

The Double Concave Friction Pendulum Bearing

Daniel Fenz

PhD. Candidate, Department of Civil, Structural and Environmental Engineering, University at Buffalo

Research Supervisor: Michael Constantinou, Professor

Summary

The Double Concave Friction Pendulum (DCFP) bearing is an adaptation of the well-known single concave Friction Pendulum bearing. The principal benefit of the DCFP bearing is its capacity to accommodate substantially larger displacements compared to a traditional FP bearing of identical plan dimensions. Moreover, by using concave surfaces having different radii of curvature and coefficients of friction, there is greater flexibility in design to optimize performance. This paper describes the principles of operation of the bearing and presents sample results of characterization testing.

Introduction

The Double Concave Friction Pendulum (DCFP) bearing consists of two facing concave stainless steel surfaces. The concept of a double concave bearing represents the first documented proposal for a seismic isolation system. The 1870 US patent of Jules Touaillon (1870) describes a double concave rolling ball bearing. It took nearly 130 years since then to practically implement a double concave isolation system. Hyakuda et al. (2001) presented the description and observed response of a seismically isolated building in Japan which utilized DCFP bearings with sliding surfaces having equal radii of curvature and coefficients of friction. Tsai et al. (2005) described a DCFP bearing and presented experimental and analytical results on the behavior of the bearing under conditions of concave surfaces of equal radii and equal coefficients of friction at the top and bottom sliding surfaces. This paper presents a more generalized form of the lateral force-displacement relationship that accounts for (a) the possibility of the upper and lower concave surfaces having different radii of curvature, (b) the possibility of the upper and lower concave surfaces having different coefficients of friction and (c) the effect of the height of the articulated slider on the lateral force-displacement relationship.

Principles of Operation

Figure 1 shows cross sections of the DCFP bearing at various stages of lateral movement: (a) zero displacement, (b) displaced with sliding occurring only on the bottom surface and (c) at maximum displacement. In Figure 1(a), the upper and lower concave surfaces have radii of curvature R_1 and R_2 , respectively and coefficients of friction μ_1 and μ_2 respectively. The radii of curvature and coefficients of friction on the upper and lower surfaces may be different. An articulated slider separates the two surfaces. The articulation is necessary for proper distribution of pressure on the sliding surfaces and to allow for differential rotation.

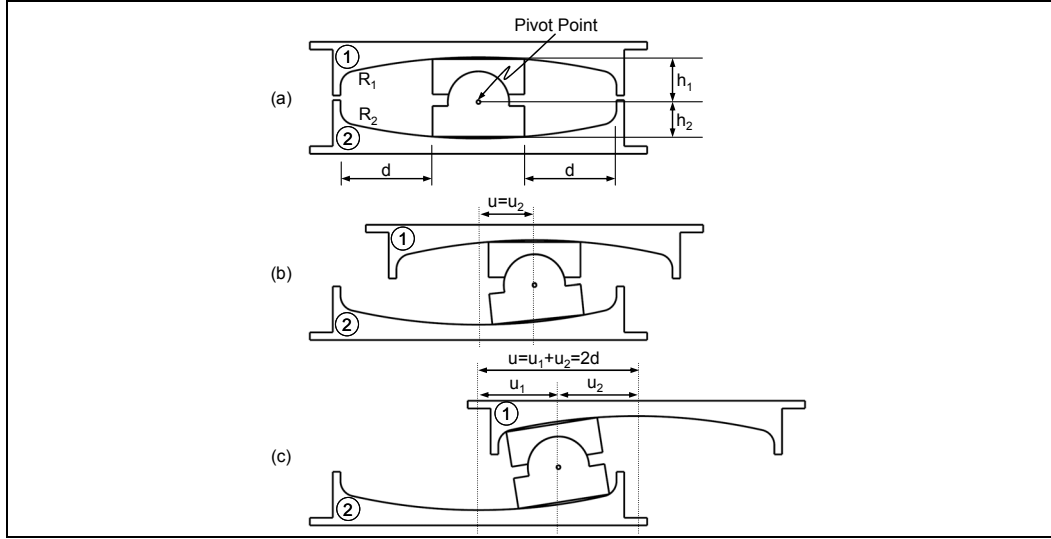


Figure 1. Cross section of DCFP bearing at various stages of lateral movement

In Figure 1(b), the bearing is shown with sliding occurring only on the lower concave surface. This is possible when the coefficient of friction on the lower concave surface is less than that on the upper surface ($\mu_2 < \mu_1$). When friction differs on the upper and lower concave surfaces, sliding initiates on the surface of least friction and is followed by sliding on both surfaces, regardless of the radii of curvature or values of the coefficient of friction on the two surfaces. This condition of sliding on only one surface occurs upon initiation or reversal of motion and is typically of small displacement amplitude.

