Forced Displacement Technique for Measuring Blunt Body Aerodynamics in a Magnetic Suspension Wind Tunnel

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ABSTRACT

The Old Dominion University/NASA Langley 6-Inch Magnetic Suspension Wind Tunnel has developed the ability to levitate blunt bodies which can oscillate freely about the yaw axis. This allows for the measurement of static and dynamic stability coefficients without sting interference. The magneic suspension controller introduces other translational forces which affect the vehicle dynamics complicating data reduction. Exciting model oscillations in a reliable way has also been a challenge. A new test method has been developed that produces capsule oscillations from forced oscillatory translational motion at the resonant yaw oscillatory frequency of the capsule. After oscillations are excited, the translational forcing motion is suspended to record free oscillation behavior as well. A data reduction method whereby a linear model of the translational and oscillatory motion is used to fit to the measured data and solve for aerodynamic coefficients has also been developed. The work presented shows that the new data reduction techniques provide a robust and repeatable mothod of measuring the aerodynamics of blunt bodies.

1. Introduction

Preliminary tests in the Old Dominion University (ODU)/NASA Langley 6-inch Magnetic Suspension Wind Tunnel (MSWT) have shown promising results, measuring static and dynamic moment coefficients from free-to-oscillate data[1]. In previous tests, free-to-oscillate capsule oscillation histories were used to solve for the dynamic damping coefficient. Many questions remain to be answered in order to gain confidence and quantify uncertainties in the measured results. Different test methodologies are being investigated to help confirm that the observed capsule oscillation histories are not corrupted by the control inputs from the magnetic suspension balance system. Furthermore, early test runs utilized a retractible sting which touched the model in such a way that a test model could be released at an initial angle of attack. The complication of that approach was that the MSBS control law had a difficult time controlling the model during the transition from sting-supported operation to freely suspended in the tunnel. New methods of using forced/prescribed motion histories to excite capsule dynamics were investigated. The results the the trials of those new methods prompted further discussion of how forced motion can be effectively utilized to better measure dynamic stability characteristics. Test technique development work also identified possible test capabilities that might be able to separate damping characteristics when a model is undergoing rotational motion versus transverse or plunging motion. This work describes a possible test technique that utilize forced translational motion to excite capsule dynamics, using a range of frequencies to identify static stability and damping characteristics.

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2. Experimental Setup

2.1 Magnetic Suspension Wind Tunnel

The ODU/NASA MSWT was originally designed with axial magnetization and full 6-DoF control in the late 1960s. For our current application, power to the MSBS coils was reconfigured and a new control algorithm was implemented to produce a vertical magnetizing field [2]. This configuration allows the levitation of models with low-aspect ratio permanent magnet cores, with 3D-printed plastic shells forming the aerodynamic shape. The spherical or cylindrical magnet cores are levitated and align with the vertical bias field creating a near frictionless bearing, permitting free yaw motion of the model. Early tests with the tunnel utilized position feedback only, but cross coupling of the commanded force fields with the model frequently resulted in high frequency oscillations about the pitch and roll axes. To enable control about the pitch and roll axes to damp unwanted oscillations, an OptiTrack® camera system was added. Three cameras track reflective targets on the model, providing roll and yaw measurements to the controller and recording yaw angles for data reduction.

A new method of driving capsule oscillations has been developed and used to extract the aerodynamics presented here. The controller commands transverse plunging oscillations of the model at different frequencies to excite capsule rotational oscillations. Test were done across a range of frequencies and as expected the largest amplitudes were observed at the natural frequency of the wind tunnel model. The natural frequency is determined by the tunnel dynamic pressure, model outer mold line, center of gravity location, and yawing moment of inertia. For the data presented, the models were driven at their resonant frequency, with a prescribed sinusoidal forcing function that caused the model to translate across the test section with an amplitude of approximately +/- 3 mm. The forced motion causes capsule oscillations to grow in amplitude, eventually reach-

