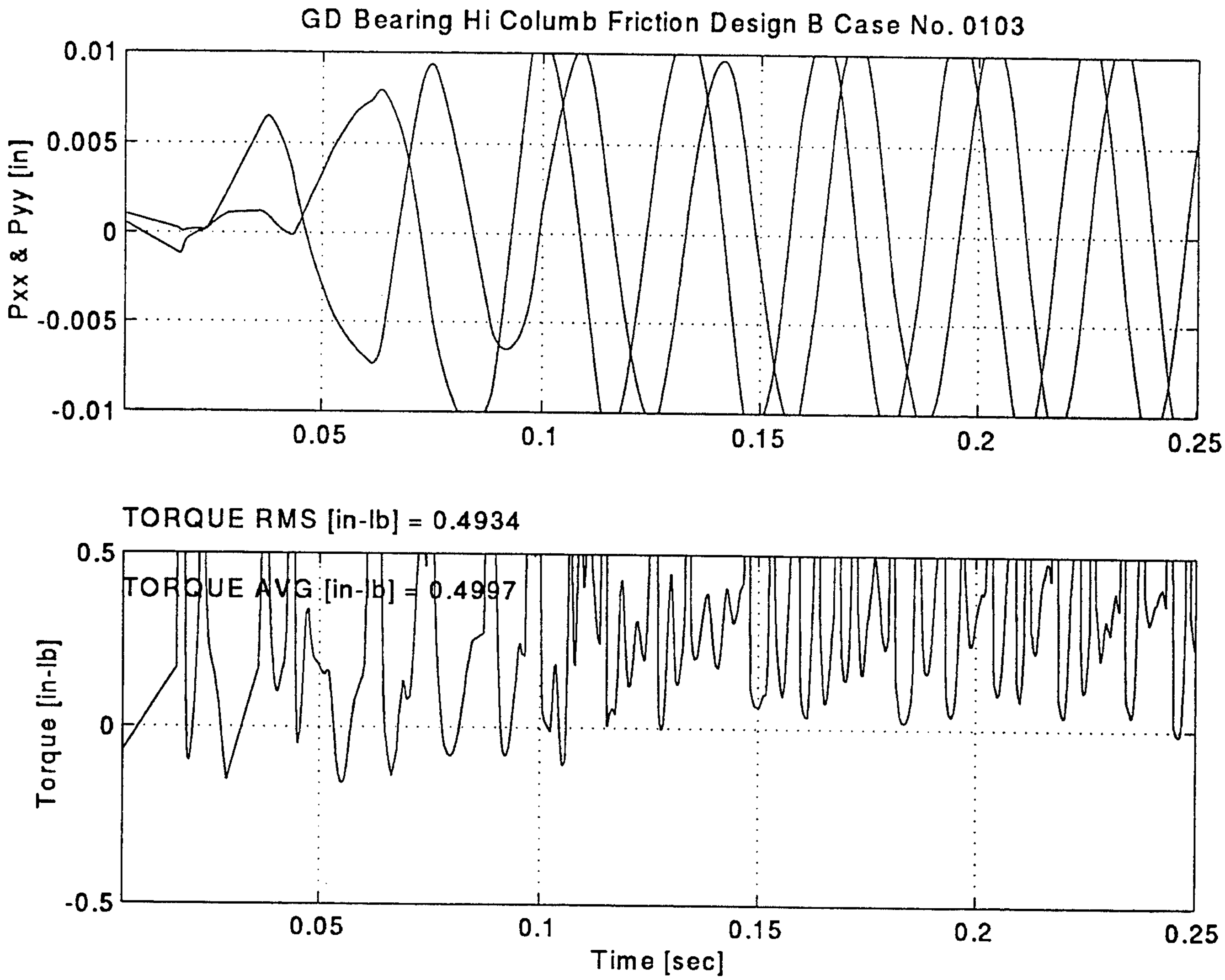

Fig 40 Design "B" High Friction Plots, Case 0103, Torque

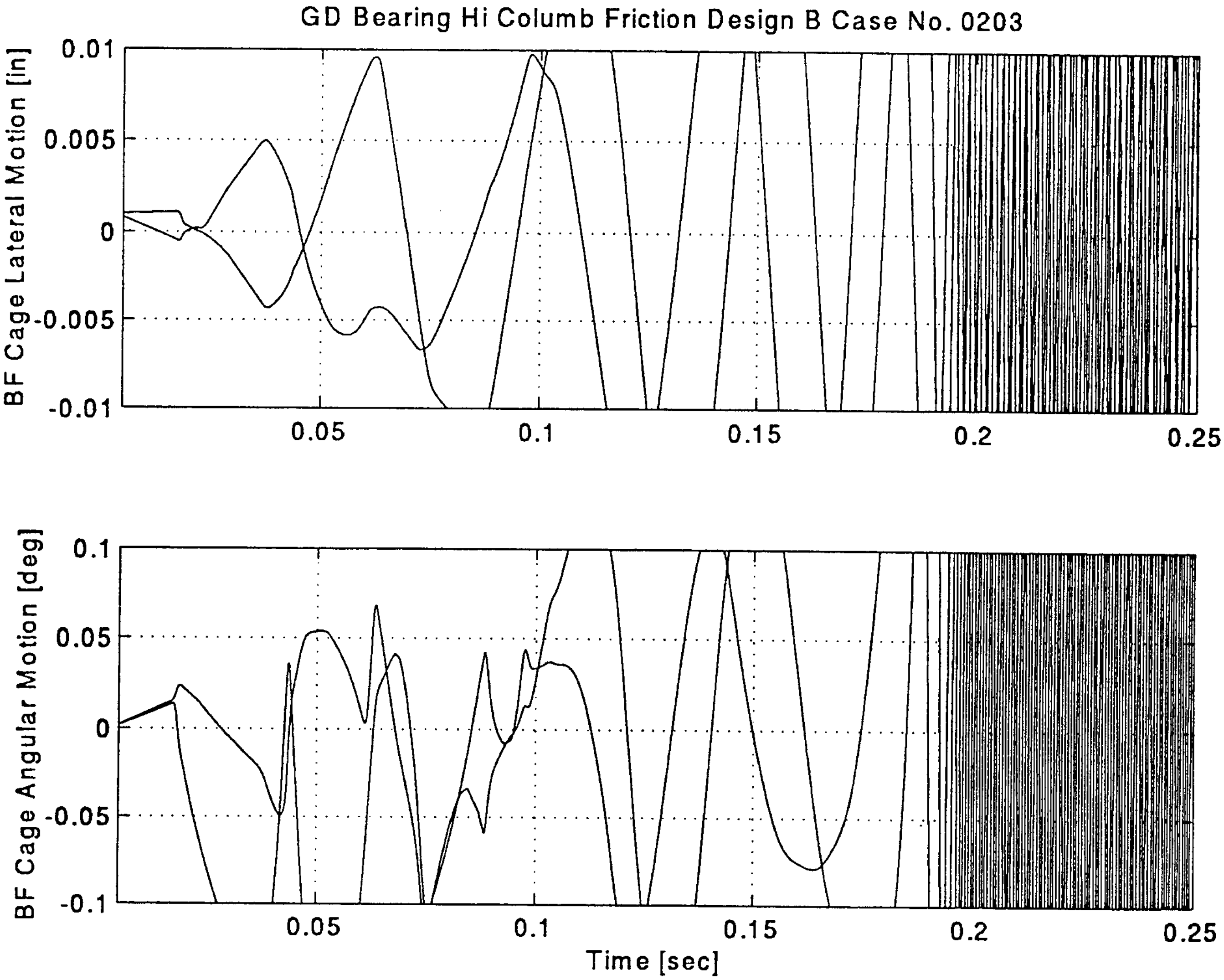

Fig 41 Design "B" High Friction Plots, Case 0203, Motions

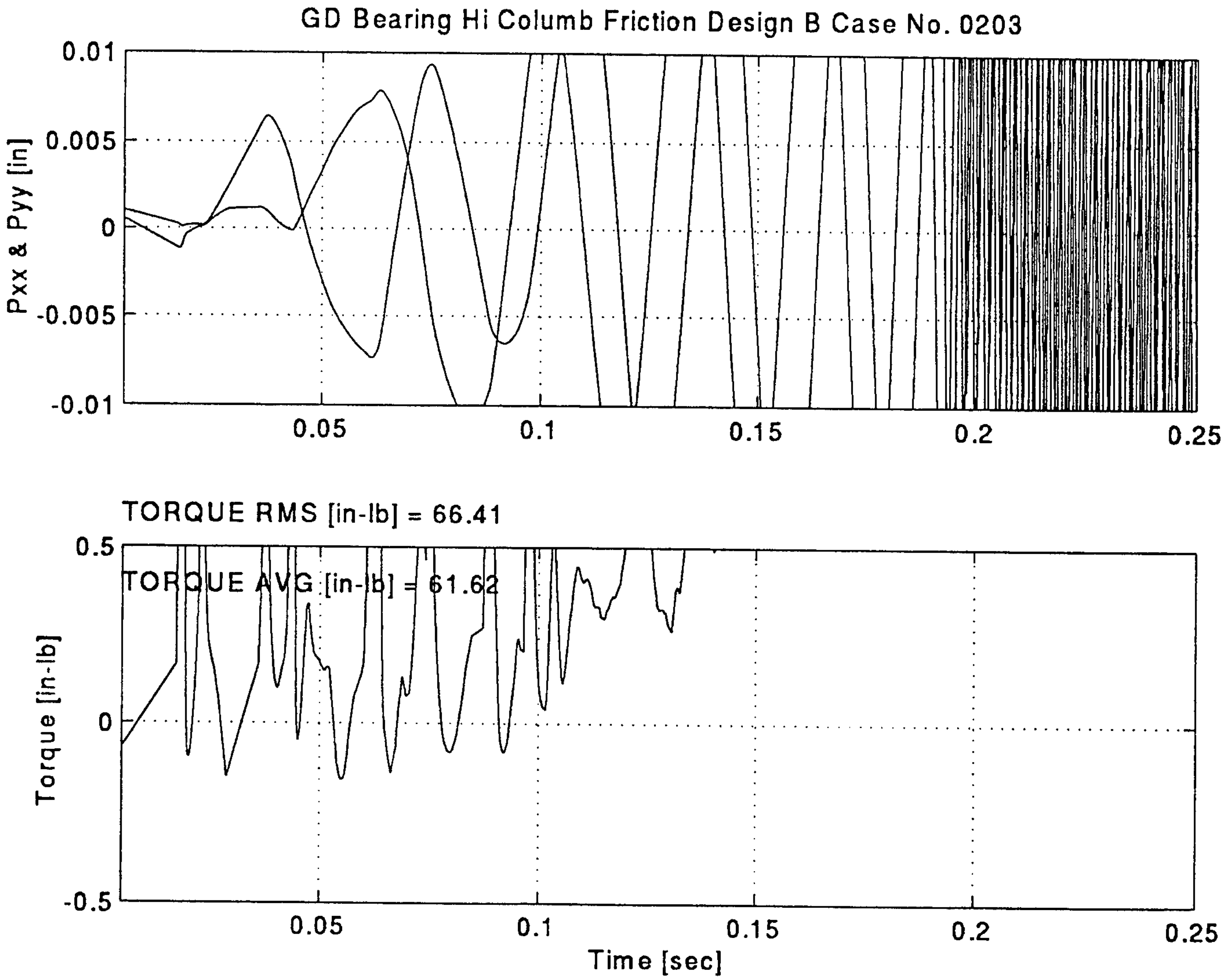

Fig 42 Design "B" High Friction Plots, Case 0203, Torque

