Table 2 Frequencies of a two-substructure free-free beam

Elastic	$n_A = 5, n_B = 4$		$n_A = 5, n_B = 4$		Exact
mode number	MacNeal $\omega^2 \times 10^{-1}$	% error	MacNeal $\omega^2 \times 10^{-1}$	% error	$\omega^2 \times 10^{-1}$
1	0.00020855	0.00	0.00028069	34.60	0.00020854
2	0.00158753	0.02	0.00175287	10.44	0.00158720
3	0.00613810	0.14	0.00720175	17.49	0.00612967
4	0.01700570	0.55	0.02282519	34.96	0.01691298
5	0.03852031	0.69	0.04155454	8.62	0.03825621
6	0.07837021	5.52	...	...	0.07427024
7	0.39281608	x	...	...	0.15736511

Conclusions

The incorporation of residual flexibility into the formulation of a free-interface substructure coupling procedure is easily accomplished and produces a very significant improvement in the accuracy of system frequencies.

References

[1]Hurty, W. C., "Introduction to Modal Synthesis Techniques," *Synthesis of Vibrating Systems*, ASME, Nov. 1971.

[2]Benfield, W. A., Bodley, C. S., and Morosow, G., "Modal Synthesis Methods," *Symposium on Substructure Testing and Synthesis*, NASA Marshall Space Flight Center, Aug. 1972.

[3]Bamford, R. M., "A Modal Combination Program for Dynamic Analysis of Structures," Jet Propulsion Lab., Pasadena, Calif., Tech. Memo 33-290, July 1967.

[4]MacNeal, R. H., "A Hybrid Method of Component Mode Synthesis," *Journal of Computers*, Vol. 1, No. 4, Dec. 1971, pp. 581-601.

[5]Klosterman, A. L., "On the Experimental Determination and Use of Modal Representations of Dynamic Characteristics," University of Cincinnati, Ph.D. Dissertation, 1971.

[6]Rubin, S., "Improved Component-Mode Representation for Structural Dynamic Analysis," *AIAA Journal*, Vol. 13, Aug. 1975, pp. 995-1006.

Free Flight Measurements of Catastrophic Water Drop Breakup

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To verify that the definition of catastrophic water drop breakup, which is based on x-ray and shadow images of the drops in the shock tube,[1-4] corresponds to the elimination of the drops' potential for erosion in flight, we conducted a free flight drop breakup and impact experiment in the Avco Rain and Dust Erosion Facility (RADEF).[5] The RADEF is a ballistic range in which material samples are flown through rain, dust, or ice environments at speeds up to 15,000 fps, suffer multiple impact erosion, and are subsequently decelerated and recovered to measure erosion damage and crater morphology. In the verification tests a single monodisperse drop generator of the type described in Ref. 5 was used. The drop size distribution was obtained from photographs of the generated drop streams. From these photographs, we can calculate the number fraction of drops with diameter exceeding any given diameter. This curve is shown in Fig. 1.

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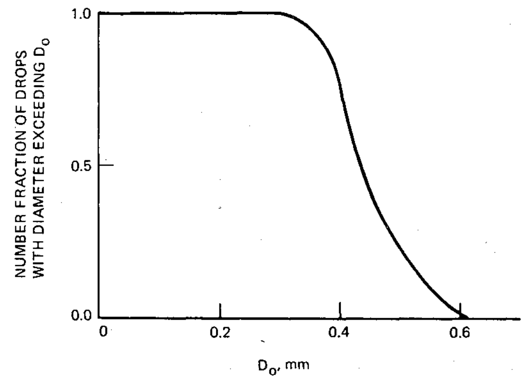

Fig. 1 Cumulative drop number fraction vs water drop diameter.

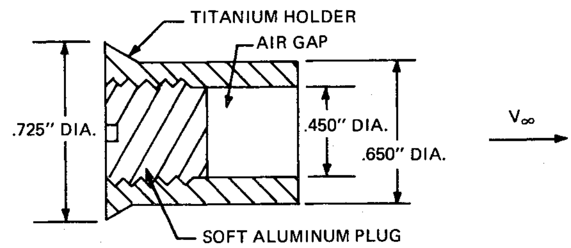

Fig. 2 Cross section of ballistic range water drop breakup and impact model.