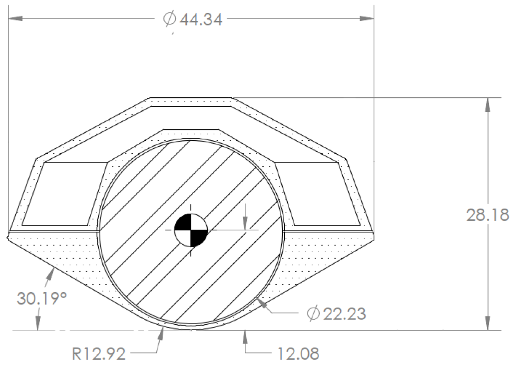

Figure 1 Design Model dimensions

Table 1 Model Mass Properties and Reference Parameters

Parameter	Symbol	Value
Diameter	d	44.21 mm
Ref. Area	S	1535.1 mm^2
Mass	m	54.0 g
Yaw Mom. of Inertia	I_{zz}	3750.6 $g \cdot mm^2$
Cg location	x_{cg}/d	0.273

ing a peak value. The transverse forcing is then suspended, allowing the model to damp down due to the model's dynamic stability. As described below, both the force plunging and free to oscillate phases are used in the data reduction process to extract aerodynamic coefficients.

2.2 Wind Tunnel Model

The model geometry tested for this test-technique development effort is based on the Genesis entry capsule. The relative dimensions approximate a scaled version of the Genesis capsule[3]. To improve overall static and dynamic stability, the center of gravity, cg, of the model was moved as far forward as was practical. For this reliable levitation and control of the model while testing, it is desirable that the overall model cg be roughly coincident with the cg of the magnet core. The core used for this model is a 7/8 inch (22.23mm) diameter neodymium grade n52 sphere. The plastic shell making up the aerodynamic outer mold line was made in two parts using a Fused Deposition Modeling 3D printer. The split plane was located at the max diameter of the model and the aft part was printed with a hollow cavity to move the assembled cg to the magnet centroid. The dimensions of the model are provided in Figure 1 and Table 1 lists the mass properties and reference parameters.

3. Wind Tunnel Testing and Data Reduction Method

The magnetically suspended capsule has no sting or other support equipment in the tunnel test section to interfere with the flow around the model and structure of its separated wake. However, the test article is not free from external forces as the balance control coils act to keep the model centered in the test section, rejecting the disturbances from aerodynamic forces (primarily drag and transverse forces as the model oscillates in yaw). The commanded forces required to keep the model centered in the tunnel are recorded and used in the data reduction process, where magnetic and aerodynamic forces must be separated. Regarding model rotation, the poles of the magnet core align with the balance's vertical magnetizing field; The model's yaw axis is then free of direct magnetic torques, and the model is essentially free to rotate about that axis. The alignment of the permanent magnet in the vertical field results in very high stiffness in roll and pitch degrees of freedom, essentially eliminating rotation about those axes (though the aforementioned camera system assists with adverse interactions that can result in high frequency self excitation about those axes).

This approach to magnetically suspending models allows the test article response in the tunnel flow to be aerodynamically dominated by yaw rotational motion with a mix of both aerodynamic and external forcing in the lateral direction. Although some aerodynamic coefficients can be estimated directly from the response, a technique was developed to account for the effect of the measured external forcing on the model. This technique models the capsule motion in yaw and lateral velocity. Using known mass and inertia properties, the response of the system to eternal forces can be predicted with a linear 4th order model that parametrically depends on the