In Figure 1(c), it is shown that the maximum displacement capacity of the DCFP bearing is $2d$, where d is the maximum displacement capacity of a single concave surface. Since sliding is possible on both concave surfaces, the displacement capacity of the DCFP bearing is substantially larger than that of a traditional Friction Pendulum bearing with identical plan dimensions.

When sliding is occurring on both surfaces, the restoring force, F_r , is given by

$$F_r = \frac{W}{R_1 + R_2 - h_1 - h_2} u \quad (1)$$

Where W is the vertical compressive load on the bearing, h_1 and h_2 are the part heights of the articulated slider and u is the total displacement of the bearing (top plate with respect to bottom plate). The friction force F_f is given by

$$F_f = \frac{\mu_1(R_1 - h_1)W + \mu_2(R_2 - h_2)W}{R_1 + R_2 - h_1 - h_2} \quad (2)$$

In most applications of DCFP bearing, the radii of the upper and lower concave surfaces will be equal, that is $R_1 - h_1 \approx R_2 - h_2$. In this case, the bearing behaves as the standard Friction Pendulum bearing with an effective coefficient of friction equal to the average of μ_1 and μ_2 .

Characterization Testing

Characterization testing of a DCFP bearing was performed to confirm the theoretical predictions of behavior. Testing was performed at the University at Buffalo using the small bearing testing machine pictured in Figure 2. The machine consists of one horizontal actuator and two vertical actuators and is capable of testing bearings under controlled conditions of vertical load, lateral movement and rotational movement. Reaction forces (vertical and lateral) are measured by a load cell mounted directly beneath the bearing and lateral displacement is measured by an internally mounted LVDT on the horizontal actuator. In addition, a string pot type displacement transducer was attached to the articulated slider to allow for direct measurement of the displacement on the bottom concave surface. Therefore, the overall motion could be decomposed into the two components on the upper and lower concave surfaces.

The tested bearing had two identical concave plates having radius of curvature of 474 mm and an articulated slider with a diameter of 76 mm and a height of 68 mm. The diameter of each concave surface was 229 mm, yielding an overall displacement capacity of approximately 150 mm. A drawing of the tested bearing is shown in Figure 3. The bearing was tested under a vertical compressive load of 60 kN. A sinusoidal lateral displacement history having amplitude of 100 mm and frequency of 0.10 Hz was imposed. The results presented in this paper are for the case of different friction on the upper and lower concave surfaces. To achieve this large difference in the coefficient of friction, a silicone based lubricant was applied to the bottom face of the articulated slider.



Figure 2. Small bearing testing machine

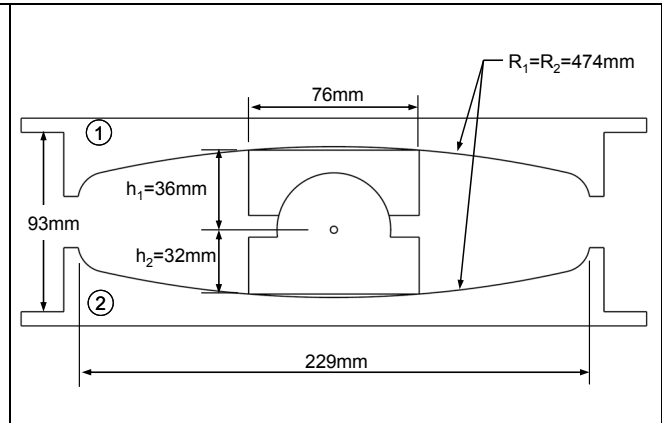


Figure 3. Dimensions of tested bearing

Results of testing are presented in Figures 4 through 6. Figure 4 shows a photograph of the bearing at maximum displacement. Figure 5 shows a comparison of normalized lateral force-displacement loops recorded during testing to the behavior predicted by equations (1) and (2). Figure 6 shows histories of bearing displacement and velocity. When friction on the two concave surfaces is different, the bearing's behavior is rigid bilinear. Upon initiation or reversal of motion, sliding occurs only on the surface of least friction. This is demonstrated by the periods of zero velocity on the upper concave surface shown in Figure 6. Accordingly, the stiffness during this period is related only to the radius of the surface upon which sliding is occurring. When sliding occurs on both surfaces, the stiffness is related to the radii of both surfaces as predicted by equation (1).



