Design and Implementation of Free to Oscillate Dynamic Stability Launch Method for a Magnetic Suspension and Balance System.

Kristen Michaela Carey
Old Dominion University
Director: Dr. Colin Britcher

ABSTRACT

Magnetic Suspension and Balance Systems (MSBS) allow for the testing of free to oscillate models in a wind tunnel without the need for a mechanical support. Current launching methods demonstrate forces on the testing models, so an alternative launching method needed to be designed. The objective of this approach is to determine dynamic stability characteristics for various re-entry capsule designs while reducing the interference that the launching methods inflicts on the tested model. This paper discusses the development and testing of a launching method for use in the MSBS Subsonic Wind Tunnel at NASA Langley Research Center.

INTRODUCTION

The Magnetic Suspension and Balance System at NASA Langley was previously tested and subsequently retired from service in the early 1990s, before being reactivated in 2016 [1]. The MSBS uses electromagnetic coils and an electromagnetic position sensor system (EPS) to suspend an aerodynamic model with an internal magnetic core. Prior to the current work, models were typically slender, but the interest now is atmospheric entry capsule geometries for NASA missions [2]. The models were scaled for the MSBS with internal cavities to house the magnetic core, usually a 0.75-inch cylindrical neodymium-iron-born (NdFeBo) permanent magnet core or a 1-inch spherical NdFeBo core. The previous launching methods for the MSBS have consisted of small stings that attach to a nylon rod mounted to a pneumatic retractor in the wind tunnel. These launching methods were designed to push up against the testing model to deflect it at a predetermined angle and then retract out of the path of the model via a pneumatic retractor. An issue with these methods is the surface area in which the test model is touching the sting attachment. When the sting is retracted, the test model tends to be pulled slightly by friction force, therefore causing interference in the data gathered. To remedy this, a new launching method needed to be designed to hold the model at a predetermined angle with as little surface area touching the model as possible. The purpose of this research was to design and test a launching method for Free to Oscillate Dynamic Stability testing in a MSBS and validate the speed in which the "grabber" could release the model. Due to the magnetic and electrical features of this type of testing, all components for a new launching method had to be nonmetallic or be located far enough from the test section to not interfere with the magnetic field and the EPS.

METHODOLOGY

1. Grabber Design:

The grabber was designed to hold a magnetically suspended model at a predetermined angle, in this case 20 degrees. The grabber assembly is composed of five main parts: the solenoid, solenoid housing, connector rod, grabber base, and grabber grippers. The solenoid was positioned at the farthest distance from the testing section to prevent the electromagnet from interfering with the EPS. The assembly of the Grabber is shown below in Figure 1.

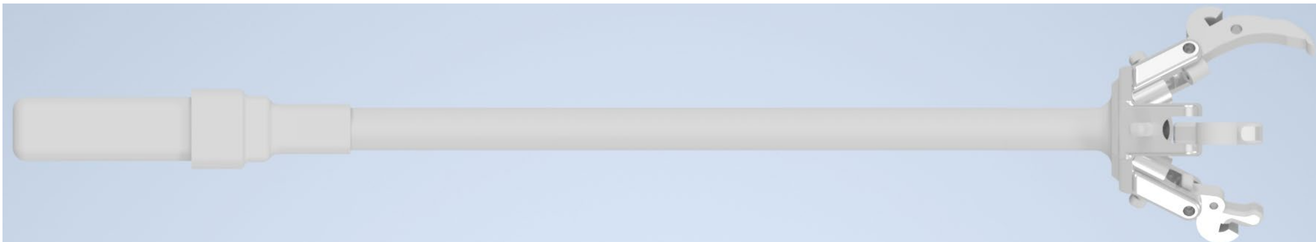


Figure 1: Grabber Assembly

2. *Solenoid*

The solenoid for the MSBS grabber needed to be small enough to fit into the assembly without protruding out in the airstream to incur blockage. To fulfill these requirements, a solenoid with a nominal diameter of 0.5 inches was chosen. The length of the solenoid was not as important as the connector rod could be lengthened or shortened if needed. The solenoid chosen for MSBS testing is shown below in Figure 2.