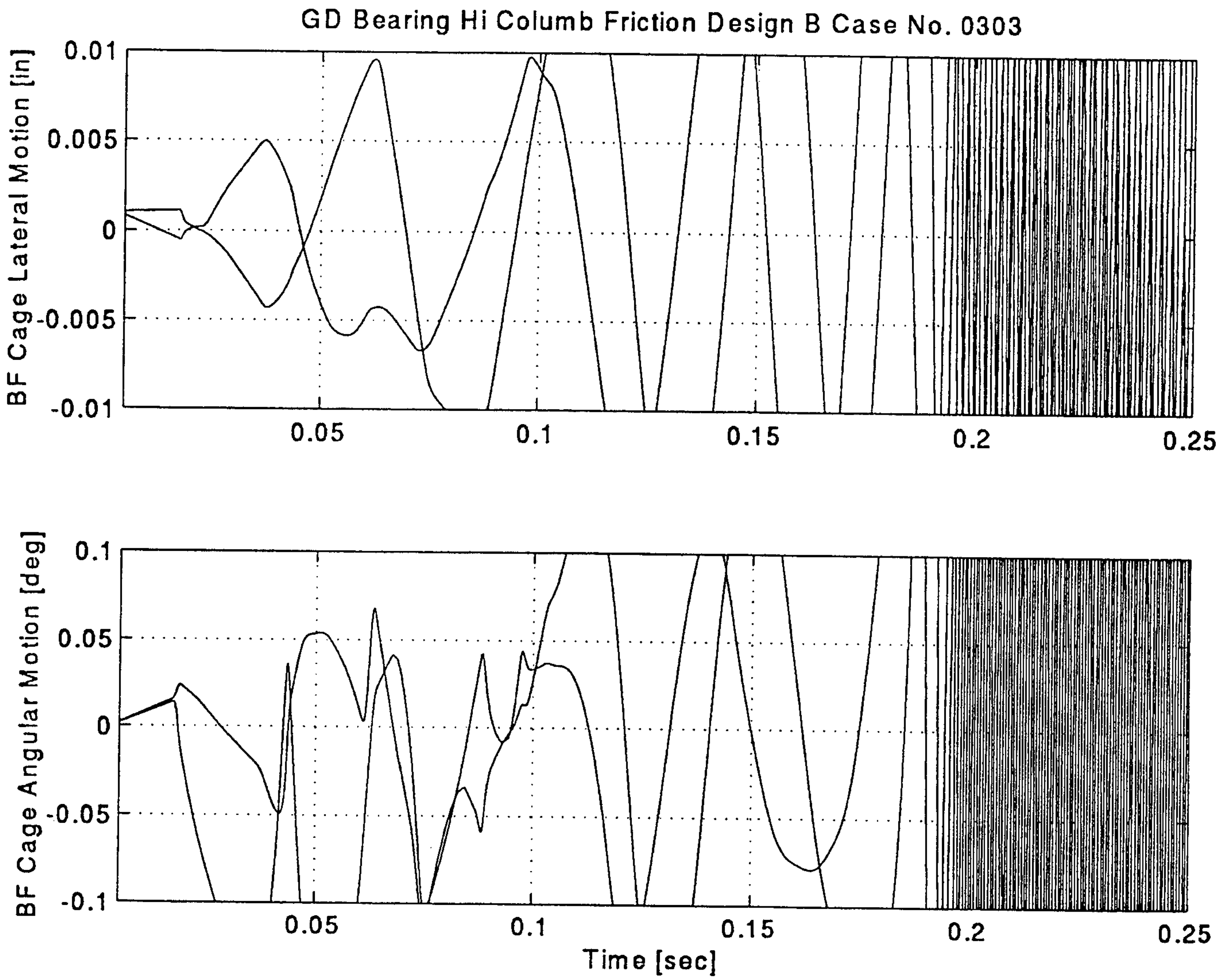

Fig 43 Design "B" High Friction Plots, Case 0303, Motions

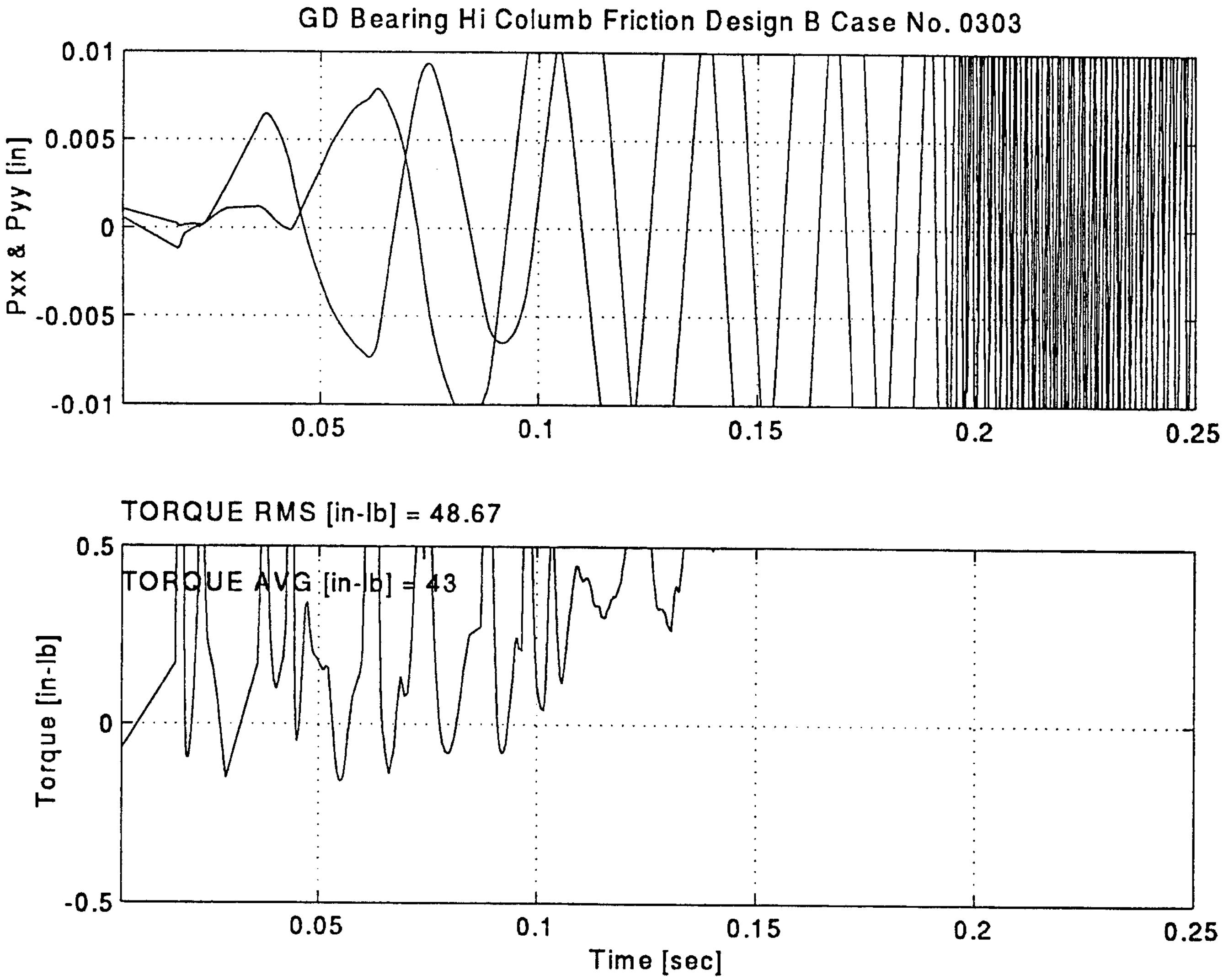

Fig 44 Design "B" High Friction Plots, Case 0303, Torque

DESIGN "B" LOW COULOMB FRICTION SIMULATION PLOTS

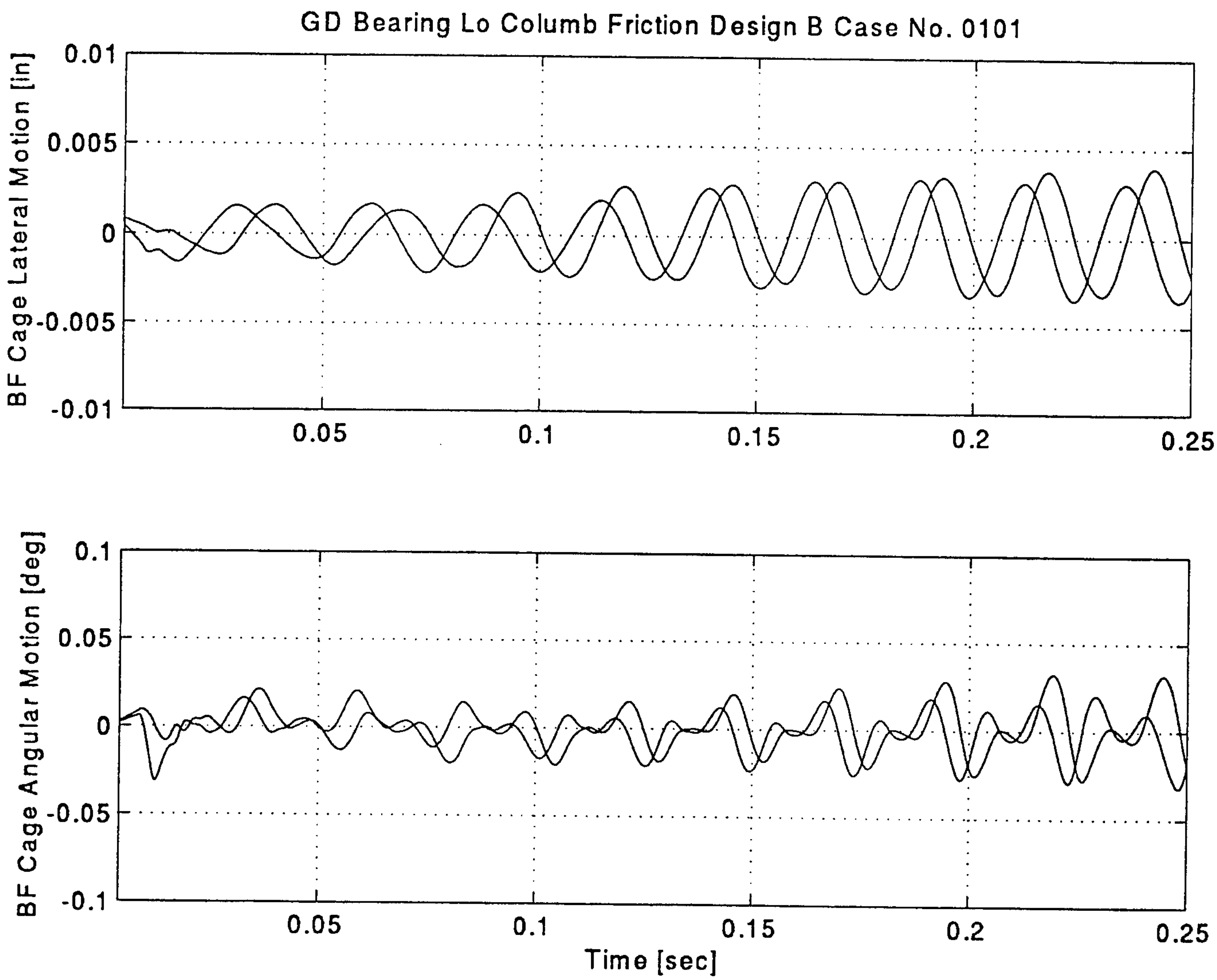