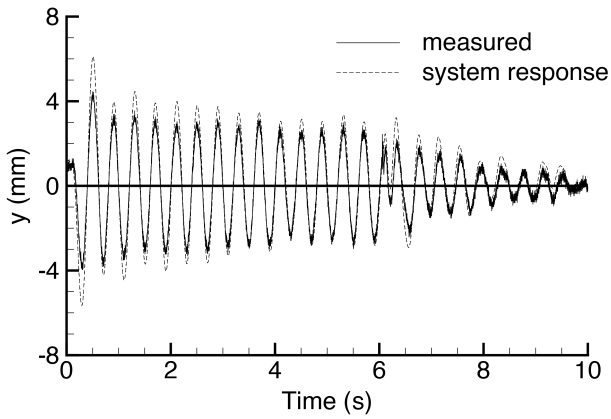

Figure 2 Plunging displacement history with model response

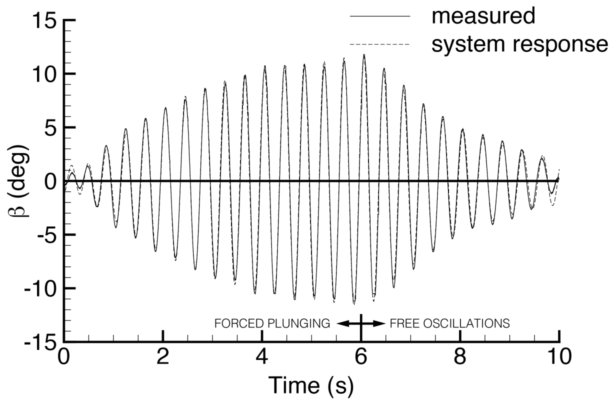

Figure 3 Sideslip angle, β, history

aerodynamic coefficients[4]. Values of aerodynamic parameters that best fit the response time history are then solved for as an optimization problem. Experimentally it was determined that a short harmonic side-force, tuned to be near the rotational resonance of the model, followed by a period of free decay, provided a good time history for the coefficient fit. Figure 3 shows the rotational response of the model to this input along with the response of the dynamic model using the fit aerodynamic coefficients. The prediction shows good tracking of both the growth and decay of yaw oscillations. Figure 2 shows a similar comparison of the lateral plunge motion of the model. This measurement of position has more noise than the yaw measurement, but the prediction model also has a good low frequency match using the fit aerodynamic parameters.

3.1 Dynamic Pressure Correction

A number of trials were conducted at nominal dynamic pressures of 100 Pa and 200 Pa. Dynamic pressure was set for each run, using calibrated static pressure taps in upstream contraction of the tunnel. The blockage of the model in the test section (projected area of the model, normalized by the cross sectional area of the test section) is on the order of 7%. Historical data suggests that the local dynamic pressure around the model was greater than measured upstream as flow accelerates around these blunt body models. A correction was determine using methods by Maskell and developed during previous tests[6, 5]. The corrected dynamic pressures were used in the data reduction process.

4. Results

4.1 Drag and Blockage Correction

A series of runs were conducted to measure the drag force as a function of dynamic pressure to determine a constant drag coefficient, C_D to use for blockage corrections. Dynamic pressure was varied from 100 to 400 Pa and drag force increased in direct proportion. The drag coefficient for the 44.1mm diameter test model (measured value) was found to be 1.081. Using the blockage correction methods described in the references cited above, a dynamic pressure correction factor of 1.2038 was determined. For the data presented below, the measured dynamic pressure, from calibrated static taps in the tunnel, is scaled by this factor. The measured drag coefficient is therefore scaled down accordingly. The corrected drag coefficient of the test model is therefore, $C_{D,corrected} = 0.898$.

4.2 Stability Aerodynamic Coefficients

Five trials were conducted at two different "nominal" dynamic pressures of 100 Pa and 200 Pa. For the 100 Pa trials, a problem with the data acquisition system prevented the dynamic pressure time histories from being recorded (the dynamic pressure was held fixed and recorded as constant for all runs used here). Data recorded just prior to the trials is used for data reduction here; The speed setting was held constant for the duration of all 100 Pa runs; While the dynamic pressure wasn't recorded during the test runs, data recorded just prior is representative of dynamic pressure for the duration. Based on the data measured prior to the data runs, dynamic pressure should remain within approximately 2% of the value used here. The measured variation should be considered an additional uncertainty on results from the 100 Pa runs.

Table 2 Aerodynamic Results, $\bar{q}_{corrected} = 120.3$ Pa

Run	C_{n_r}	C_{n_β}	C_{L_β}
11	-0.144	0.114	0.554
12	-0.105	0.114	0.557
13	-0.127	0.115	0.561
14	-0.129	0.113	0.539
15	-0.146	0.114	0.558
Avg.	-0.130	0.114	0.554

Table 3 Aerodynamic Results, $\bar{q}_{corrected}$ =251.1 Pa

Run	C_{n_r}	C_{n_β}	C_{L_β}
5	-0.088	0.116	0.612
6	-0.122	0.116	0.630
7	-0.134	0.115	0.618
8	-0.119	0.115	0.615
9	-0.109	0.116	0.605
Avg.	-0.114	0.116	0.616

The linear model used for data reduction included the effects of a cg offset which could be solved for. The changes to the model done to move the magnet core as forward as possible resulted in a small offset of the cg, aft of the magnet center. For the results shown here, each run was reduced, solving for a cg offset. The values from all 10 runs were averaged and then held fixed for the final reduction of each run. The average cg offset over all 10 trials was 0.149mm aft of the magnet center with a standard deviation of the measured values of 0.02mm. The computer aided design, CAD, model used to design the plastic shell indicated an expected cg offset of 0.215mm (approximately 3 standard deviations from the measured values). The difference between the CAD model and measured is likely well within the tolerances of the as-printed, as-assembled final model.