Figure 2: Solenoid for MSBS testing.

The solenoid has a 0.25-inch throw with a power draw of 2.5 watts. A power system for the solenoid needed to be designed.by using parts in the NASA Langley MSBS Subsonic lab, a 12-volt regulator was used to be powered by a 15-volt power supply. A cable was installed to connect to the solenoid power cables. Since the solenoid would be turned on and off, without it being powered on for a prolonged amount of time, a 15-volt power supply was deemed acceptable.

3. *Solenoid housing*

The solenoid housing was designed to screw onto the pneumatic retractor rod and have the solenoid slide into place inside. Then a small cap, as seen in 3, snapped into place securing the solenoid and space for the solenoid arm to actuate. The cap and solenoid housing are shown below in Figures 3 & 4 respectfully.

Figure 3: Cap for Solenoid Housing for MSBS testing.

Figure 4: Solenoid housing with Solenoid base inside for MSBS testing.

4. *Connector Rod*

The connector rod is a hollow rod 6 inches in length that screws into the top of the solenoid housing as well as the grabber base. The wires that power the actuation of the grabber grippers are housed in this section.

5. Grabber Base

The grabber base has a hollow cylindrical section that the connector rod screws into. The base spreads outward to form three arms for the "grippers" to connect via small pins. There are small loops at the center of the base that act as cable guides to keep the cables from interfering with the model. There are also small hooks attached to the backside of the grabber base that hold the elastic bands that connect from the base to the grippers. The grabber base is shown below in Figure 5.

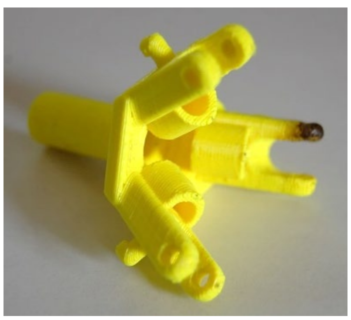


Figure 5: 3D printed Grabber base for MSBS testing.

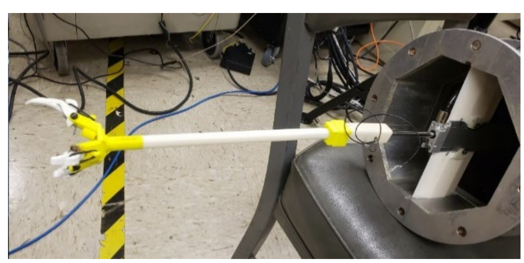
6. Grabber grippers

The grabber "grippers" were designed to hold a test model at a fixed angle of 20 degrees. For this to be achieved, the grippers had to be two different sizes. Based on the geometry of the Stardust entry vehicle[1] model in Autodesk Inventor, the gripper lengths were chosen to be 1.33 inches for the long gripper, and 0.87 inches for the short grippers. Each gripper features a mounting hole that is held to the grabber base by a small pin. There is also a small hole in the middle of the grippers that the cable guides through to actuate the grippers when the cable is retracted. For the release motion of the grabber, there are small hooks featured on the back of the grippers that hold small elastic bands that connect to the grabber base. The long and short grippers are shown below in Figure 6.

Figure 6: 3D printed Long Gripper and Short Grippers for MSBS testing.

7. Grabber Assembly

For the assembly, the solenoid slid inside the solenoid housing with the cap locking it into place. The cables were connected to the solenoid and guided through the connector rod. The rod was screwed into the solenoid housing cap and then fastened into the grabber base and the cables were pulled through. From there, the grippers were mounted to the grabber base by small pins and the cables were guided through the grabber base and into the grippers. The small elastic bands were then attached to the grabber base hooks and the cutouts on the grippers. Manual adjustment was needed to set the grippers at the correct position so that the grabbing motion of the assembly would sufficiently hold the model. Once the grabber was assembled, it was installed into the subsonic MSBS wind tunnel for future testing as shown in Figure 7.



