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8 Erdman, A. G., Imam, Imdad, and Sandor, G. N., "Applied Kineto-Elastodynamics," *Proceedings of the 2nd OSU Applied Mechanism Conference*, Stillwater, Okla., Paper No. 21, Oct. 1971.

9 Sadler, J. P., and Sandor, G. N., "Kineto-Elastodynamic Harmonic Analysis of Four-Bar Path Generating Mechanisms," *Proceedings of the 11th ASME Conference on Mechanisms*, Columbus, Ohio, ASME Paper No. 70-Mech-61.

10 Sadler, J. P., and Sandor, G. N., "A Lumped Parameter Approach to Vibration and Stress Analysis of Elastic Linkages," 12th ASME Mechanisms Conference, San Francisco, Calif., ASME Paper No. 72-Mech-44.

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12 Winfrey, R. C., Anderson, R. V., and Gnilka, C. W., "Analysis of Elastic Machinery With Clearances," 12th ASME Mechanisms Conference, San Francisco, Calif., ASME Paper No. 72-Mech-37.

13 Dubowsky, S., and Freudenstein, F., "Dynamic Analysis of Mechanical Systems With Clearances, Part 1: Formation of Dynamic Model," *JOURNAL OF ENGINEERING FOR INDUSTRY, TRANS. ASME, Series B, Vol. 93, No. 1, Feb. 1971, pp. 305-309.*

14 Dubowsky, S., and Freudenstein, F., "Dynamic Analysis of Mechanical Systems With Clearances, Part 2: Dynamic Response," *JOURNAL OF ENGINEERING FOR INDUSTRY, TRANS. ASME, Series B, Vol. 93, No. 11, Feb. 1971, pp. 310-316.*

DISCUSSION

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The authors are to be commended for their comprehensive display of experimental results for verifying the validity of the analysis results obtained by the finite-difference method³ and by finite beam element approach for the study of dynamic response of an elastic mechanism.

In 1970, a similar experiment involving a spatial slider-crank mechanism was conducted at Ohio University. The mechanism model and experimental setup appeared in the paper by Armentrout and Chen.⁴ The coupler was connected to the crank by a ball-and-socket joint. The model was constructed in such a manner that the length of the crank could be adjusted to give a variety of combinations of coupler-to-crank link length ratio. The input crank was driven by a 1/8-hp electric motor through a friction drive. An 8-in.-dia flywheel was mounted on the crankshaft to minimize the speed fluctuation.

Both strain gages and accelerometers were mounted at a number of points in each of the three componential directions along the coupler link for the measurements of strains and accelerations at those points.

The accelerometer (Endevco, Model 2242) was mounted at the point of interest on the coupler in the direction of which we wanted to measure its component of acceleration. The output of the accelerometer was then fed into an impedance matching amplifier (Kistler, Model PT-14), and the signals from the amplifier were recorded on an oscillograph. The accelerometer-amplifier network

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³ Sadler, J. P., "On the Analytical Lumped Mass Model of an Elastic Four-Bar Mechanism," *JOURNAL OF ENGINEERING FOR INDUSTRY, TRANS. ASME, Series B, Vol. 97, No. 2, May 1975, pp. 561-565.*

⁴ Armentrout, T. B., and Chen, F. Y., "Dynamic Response of a Harmonic Spatial Slider-Crank Mechanism," *Communications of Third Congress, IF-ToMM, 1971, Vol. F, pp. 1-35.*

had been properly calibrated before the recordings were taken. The recorded results (not shown here) showed many overtones. These overtones in the recordings perhaps could be traced to the cause of joint clearances of the imperfect model construction as well as the lack of rigidity of the bench support upon which the test model was mounted. The discussor must realize that spatial mechanisms are generally more difficult than planar mechanisms insofar as the tolerance control in model construction and measurements is concerned. The discussor also feels that strain gage measurement may not be the best way because there are many wire connections to the strain gages which dance around with the moving mechanism. This would cause dubious accuracy in the bending strain measurements. It seems desirable that, in the future, other possible experimental means such as optical technique be explored.

Earlier work on measurement of vibrations of a four-bar flexible linkage has been reported by Gayfer and Mills.⁵ Their experiment was based on instantaneous mechanism configuration approach and their data were checked by the method of receptances.

⁵ Gayfer, J. R., and Mills, B., "Small-Amplitude Vibrations of the Four-Bar Linkage Chain," *Journal of Mechanical Engineering Ser., Vol. 7, No. 3, 1965, pp. 252-258.*

Authors' Closure

The authors wish to thank Professor Chen for his comments and kind remarks. The experiments with a three-dimensional mechanism which he describes are very interesting and should prove useful in the analysis of the effects of flexibility on the dynamic performance of elastic mechanisms.

In our experimental apparatus, the strain gage wires were taped to the links at selected points to minimize the influence of wire movement on strain measurement. The resulting unavoidable noise due to wire movement was judged to be only a fraction of a percent of the link bending strains.

We agree that optical methods provide an ideal means of displacement measurement without adding mass or stiffening to the mechanism being studied. A demonstration of this has been given by Professor Erdman, et al.⁶ It should be noted, however, that if the primary concern of the investigation is related to the fatigue of the device, direct strain measurement is probably preferred to the determination of the state of strain from displacement or acceleration data.

Finally, the authors are aware of the previous work of Gayfer and Mills,⁷ but would point out that this work is concerned with the determination of the vibration characteristics of a pinned structure as it assumes various positions in the cycle of a four-bar mechanism. That is, measurements were made while the input crank was either cantilevered or the excitation element. No data were taken with the input link rotating as it normally would in operation.

⁶ Erdman, A. G., et al., "Experimental Motion Analysis via a Stereo-Photography Technique: Application to the Human Jaw and Mechanical Linkages," ASME Paper No. 74-Det-58.

⁷ Gayfer, J. R., and Mills, B., "Small Amplitude Vibrations of the Four-Bar Linkage Chain," *Journal of Mechanical Engineering Science, Vol. 7, No. 3, 1965, pp. 252-258.*