Figure 4. Photograph of the bearing at maximum displacement

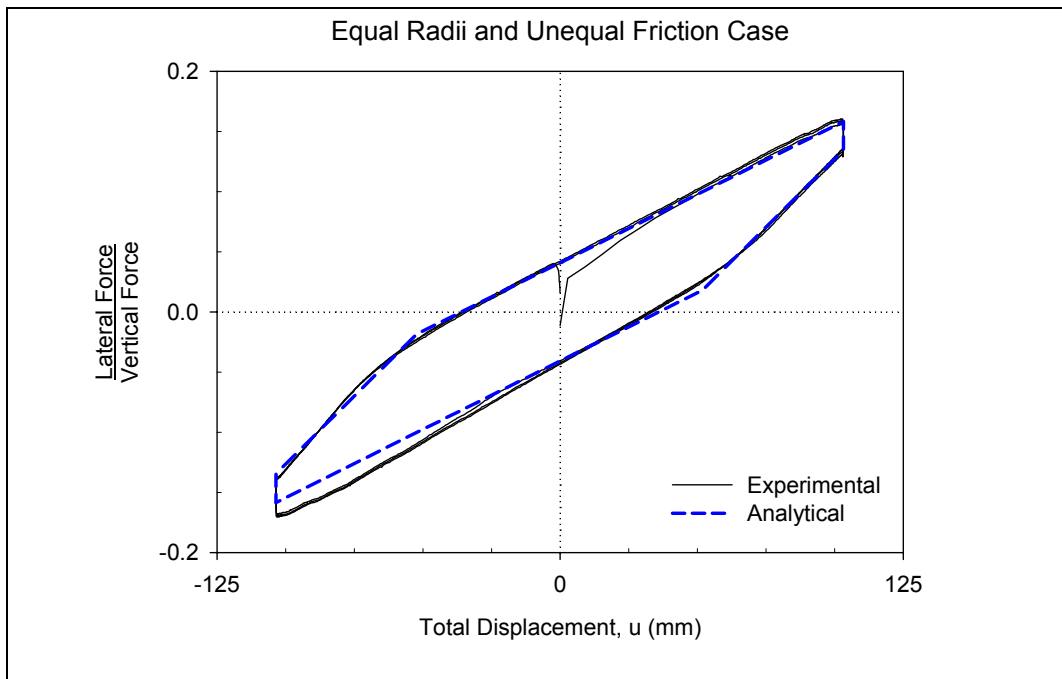


Figure 5. Normalized lateral force-displacement relationship for tested bearing

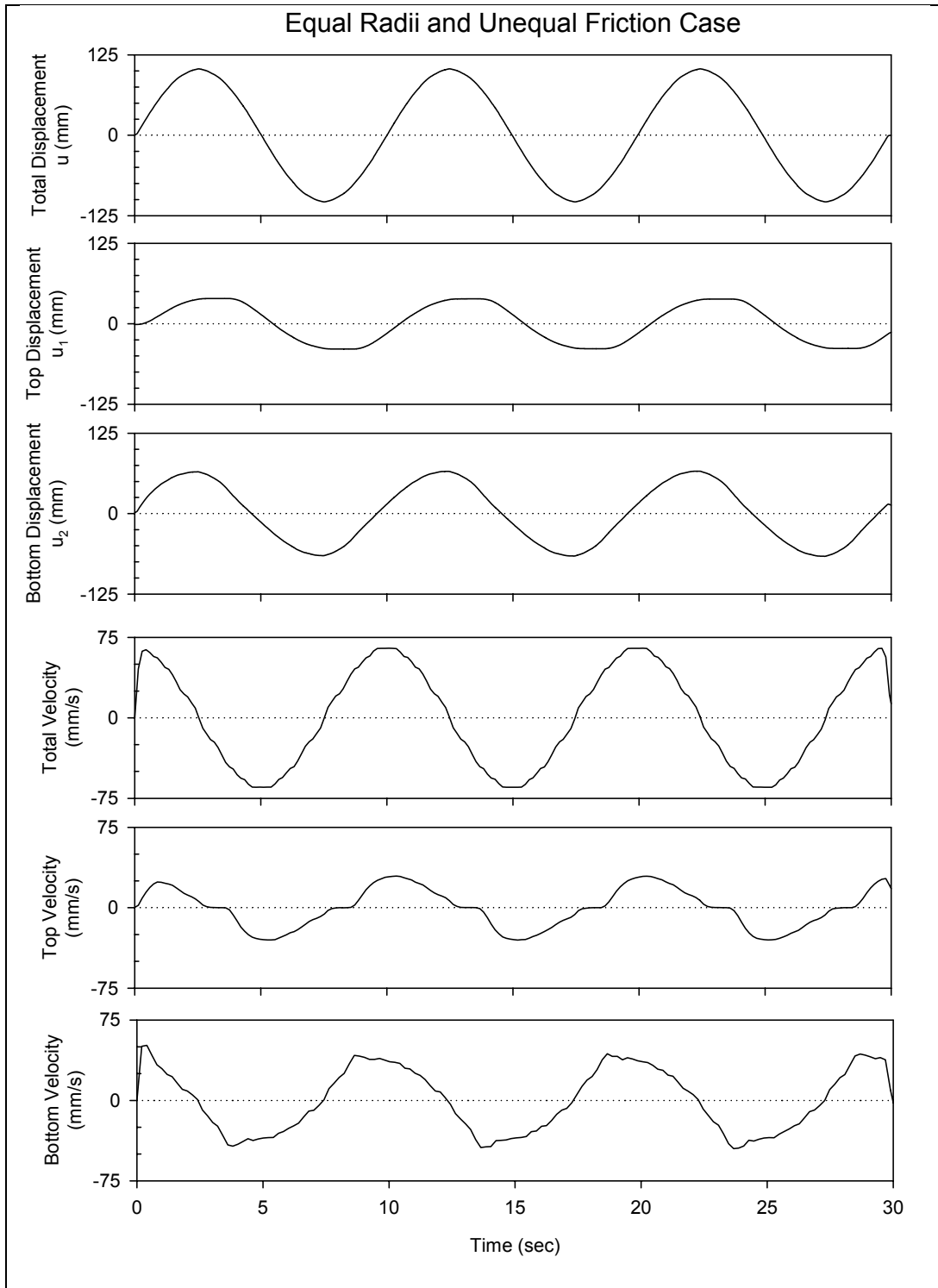


Figure 6. Histories of displacement and velocity demonstrating sliding temporarily occurring only on lower concave surface (i.e. zero velocity on top surface) upon reversal of motion

Concluding Remarks

Since sliding can occur on both the upper and lower concave surfaces, the Double Concave Friction Pendulum bearing has a displacement capacity that is substantially larger than a traditional Friction Pendulum bearing of identical plan dimensions. This key feature of the behavior results in significant savings in terms of the material cost of isolators. This may also lead to seismic isolation being a viable option in applications where very large displacement demands would have precluded its use in the past.

Moreover, there is the possibility of using upper and lower concave surfaces having different radii of curvature and coefficients of friction. There are four parameters that can be varied (R_1 , R_2 , μ_1 and μ_2) rather than just two (R and μ) as with the traditional Friction Pendulum bearing, thereby offering more options to optimize performance. These possibilities can be exploited to improve performance of nonstructural components or to improve performance for near source excitations. The author will examine these issues with a parametric study and shake table testing in future work.

Acknowledgements

This research was carried out under the supervision of Dr. Michael Constantinou, and primarily supported by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award number EEC-9701471 to the Multidisciplinary Center for Earthquake Engineering Research. In addition, the author wishes to thank Earthquake Protection Systems Inc. for providing the tested bearing.

References

- Fenz DM and Constantinou MC (2005): Behavior of the double concave Friction Pendulum bearing. Submitted for review and possible publication in *Earthquake Engineering and Structural Dynamics*.
- Hyakuda T, Saito K, Matsushita T, Tanaka N, Yoneki S, Yasuda M, Miyazaki M, Suzuki A, Sawada T (2001): The structural design and earthquake observation of a seismic isolation building using Friction Pendulum system. *Proceedings, 7th International Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures*, Assisi, Italy.
- Touaillon J (1870): *Improvement in Buildings*. United States Patent Office, Letters Patent No. 99,973, February 15.
- Tsai CS, Chiang TC, Chen BJ (2005): Experimental evaluation of piecewise exact solution for predicting seismic responses of spherical sliding type isolated structures. *Earthquake Engineering and Structural Dynamics*, **34**(9),1027-1046.