[1] Stardust has been chosen as a standard model geometry for development of the MSBS

Figure 7: Grabber attached to Pneumatic Retractor in Subsonic MSBS Wind Tunnel.

8. *Grabber Opening:*

For preliminary tests of the grabber's opening time, speed tests were conducted in the NASA Langley Subsonic MSBS. For these tests, the grabber was fastened to the pneumatic retractor and the opening was recorded at 180 frames per second. The grabber in the camera view is shown in Figure 8.

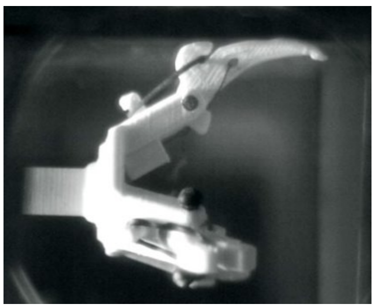


Figure 8: Grabber in camera view

The recordings were then analyzed to determine the time frame in which the grabber opened. The initial opening was subtracted from the fully open frame to find the total frames that the grabber took to open. The frames were then converted to seconds. The data gathered is shown below in Table 1.

Table 1: Grabber Opening		
	Trial 1	Trial 2
Start (Frame)	19	18
Fully Open (Frame)	23	23
Time to Open (seconds)	0.0221	0.027
Average Open (seconds)	0.02455	

As shown in Table 1, the grabber opened at an average of 0.02455 seconds.

[You do not seem to mention the retraction?]

MSBS SIMULATION

A simulation was created in MATLAB/Simulink to simulate three degrees of freedom free to oscillate flight testing in the subsonic MSBS as a proof of concept to verify the grabber would be clear of the model in sufficient time. The purpose of this simulation was to verify the frequency of oscillation and the time steps in between each oscillation. For reference, the time needed for the various sting attachments to be clear of the testing model is at the first oscillation as the frequency reaches the first mark of zero, or during any excursion due to release at non-equilibrium conditions. For the building of the simulation, the Simulink code required the Aerodynamic Blockset, and the 3 degrees of freedom Blockset.

1. *Aerodynamic blockset*

The aerodynamic forces and moments block set computes the aerodynamics forces and moments applied on the testing model based on the inputs of the aerodynamic coefficients, dynamic pressure, center or pressure, and center of gravity. The outputs of this blockset are forces and moments on the testing body in the x, y, and z direction.

a. Aerodynamic coefficients

The aerodynamic coefficients needed for the simulation are the axial force coefficient, normal force coefficient, and the pitching moment coefficient. Since this simulation is for 3 degrees of freedom and is only looking for axial and vertical movement with the pitching angles, the side force, rolling moment, and yawing moment coefficients were not needed. . The axial force, normal force, and pitching moment coefficients for the blunt testing model, mainly focused on Stardust, were found based on previous testing by Mitcheltree et al [3]. Since the simulation varies constantly, the aerodynamic coefficients were calculated in the simulation with this equation:

$$AeroCoeff = (Slope * \alpha) + y \qquad (1)$$

Where the slope is the slope of the graph for the respective coefficient measurements, and the y is the y-intercept of the graph for the respective coefficient measurements, and α is the alpha value at the time. This equation ensures that the coefficient varies per degree with respect to alpha. The slope of the axial force coefficient was found to be around 0.0001 deg^{-1} with a y-intercept of 0.875. As shown in Figure 9.

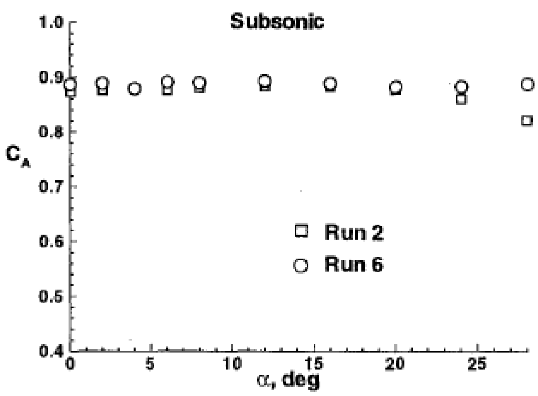


Figure 9: Axial Force Coefficient measurements from Mitcheltree et al.