Fig 45 Design "B" Low Friction Plots, Case 0101, Motions

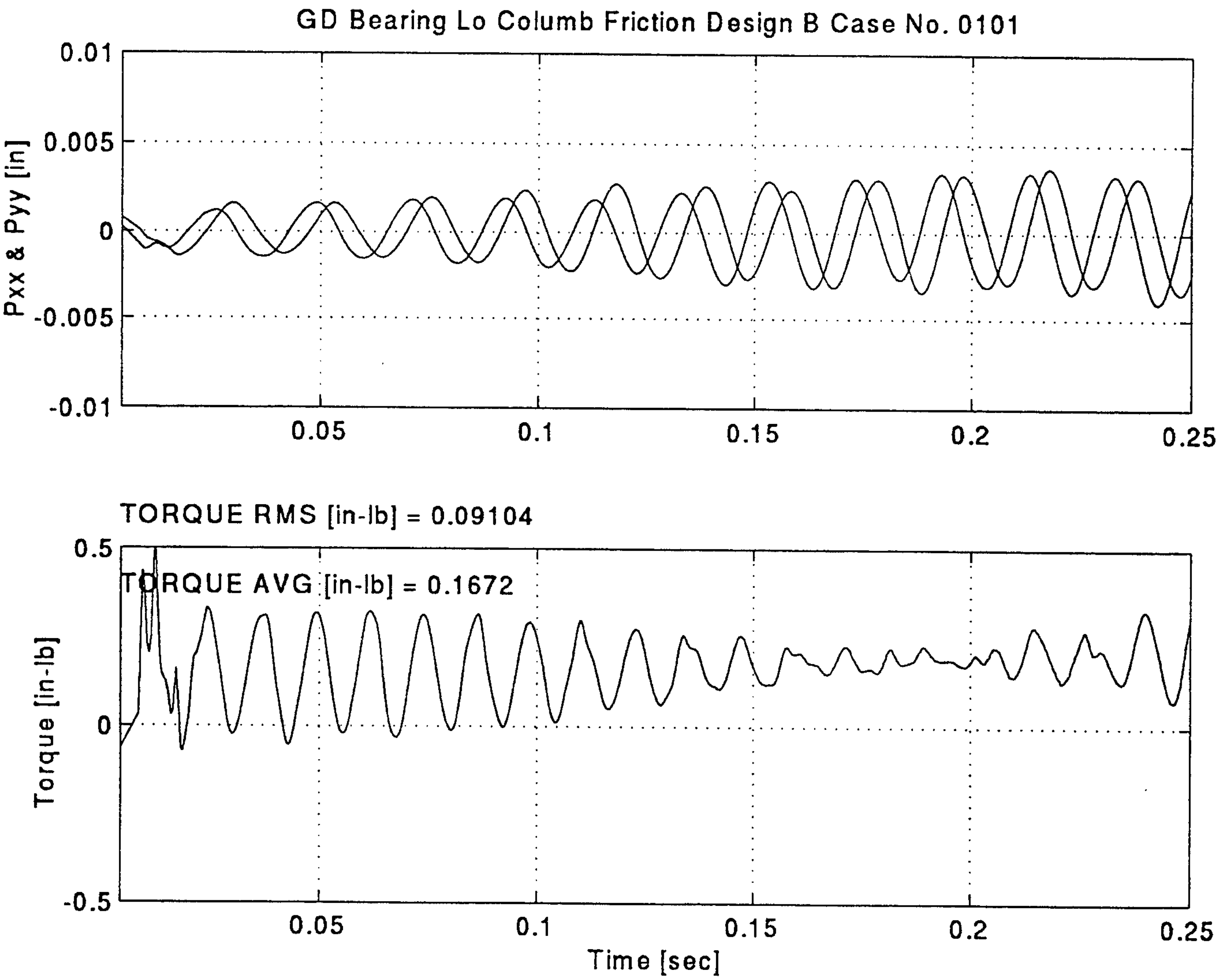

Fig 46 Design "B" Low Friction Plots, Case 0101, Torque

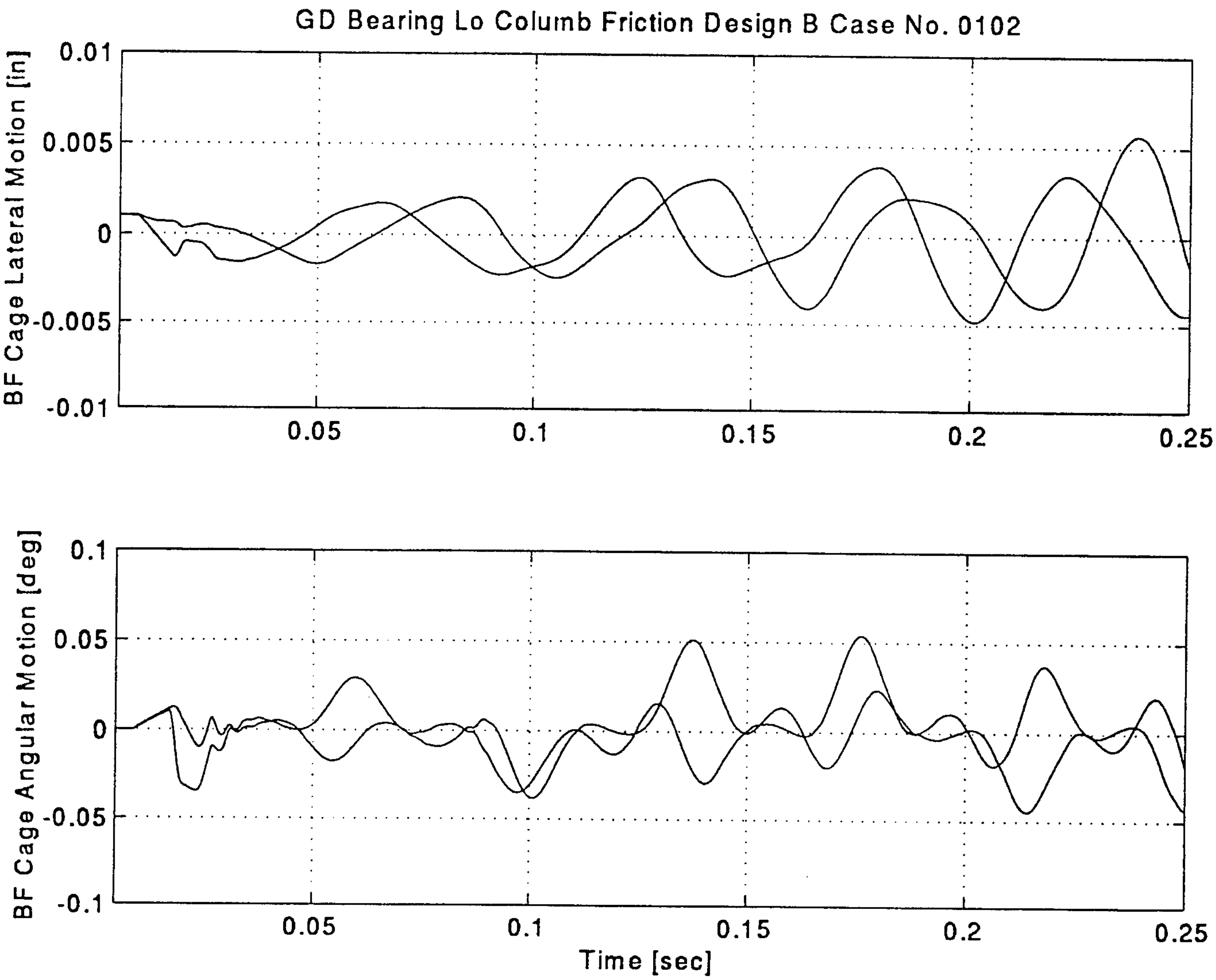

Fig 47 Design "B" Low Friction Plots, Case 0102, Motions

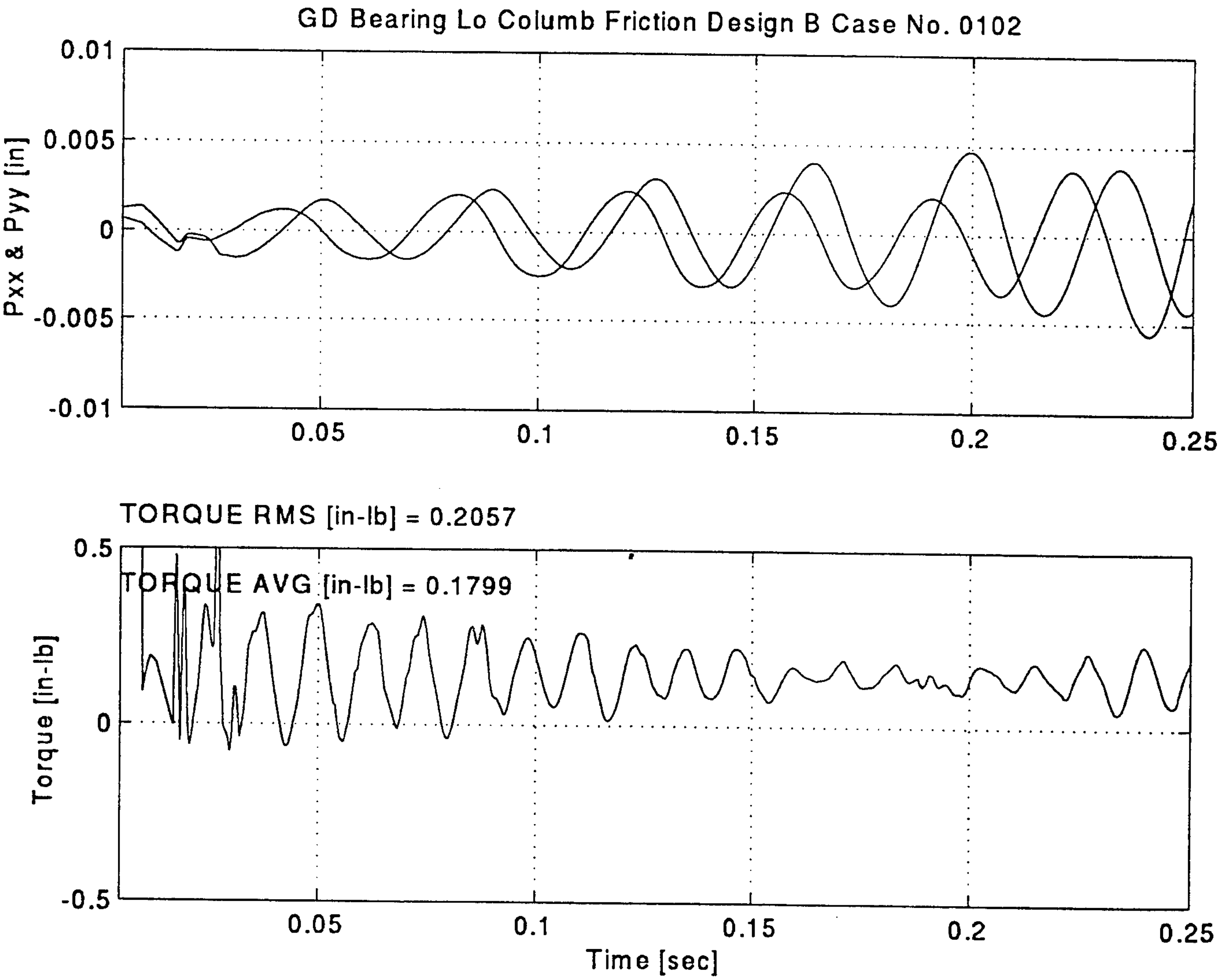

