

Table 4 Natural frequencies of the circular membrane considering the added mass

| Case | Model by Eq.(21) | | | | Model by Eq.(12) | | | |
|------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| | 1st mode f_1 (Hz) | 2nd mode f_2 (Hz) | 3rd mode f_3 (Hz) | 4th mode f_4 (Hz) | 1st mode f_1 (Hz) | 2nd mode f_2 (Hz) | 3rd mode f_3 (Hz) | 4th mode f_4 (Hz) |
| A1 | 12.76 | 24.44 | 35.97 | 39.16 | 12.151 | 19.90 | 27.21 | 28.675 |
| A2 | 13.81 | 26.08 | 38.05 | 41.36 | 13.186 | 21.568 | 29.455 | 31.073 |
| A3 | 15.16 | 28.10 | 40.53 | 43.99 | 14.541 | 23.735 | 32.365 | 34.194 |
| A4 | 17.59 | 31.44 | 44.44 | 48.09 | 17.019 | 27.653 | 37.595 | 39.848 |
| B1 | 17.76 | 33.99 | 50.04 | 54.47 | 16.901 | 27.686 | 37.849 | 39.886 |
| B2 | 19.21 | 36.28 | 52.92 | 57.54 | 18.342 | 30.001 | 40.971 | 43.221 |
| B3 | 21.09 | 39.09 | 56.37 | 61.18 | 20.226 | 33.013 | 45.019 | 47.562 |
| B4 | 24.47 | 43.73 | 61.81 | 66.90 | 23.673 | 38.465 | 52.294 | 55.428 |
| C1 | 22.93 | 43.91 | 64.64 | 70.36 | 21.832 | 35.763 | 48.890 | 51.522 |
| C2 | 24.81 | 46.86 | 68.36 | 74.32 | 23.692 | 38.753 | 52.923 | 55.829 |
| C3 | 27.25 | 50.49 | 72.82 | 79.03 | 26.126 | 42.643 | 58.151 | 61.437 |
| C4 | 31.61 | 56.49 | 79.84 | 86.41 | 30.579 | 49.686 | 67.549 | 71.597 |
| D1 | 37.38 | 67.91 | 96.83 | 104.93 | 36.019 | 58.648 | 79.846 | 84.502 |
| D2 | 39.61 | 70.88 | 100.25 | 108.51 | 38.301 | 62.244 | 84.633 | 89.693 |
| D3 | 42.27 | 74.28 | 104.05 | 112.49 | 41.080 | 66.597 | 90.394 | 95.975 |
| D4 | 46.52 | 79.30 | 109.49 | 118.13 | 45.585 | 73.568 | 99.561 | 106.07 |
| E1 | 49.57 | 90.04 | 128.39 | 139.12 | 47.757 | 77.760 | 105.87 | 112.04 |
| E2 | 52.51 | 93.98 | 132.92 | 143.87 | 50.783 | 82.529 | 112.21 | 118.92 |
| E3 | 56.05 | 98.48 | 137.96 | 149.14 | 54.467 | 88.295 | 119.85 | 127.25 |
| E4 | 61.68 | 105.14 | 145.17 | 156.63 | 60.440 | 97.542 | 132.01 | 140.63 |

4. Conclusions

Added mass estimation is a key issue in wind-induced vibration analysis of membrane structures. In this paper, the boundary element method was applied to estimate the added mass for open flat membranes vibrating in still air. Two added mass models were proposed and discussed, one only considering the effect of the membrane geometric shape, and the other considering the effect of the geometric shape and the mode shape of membranes. Comparison with the data from the tests on the circular membrane, it showed that the estimation of the added mass by the proposed approaches based on the boundary element method was reasonable and suitability. The main findings were:

- 1) Added mass of air has a significant influence on the natural frequency of membrane structures in vibrating.
- 2) The proposed added mass model based on the effect of the geometric shape can have a good agreement with the test results in low-order modes, and the error will be increase as the order of vibration modes increases.

- 3) The proposed added mass model based on the effect of the geometric shape and the mode shape can have a better conformity with the test results both in low-order modes and high-order modes.

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