The slope of the Normal force coefficient was found to be around 0.0031 deg^{-1} with a y-intercept of 0. As shown in Figure 10.

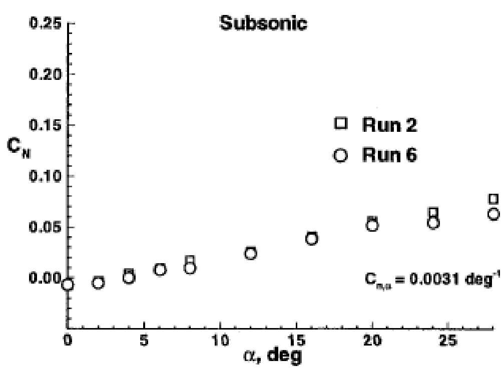


Figure 10: Normal Force Coefficient measurements from Mitcheltree et al.

The slope of the Pitching Moment Coefficient was found to be around -0.00276 deg^{-1} with a y-intercept of 0. As shown in Figure 11.

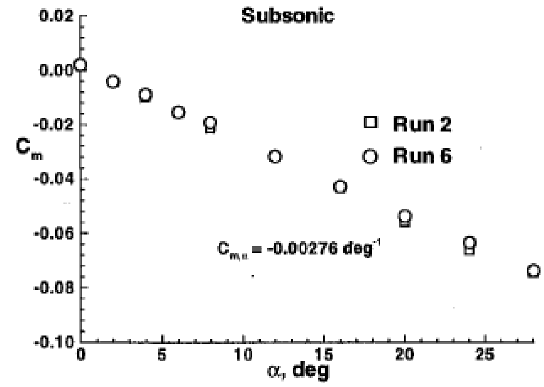


Figure 11: Pitching Moment Coefficient measurements from Mitcheltree et al.

b. Starting values (Velocity, Density of Air, Dynamic Pressure, Center of gravity, Center of pressure, Reference area, Reference Span, reference Length)

For the purposes of simulating a magnetically suspended model, the center of gravity and center of pressure can be set at the origin or 0,0,0 in the x,y,and z axes. The starting velocity of a subsonic tunnel usually is in between 10 to 40 m/s, but for proof of concept, 25 m/s was chosen. The density of the air is 1.225 kg/m^3. The density and velocity values were put into the Simulink code to calculate the correct dynamic pressure for the wind tunnel. The model parameters for the testing body were based on the 1.75-inch Stardust model. For Simulink purposes, metric units were used. For this, the reference span was found to equal the diameter of the testing model, or 0.0444 meters. The reference length (depth of the model) was found to be 0.0289 meters. The reference area is the frontal area of the model in the airstream, this was found to be $1.55*10^{-3}$ m^2.

2. Three degree of freedom blockset

The three degree of freedom (3dof) blockset integrates the three-degrees-of-freedom equations of motion using the input of F_x, F_z, and M_y. F_x is the axial force, F_z is the vertical force, and M_y is the pitching moment. The outputs of this blockset are the pitch attitude, pitch angular rate, pitch angular acceleration, location of body, velocity of body, and acceleration of body. As this simulation was meant to find the pitching oscillation of the model, the only output needed was the pitching attitude.

a. F_x, F_z, M_y values

The F_x, F_z, M_y values were plugged into the 3dof blockset from the output of the Aerodynamic blockset.

b. Initial velocity, initial body attitude, Initial incidence, initial position, initial body rotation rate. Initial mass, Inertia, Acceleration due to gravity.