Fig 48 Design "B" Low Friction Plots, Case 0102, Torque

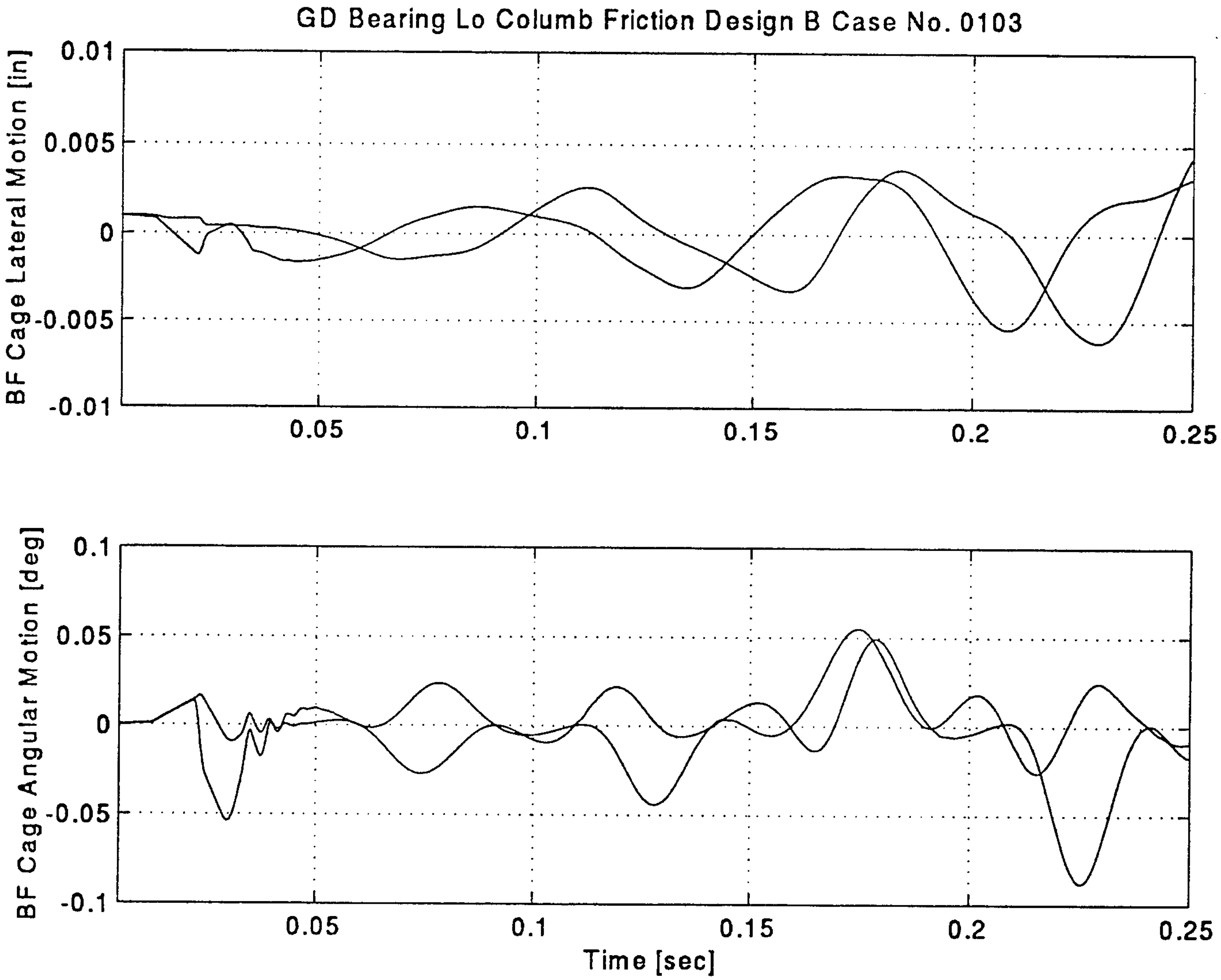

Fig 49 Design "B" Low Friction Plots, Case 0103, Motions

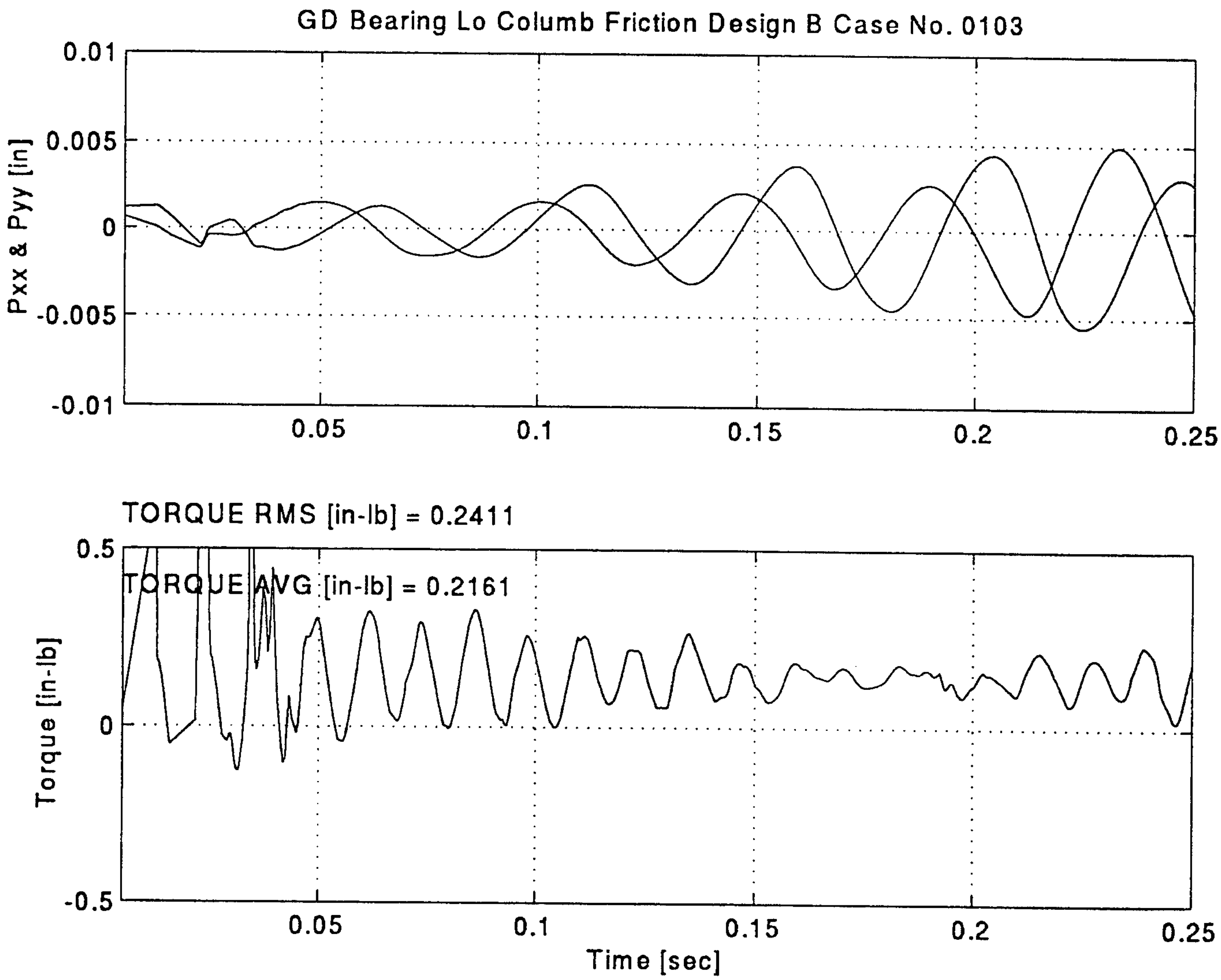

Fig 50 Design "B" Low Friction Plots, Case 0103, Torque

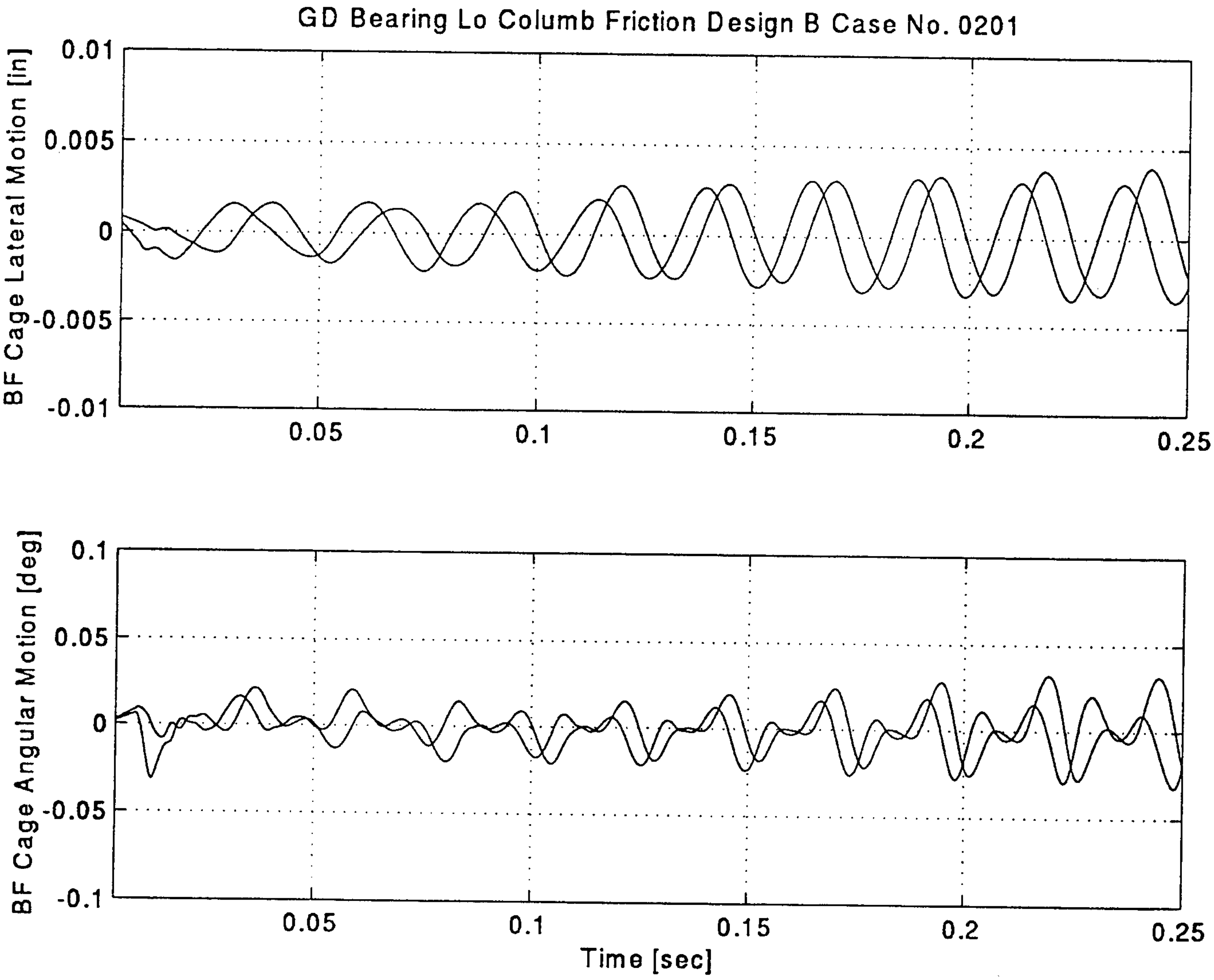