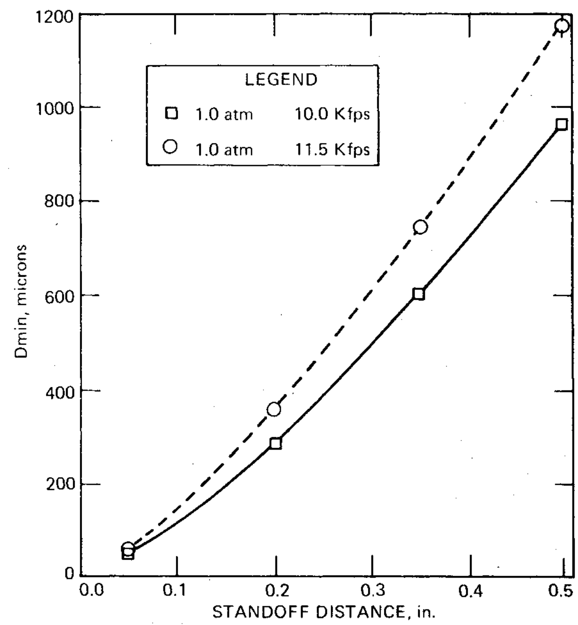

Fig. 3 Initial diameter of smallest drop reaching surface obtained from correlations of shock tube data.

Since the two stage light gas gun in the RADEF cannot launch models larger than 0.8 inches in diameter at hypervelocities, it was necessary to fire recessed models through the rain field in order to achieve effective shock standoff distances large enough to shatter drops of the size produced by the generator. At hypersonic speeds and when viewed in the frame of reference of the undisturbed drops, there is only a small variation in aerodynamic conditions between the concave model shock wave and the cavity bottom. Similarly viewed, the flow is also nearly uniform along the stagnation streamline of a hypersonic convex body with the equivalent shock standoff distance flying at the same (hypersonic) speed through the same ambient conditions. A sketch of the model used in the RADEF tests is shown in Fig. 2. The insert in the base of this model was soft aluminum and the cavity depth was varied from 0.05 in. to 0.35 in. by changing the length of the aluminum insert. Adding to this cavity depth the actual shock standoff distance of the model, which was 0.082 in. at 10,000 fps and one atm, yields an effective standoff distance that varies from 0.132 to 0.432 in. The larger value is sufficient to shatter the 0.4 to 0.5 mm drops produced by the generator, according to the catastrophic breakup criterion developed using shock tube measurements and reported as Eq. (28) of Ref. 4. The calibration of the drop generators also indicated that, in the absence of shock layer shielding, the aluminum insert in the model would encounter, on average, twelve drops during its traversal of the drop generator field.

If the generated drops were all exactly the same diameter, one would expect to see the evidence of impacts on the aluminum surface abruptly vanish at a standoff distance corresponding to the drop breakup time. However, since there was some distribution of drop diameters around the modal diameter, the expected number of impacts will decrease steeply but smoothly from twelve, the number expected in the absence of shock layer shielding, to zero, at the cavity depth corresponding to the breakup time of the largest drop in the distribution. Knowledge of the predicted minimum initial diameter drop that will survive shock layer traversal (based on the shock tube data and calculated as discussed in Ref. 4) and the drop size distribution given in Fig. 1 can be used to calculate this curve of expected number of impacts vs standoff distance. The predicted minimum initial drop diameter is plotted vs standoff distance in Fig. 3.‡ Combining these results with the distribution of drop sizes shown in Fig. 1 (and the expected number of impacts without shock layer shielding, twelve) yields the solid line in Fig. 4 of predicted number of impacts vs effective standoff distance, the distance from the bow shock to the back of the cavity in the model. Also shown, as the dashed lines, are the predictions based on the calculated uncertainty in the coefficient 35 in the breakup correlation, Eq. (28) of Ref. 4, about plus or minus 20%.