As stated previously, the initial velocity was set to 25 m/s. For this simulation, initial incidence and attitude were set to 20 degrees. This was chosen to match the angle for the grabber for comparison. The initial position was set to [0,0] since the model is magnetically suspended to the origin. The initial body rotation rate was set to 0 as the model does not rotate on its own. The initial mass was set to 0.057 kg, based on the mass taken from a 3D printed stardust model with the magnetic core inside. The inertia was calculated to be 1.1262 $*10^{-5}$ kg*m^2 by using Equation 2:

$$Inertia = \frac{2}{5} * mass * radius^2 \qquad (2)$$

Where mass has been determined and the radius used is from the Stardust nose diameter of 1.75 inches. The acceleration due to gravity was set to zero as the model is magnetically suspended, therefore does not incur gravitational forces.

3. Pitching oscillation results

The pitching attitude oscillation is shown below in Figure 12.

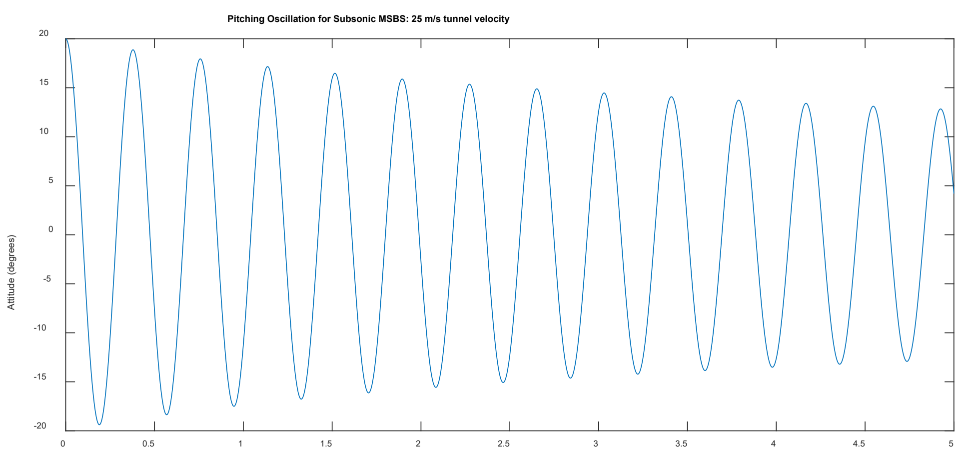


Figure 12: Pitching Attitude for MSBS at starting velocity at 25 m/s.

The data from the graph was analyzed to find the approximate time that the model's attitude would first arrive at zero degrees, to do this. The value for attitude equals zero was interpolated from the data points just before and just after the perceived zero value. The equation used was a linear interpolation equation, Equation 3, which is acceptable given the small step size of the data.

$$T_0 = T_1 + (0 - \theta_1) * \left(\frac{T_2 - T_1}{\theta_2 - \theta_1}\right) \qquad (3)$$

$$T = 0.1 + (-0.5293) * \left(\frac{0.104 - 0.1}{-0.6949 - 0.5293}\right) \qquad (4)$$

Using Equation 4 above, the time in which the attitude of the model body would first cross zero degrees, and the grabber would have to be removed to prevent interference is 0.101729 seconds.

DISCUSSION

As shown in the results section for the high-speed video of the grabber, the grabber opened at an average time of 0.02455 seconds. The simulation showed that the grabber needed to be opened and out of the path of the suspended model in 0.101729 seconds. Therefore, the grabber opens in enough time for it to be pulled out of the path of the model by the pneumatic retractor. As the grabber will open and then be retracted downstream, the time step in which the retractor pulls the grabber downstream can be refined by trial and error in future testing.

CONCLUSION

A launching method was designed to release a magnetically suspended model at a predetermined angle while minimizing the surface area in which the model was contacted. Analysis was conducted to determine the release speed of the grabber and the validity of the release speed was confirmed by conducting a simulation to determine the require time for release and retraction.

FUTURE WORK

Future work for this project would include the further design and implementation of a grabber in upcoming MSBS testing and the comparison of data from the sting attachment testing methods and the grabber testing method. Another application to be expanded upon is the implementation of the grabber, or similar design, in a supersonic MSBS testing setting.

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