Fig 51 Design "B" Low Friction Plots, Case 0201, Motions

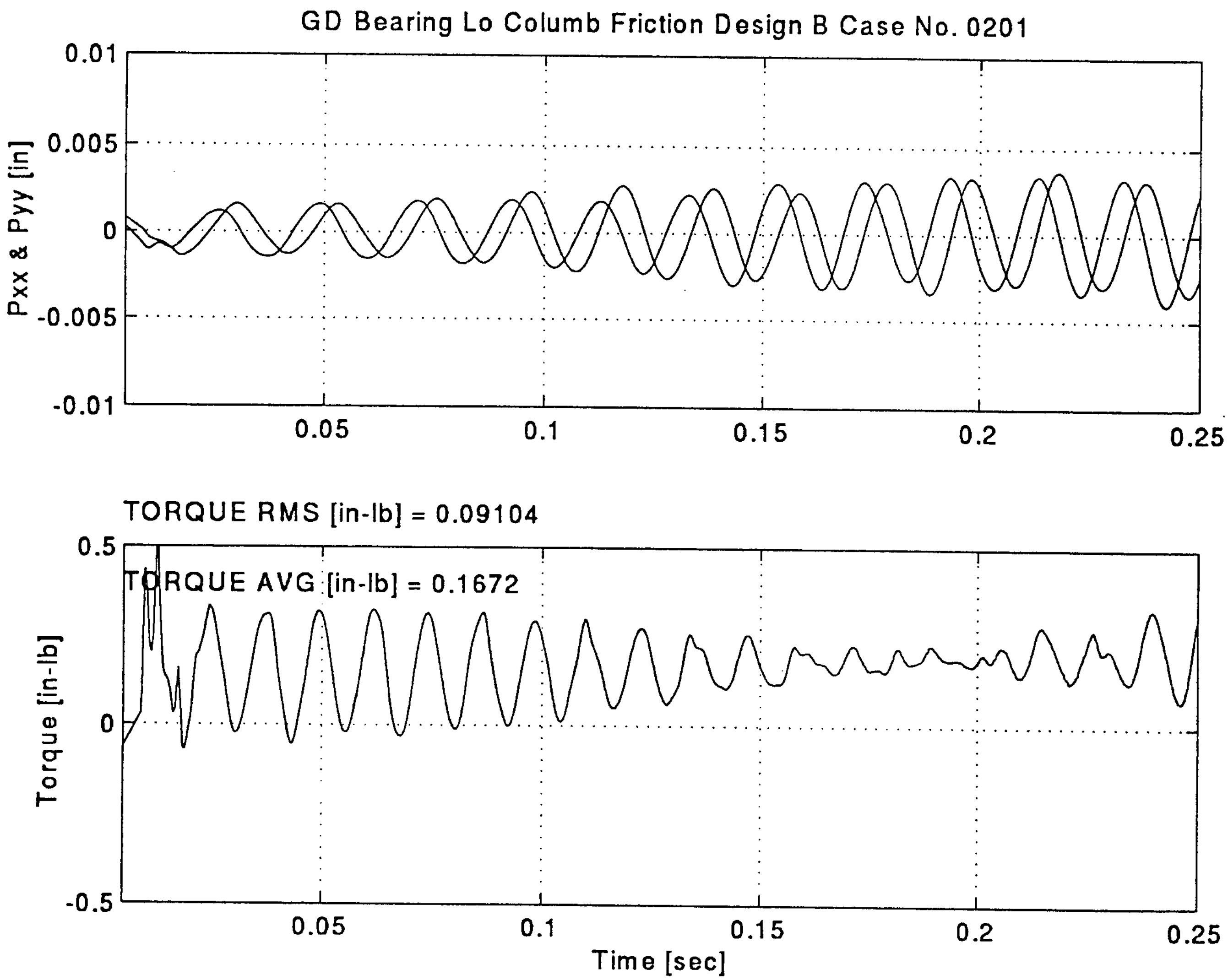

Fig 52 Design "B" Low Friction Plots, Case 0201, Torque

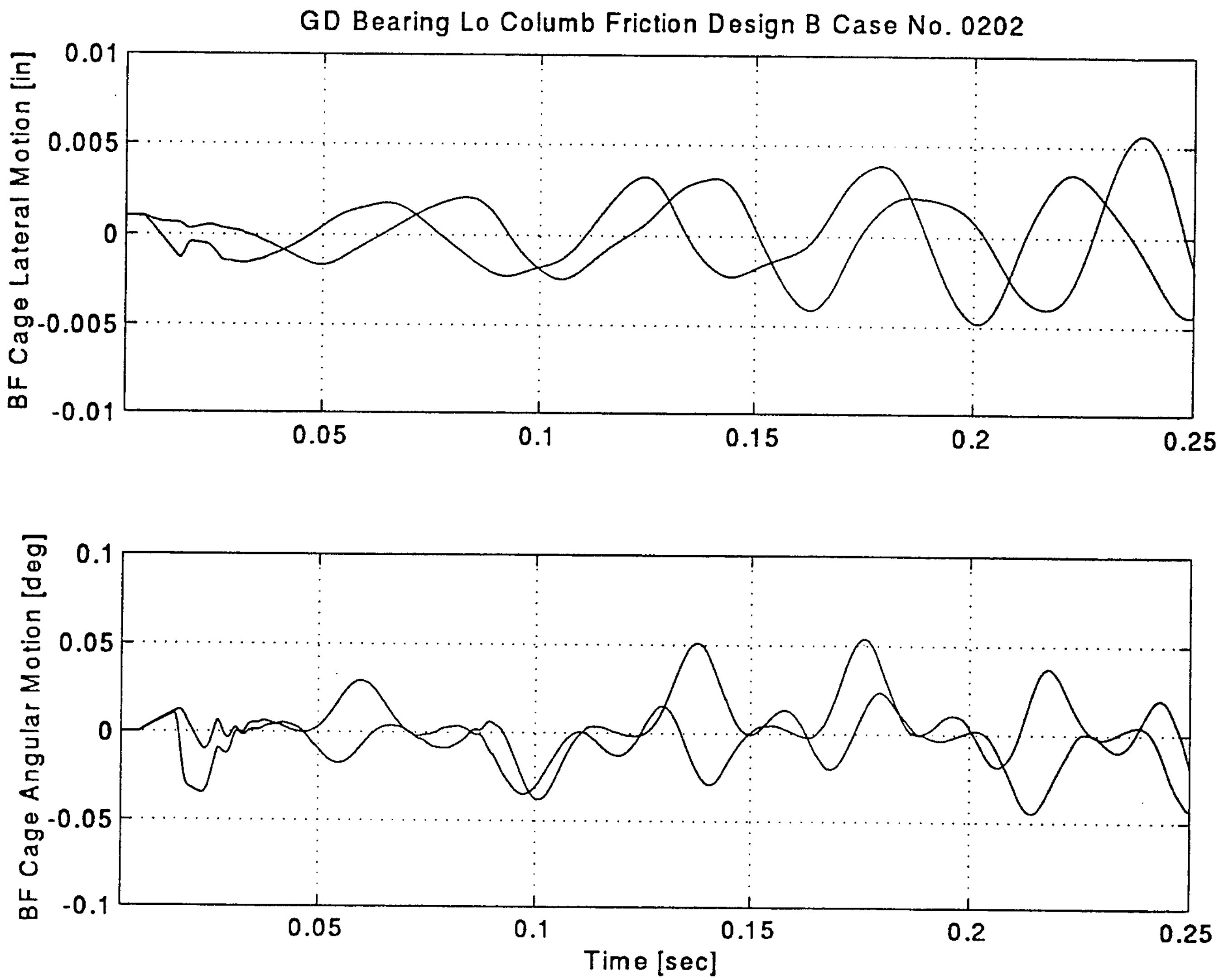

Fig 53 Design "B" Low Friction Plots, Case 0202, Motions