To verify the prediction, twelve test firings were made at 10,000 ±150 fps and one atm with cavity depths from 0.05 to 0.35 in. After each test the number of impacts on the recovered model was counted. Eleven and twelve craters were observed in the two tests with the shallowest cavities, a result in agreement with the photographic calibration of the drop field. On the models recovered after these tests, the craters caused by the largest drops were quite distinct, deep, and with well formed lips. The smallest craters were less distinct, indicating that the smallest drops in the distribution are already beginning to lose some of their erosive potential. As the cavity depth was increased the number of craters observed decreased and the depth and distinctness of those observed also decreased markedly. After recovering a model with a 0.200 in. cavity, and by using the wax filling technique, we determined that the volume of the three largest craters was only 20% of the volume of the three largest craters measured on the model with the shallowest (0.05 in.) cavity. Thus, although on the 0.200 in. cavity model the largest drops had not yet reached breakup by our criterion, it is clear from this comparison that they have already been much reduced in damage potential. The recovered models with a cavity depth of 0.250 in., that is, with an effective shock standoff distance of 0.332 in., showed, under microscopic examination, very shallow craters, each of which appeared to be formed by a cluster of

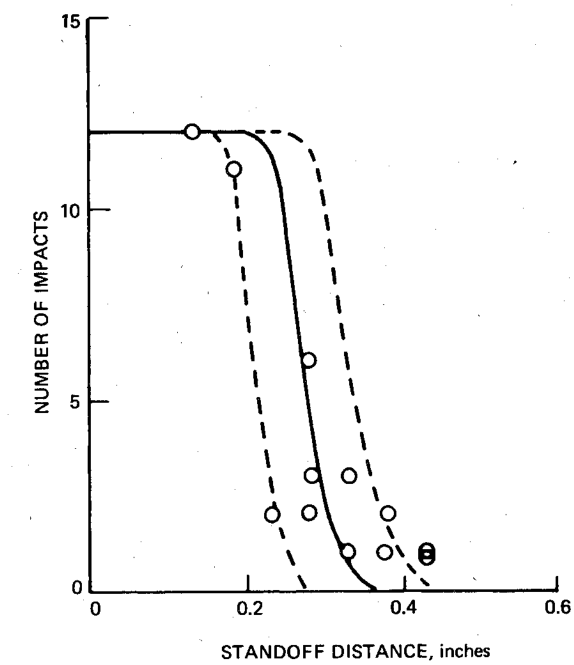

Fig. 4 Predicted and measured number of drop impacts plotted vs standoff distance.

drops. This observation suggested that at this stage the drops were undergoing catastrophic breakup, that is, the drops were being fragmented by the growth of unstable Rayleigh-Taylor waves on the drops' front surfaces.[4] In the models with the deeper cavities, there were no real craters with volume large enough to be measured by filling with wax, only areas in which the original machining marks on the aluminum surface were slightly blurred.

The observed numbers of impacts are plotted as circles vs standoff distances in Fig. 4. The agreement between the prediction, based on the criteria for catastrophic breakup,[4] and the data is good. Although more data lie to the right of the predicted curve near the bottom than to the left, indicating a slightly larger breakup time than predicted, this difference is of small physical significance for two reasons. First, the data lie mostly within the predicted uncertainty band. Second, this test is a conservative one, since we merely counted crater numbers and took no account of the fact that the observed crater sizes showed that the damage inflicted on the surface by the drops in the later states of catastrophic disintegration was greatly reduced before all evidence of impact vanished. These tests indicate therefore that a water drop has lost its erosive potential at the time of catastrophic breakup given by the criterion and correlation, reported as Eq. (28) of Ref. 4.

References

[1]Reinecke, W. and Waldman, G., "An Investigation of Water Drop Disintegration in the Region Behind Strong Shock Waves," *Proceedings of the Third International Conference on Rain Erosion and Related Phenomena*, Hartley Witney, Hampshire, England, Aug. 1970.

[2]Waldman, G. and Reinecke, W., "Particle Trajectories, Heating and Breakup in Hypersonic Shock Layers," *AIAA Journal*, Vol. 9, June 1971, pp. 1040-1048.

[3]Waldman, G., Reinecke, W., and Glenn, D., "Raindrop Breakup in the Shock Layer of a High-Speed Vehicle," *AIAA Journal*, Vol. 10, Sept. 1972, pp. 1200-1204.

[4]Reinecke, W. and Waldman, G., "Shock Layer Shattering of Cloud Drops in Reentry Flight," AIAA Paper 75-152, Pasadena, Calif., 1975.

[5]Reinecke, W. and McKay, W., "The Avco Rain and Dust Erosion Facility (RADEF)," Avco Corporation, Wilmington, Mass., AVSD-0146-73-CR, April 1973.

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