Table 2 shows the results of the 100 Pa (120 Pa corrected) runs. The coefficients extracted are very repeatable. The yaw damping and static stability coefficients appear to be in good agreement with recent tests of the Dragonfly entry vehicle (a new mission to Titan utilizing an aeroshell based on Genesis). Formal comparisons will be documented in papers to follow, once the Dragonfly data is published. A more formal uncertainty analysis will also be completed and documented. The data reduction process showed that it is critical to obtain good mass properties (moments of inertia and cg location) and correct for blockage effects.

Table 3 shows results at a higher dynamic pressure. These trials successfully recorded dynamic pressure for all trials with the variation of only 0.6

Pa across the five runs. The variability in C_{n_r} is a little greater for this dynamic pressure. As dynamic pressure in the tunnel is increased, the controller is less responsive and the model position tends to wander more during each trial. This extra motion is not extreme (the forced translation motion used to excite dynamics is still the dominant motion), but is suspected to contribute some error in the data reduction. A higher fidelity set of equations modeling the dynamics, capturing more degrees of freedom, might address this concern, but for now the ability to conduct multiple repeats very quickly allows for the averaging of many runs. The repeatability in the static stability coefficient is consistent with the strong oscillatory signal provided by the natural frequency of the model. The difference in dynamic stability at the two dynamic pressures tested is not unexpected. Forced oscillation test data at subsonic conditions can show significant variation of damping with reduced frequency. Comparisons with Dragonfly data will be conducted in the future, when that data is published, to see if the trend with dynamic pressure is consistent with data collected using more traditional techniques. A more detailed and systematic uncertainty analysis is the next task as work to go. However, the robustness of the data reduction process, which yields consistent/repeatable aerodynamic coefficients means that the data from the MSWT are finally ready for meaningful comparison with data from established test facilites.

5. Conclusion

A new test method has been developed that provides a robust and repeatable measurements of static and dynamic stability coefficients of blunt bodies in the NASA/ODU 6-Inch MSWT. Translational plunging at the yaw oscillatory resonant frequency drives yaw motion up to desired amplitudes. The amplitude of the translational motion provides some control over the peak yaw amplitude. Upon reaching peak amplitude, the forcing oscillations are suspended allowing the capsule to oscillate freely. For the vehicle tested here, the model damped down to small amplitudes. A linear systems of equations that models the translational and rotational modes is used to fit a response to the test data to solve for the aerodynamic parameters. This response model can be fit through the entire duration of each run, not just the free-to-oscillate phase. Blockage effects were estimated to correct for the local dynamic pressure around the model. The final results are repeatable and look reasonable based on preliminary comparisons to data collected on similar geometries. When recent forced oscillation data on a similar configuration is published, this data will be compared to assess and validate the ability of the MSWT to measure blunt body aerodynamics. Results to date look very promising and this method is expected to be useful looking at sensitivities to reduced frequency, cg location, vehicle shape and other design parameters.

6. Acknowledgements

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References

[1] M. *Schoenenberger*, D. Cox, C. P. Britcher, *Blunt Body Pitch Damping Measurements from Multiple Subsonic Free-to-Pitch Magnetic Suspension Trials,* ICFD 2021, OS6-1, 2021

[2] C. Britcher, C. Hull, D. Cox, M. Schoenenberger, *Comprehensive Static and Dynamic Modeling of a Magnetic Suspension and Balance System*, ICFD2024, OS6, 2024.

[3] F. Cheatwood, G. Winchenbach, W. Hathaway, G. Chapman, *Dynamic Stability Testing of the Genesis Sample Return Capsule*, AIAA 2000-1009.

[4] C. Britcher, D. Cox, M. Schoenenberger, H. Shehata, C. Hull, B. McGovern, *Development of Data Reduction Methods For Dynamic Stability Tests In A Magnetic Suspension and Balance System*, Poster 100, Session B. International Planetary Probe Workshop, www.ippw2024.org, Williamsburg, VA, 2024.

[5] C. P. Britcher, B. McGovern, D. Cox, M. Schoenenberger, *An Investigation of Bluff Body Blockage Corrections Using the NASA/ODU 6-inch MSBS.* ICFD 2022, OS6-1, 2022.

[6] E.C. Maskell, *A Theory of the Blockage Effects on Bluff Bodies and Stalled Wings in a Closed Wind Tunnel.* R&M 3400, Nov.1963.