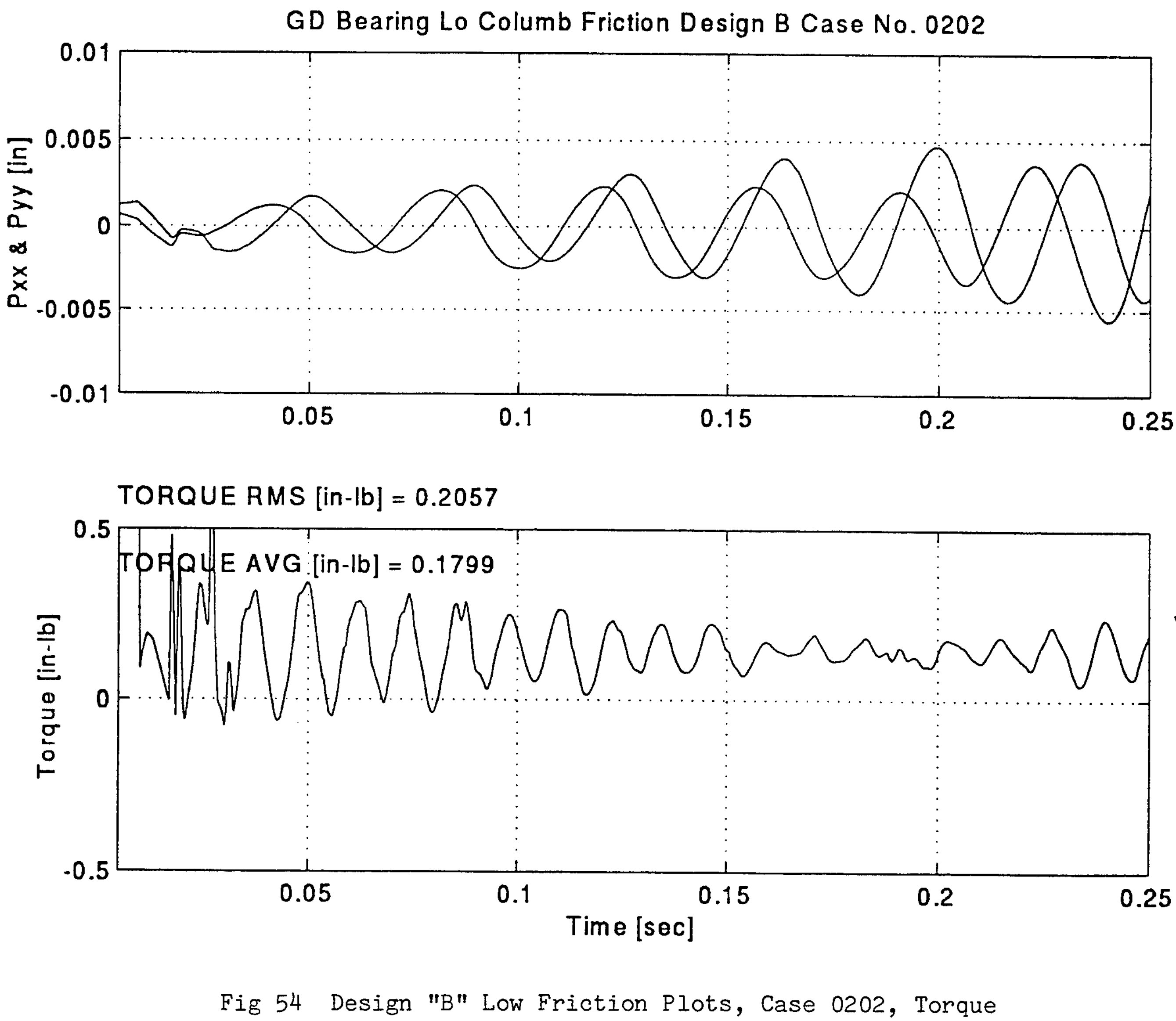

Fig 54 Design "B" Low Friction Plots, Case 0202, Torque

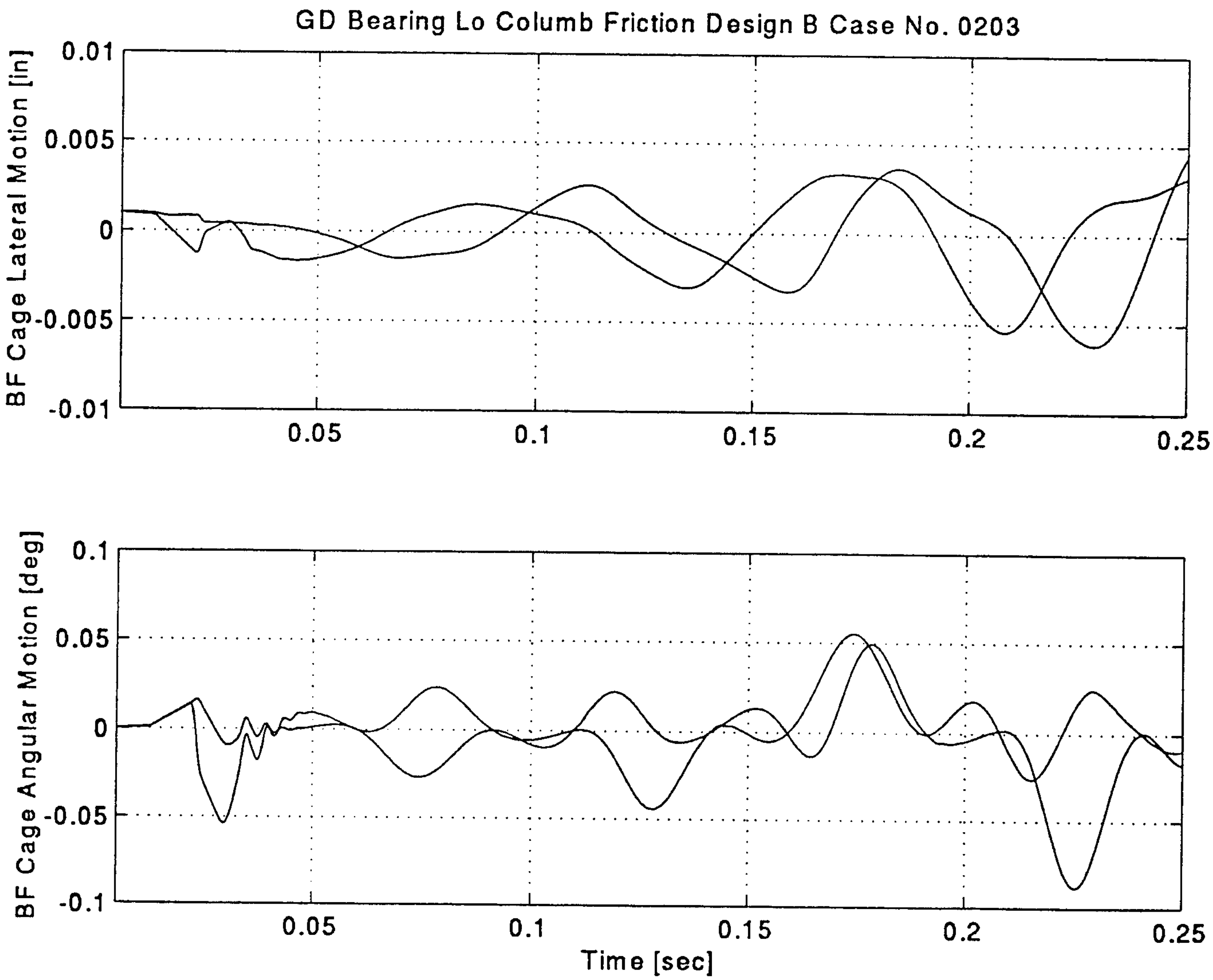

Fig 55 Design "B" Low Friction Plots, Case 0203, Motions

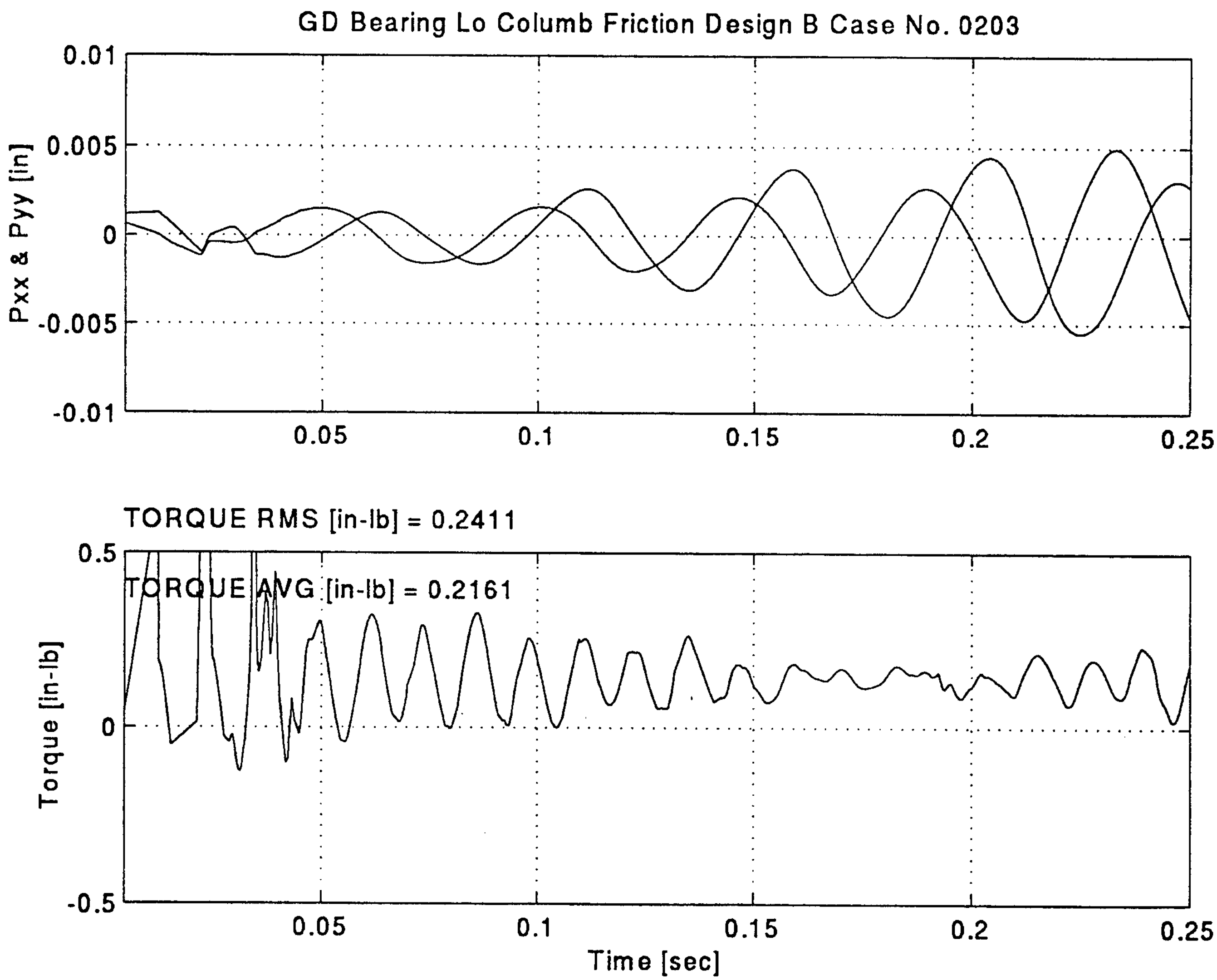

Fig 56 Design "B" Low Friction Plots, Case 0203, Torque

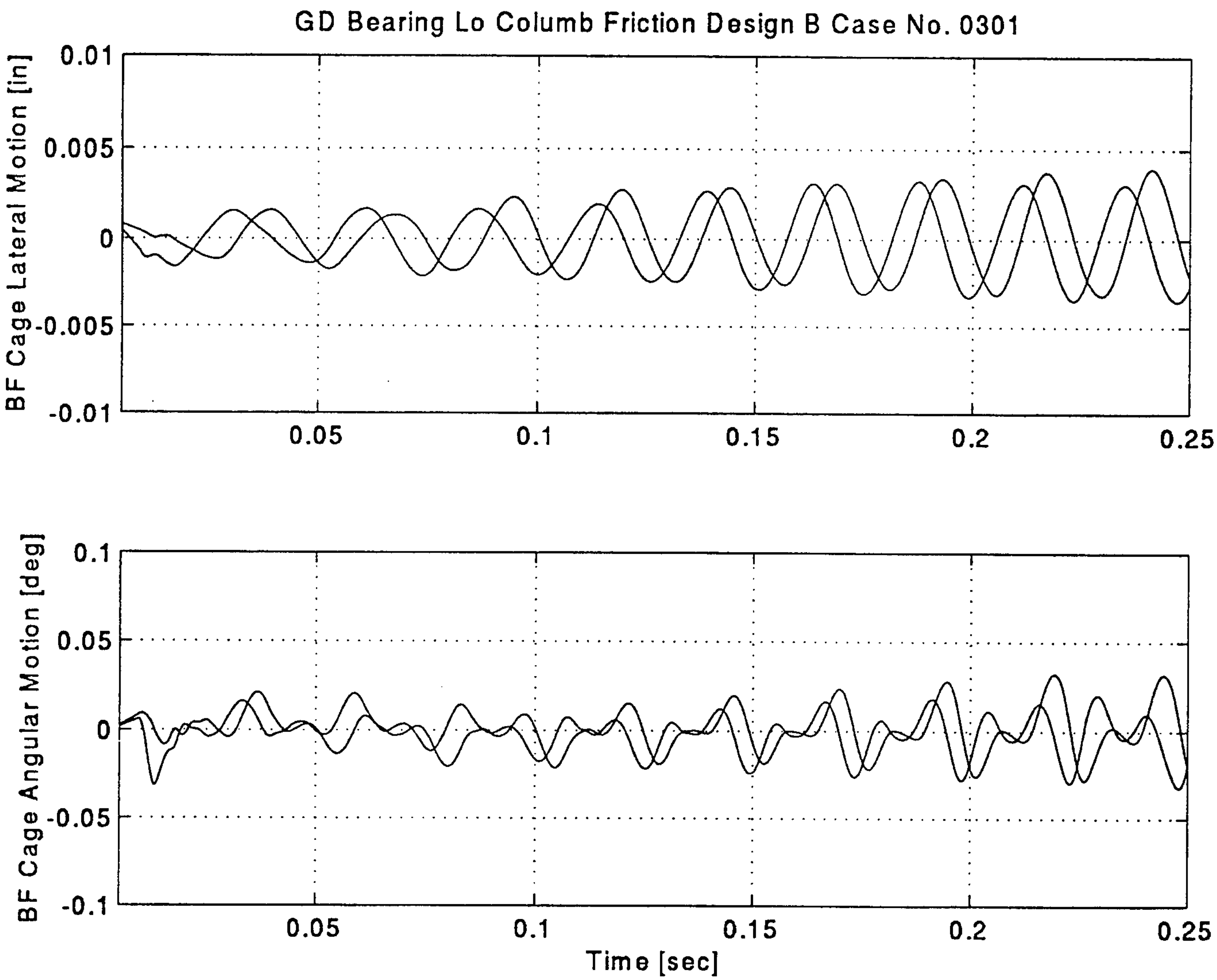

Fig 57 Design "B" Low Friction Plots, Case 0301, Motions

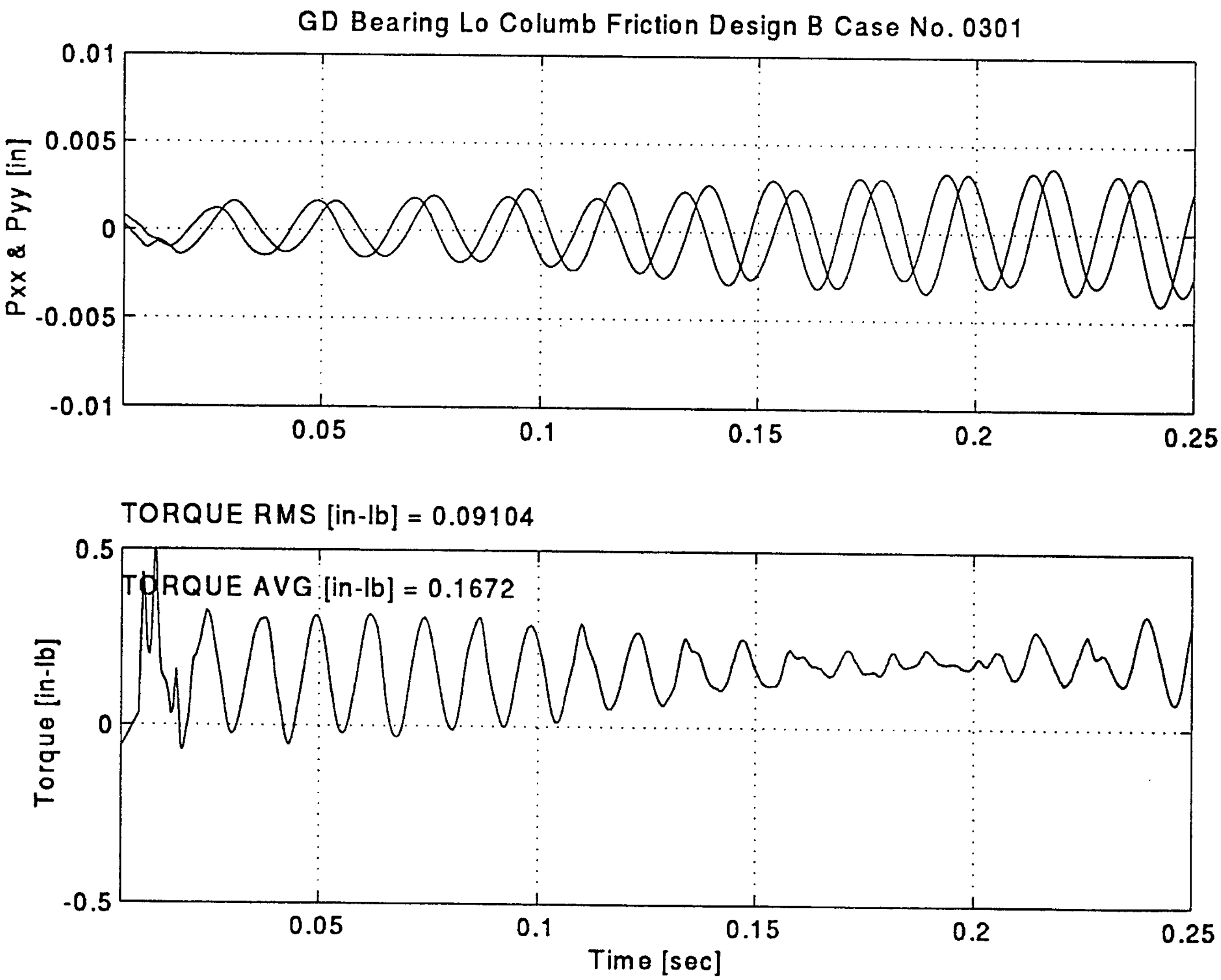

Fig 58 Design "B" Low Friction Plots, Case 0301, Torque

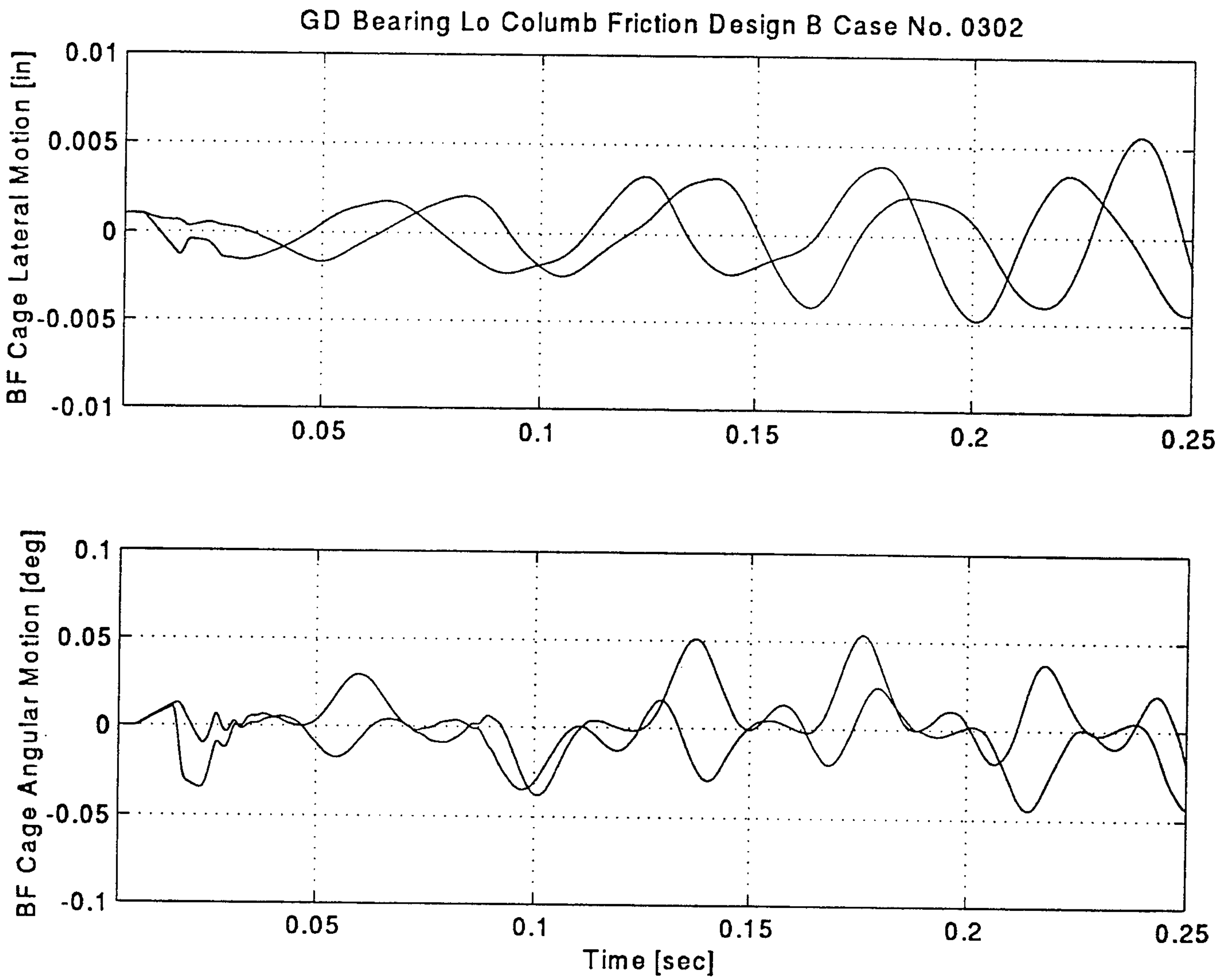

Fig 59 Design "B" Low Friction Plots, Case 0302, Motions

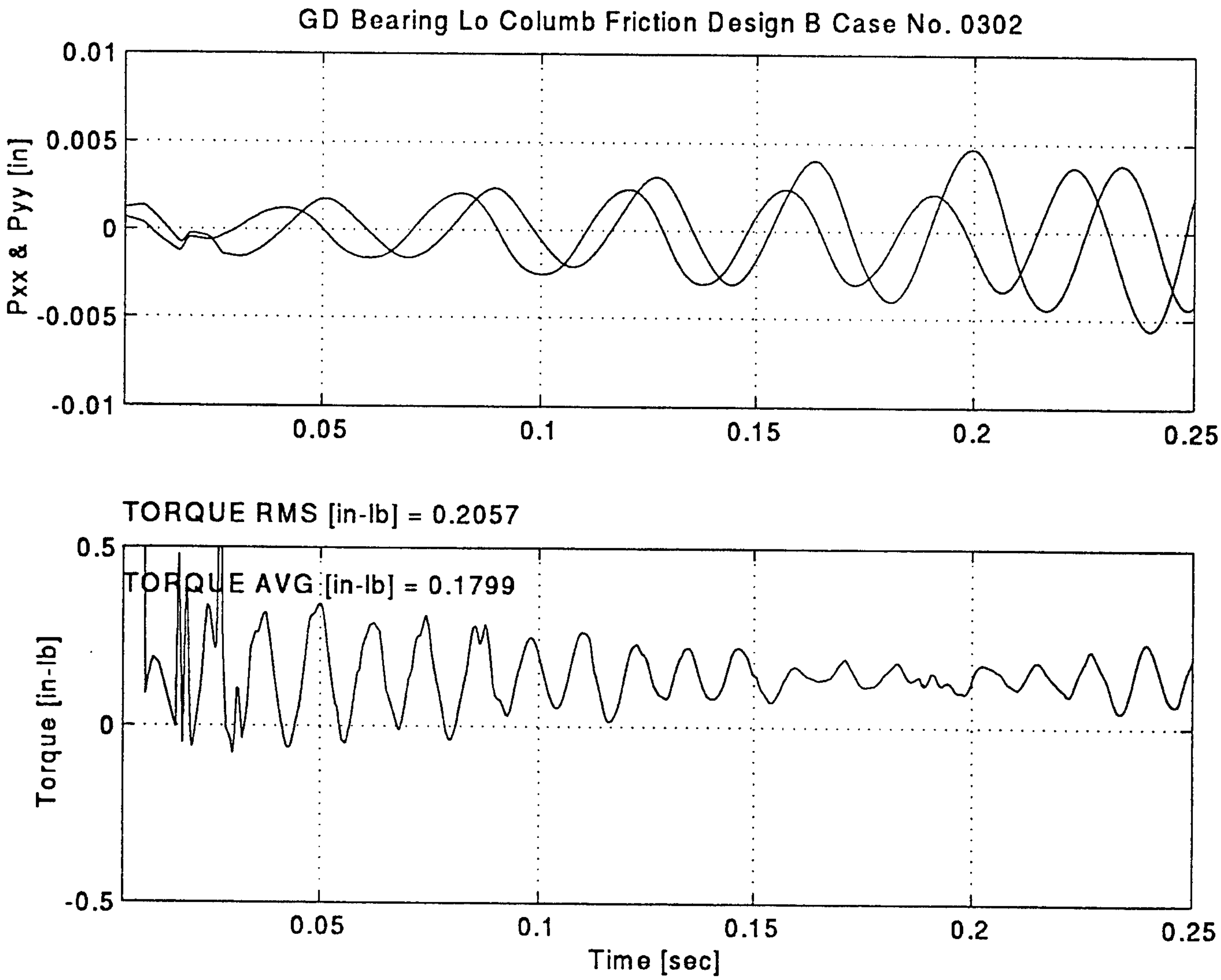

Fig 60 Design "B" Low Friction Plots, Case 0302, Torque

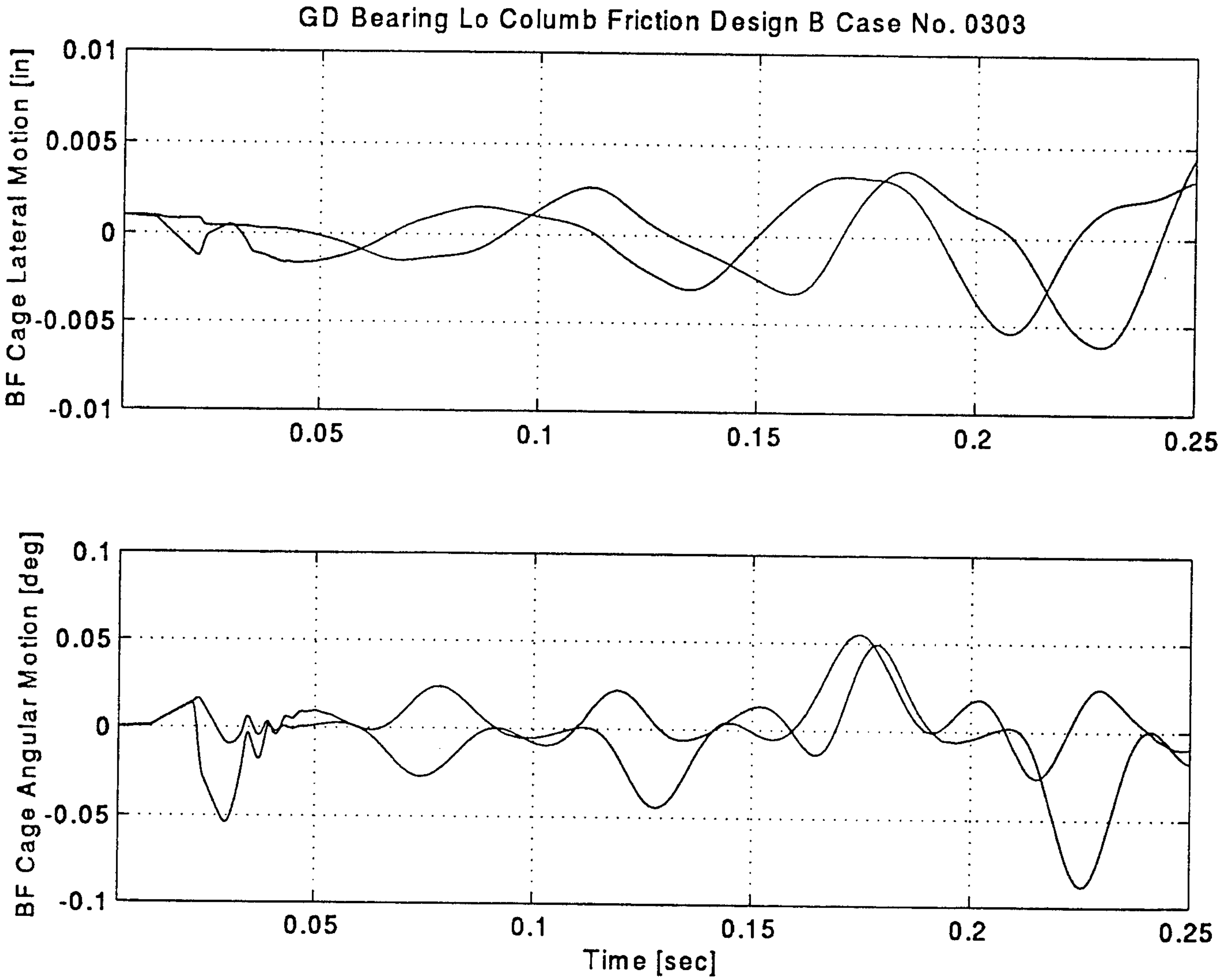

Fig 61 Design "B" Low Friction Plots, Case 0303, Motions

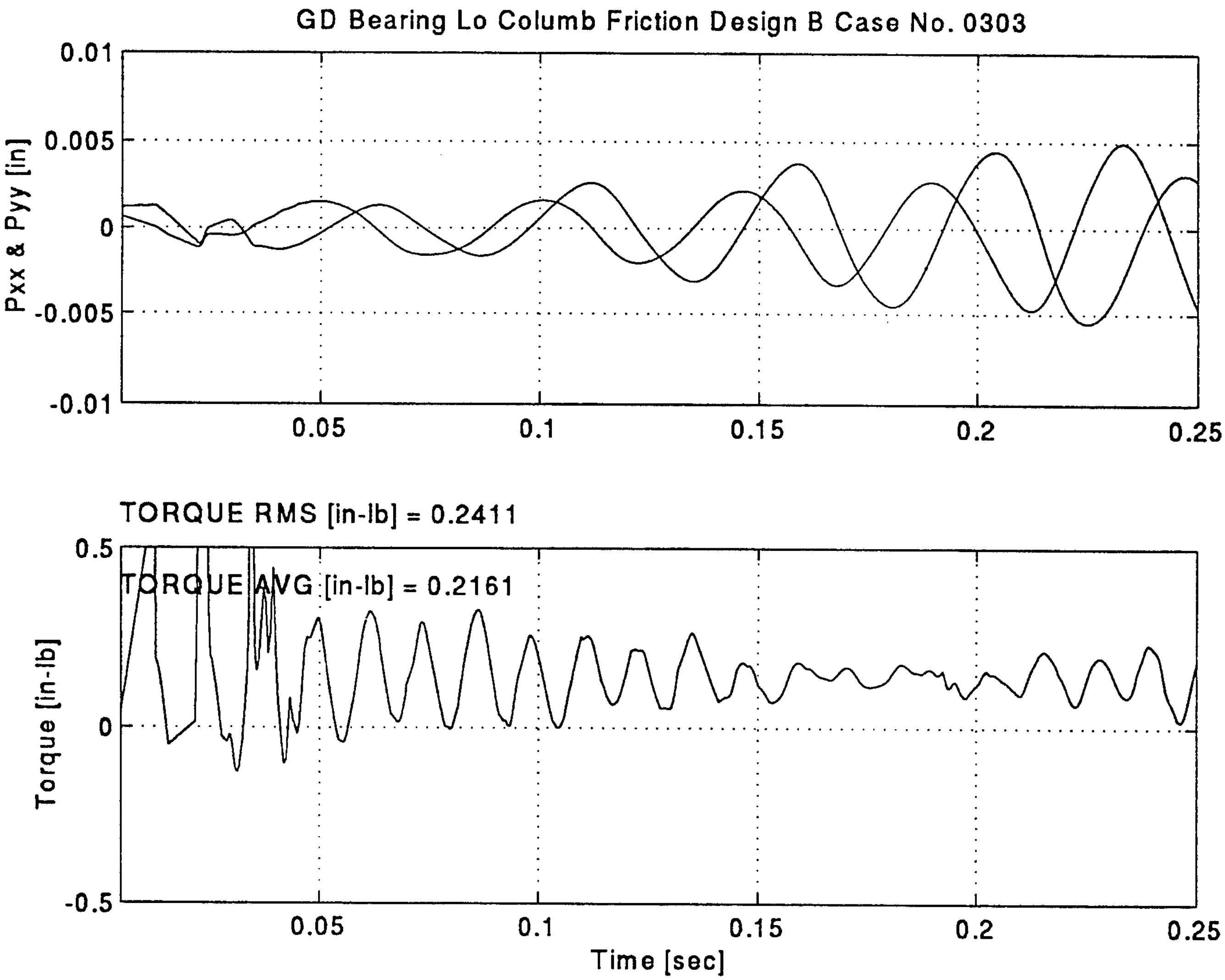

Fig 62 Design "B" Low Friction Plots, Case 0303, Torque