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Oxford 3-DoF Magnetic Suspension & Balance System: Update on Recommissioning Efforts

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ABSTRACT

This paper provides an update on recommissioning efforts currently underway for the Oxford 3 -DoF Magnetic Suspension and Balance system (MSBS), developed in the mid-1970s to measure lift, drag, and pitching moment of cones at hypersonic rarefied flow conditions representing Earth re-entry flight at high altitudes (>60 km). The balance has not been operated in approximately 20 years and requires a full restoration. A synopsis of the works underway to recommission and update the balance is provided, including the state of the cores and coils.

1. Introduction

During the 1960s and 1970s doctoral researchers at the University of Oxford recognised the utility of magnetic suspension technology for enabling measurement of aerodynamic forces under high altitude, rarefied hypersonic flow conditions such as those produced by the Oxford Low Density Tunnel (LDT). This wind tunnel is a continuous blowdown facility which currently operates with a Mach 6 contoured nozzle (exit diameter 107.5 mm) at supply temperatures in the range ambient to 470 K and supply pressures in the range 800 Pa to 3500 Pa (absolute) [1]. At these conditions, the nozzle exit density is sufficiently low that the mean free path (A) of the gas molecules is comparable with the model size (L), with Knudsen numbers (Kn = A/L) between 0.01 and 0.1 achievable for a reference length of 10 mm.

The LDT operates in the rarefied slip and transition regimes, where continuum assumptions break down, equivalent to altitudes above 60 km. In these regimes, diffuse shock waves and large viscous interaction regions exacerbate the influence of a sting in traditionally mounted models. Further, the small model size, necessary to achieve high Knudsen numbers, coupled with the low flow densities, results in force magnitudes on the order of milli-Newtons which cannot easily be measured with strain-based force balances. MSBS technology circumvents these difficulties. Two balances were developed in-house at Oxford, specifically for use with the LDT which placed several constraints on the designs; primarily, the entire balance must be contained within the test section of the facility (1.5 m diameter x 1.5 m width) and be able to operate under vacuum conditions. Doherty [2] provides a detailed summary of the history of the development at Oxford; a brief overview is provided in the following paragraphs.

The first MSBS at Oxford was developed by Altmann [3] in the late 1960s, to study the effects of rarefaction on sphere drag [3, 4]. This balance controlled only the vertical (lift) and streamwise (drag) directions and the model detection system consisted of a set of overlapping circular photodiodes. Drag on liquid Nitrogen (LN2) cooled spheres with diameters between 1.5875(25) mm (1/16 in.) and 6.3500(25) mm (1/4 in.) was measured at conditions ranging between Kn = 0.03 to Kn = 10 (free-molecular flow) with a reported uncertainty of just 2.6%.

Fig. 1 The current Oxford MSBS with cooling system tubing removed.

The second and current MSBS (shown in Figure 1) was later designed in the mid 1970s by Haslam-Jones [5] with the aim of measuring lift, drag and pitching moments on cones at incidence. It was developed as a 3-component system and again featured a photodiode-based model detection system and all analogue power suppliers and controller. The position detection system received several improvements, but the operation principle remains unchanged: a light source casts a shadow of the model onto the detector (presently a quadrant photodiode, Figure 2), whose signal output is proportional to the illuminated proportion of its domain. Appropriate comparisons of combinations of signals are used as inputs in the control system. This current MSBS system was used over the next 25 years to examine forces on cones. Researchers examined the effect of wall-to-stagnation

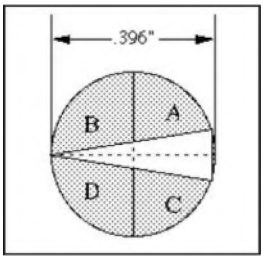

Fig. 2 Schematic showing a model and quadrant photodiode as part of the optical detection system [8].

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temperature ratio (using LN2 cooled models) [6], nose bluntness [6], incidence [7,8] and the effect of wake survey probes on the measured forces [8], as well as force measurements on axially aligned cylinders and aerobrake-like geometries [8]. Reported uncertainties in force coefficients were typically 2 % or less.

In combination, MSBS technology and the LDT facility provide capability that was, and still is, unavailable anywhere else in the world. Both have an important role to play in understanding high-altitude hypersonic vehicles and satellite demise aerothermodynamics. The remainder of this paper is focussed on describing the status of recommissioning of the 3 -DoF MSBS, including a description of the electromagnet layout, and status of the cores and coils, and plans for the overall system integration with the LDT which itself was recommissioned in the last decade [1].

2. Electromagnet Layout

The electromagnet layout of the Oxford 3 -DoF MSBS is shown schematically in Figure 3. It utilises a pair of air-cored drag coils to magnetise a steel model and generate an axial flux gradient to apply a force on the model. To vary the applied axial electromagnetic force, the difference in supplied current between the front and rear drag coils is varied, whilst maintaining constant mean current (thereby keeping magnetisation constant). Originally, a pair of horseshoes of laminated electrical steel (Transil 107) formed the cores for two lift coils and four pitch coils. The lift coils generate a vertical gradient in the axial magnetic flux to impart a lifting force, whilst the pitch coils together generate a uniform vertical field perpendicular to the magnetising field thus imparting a torque on the model.

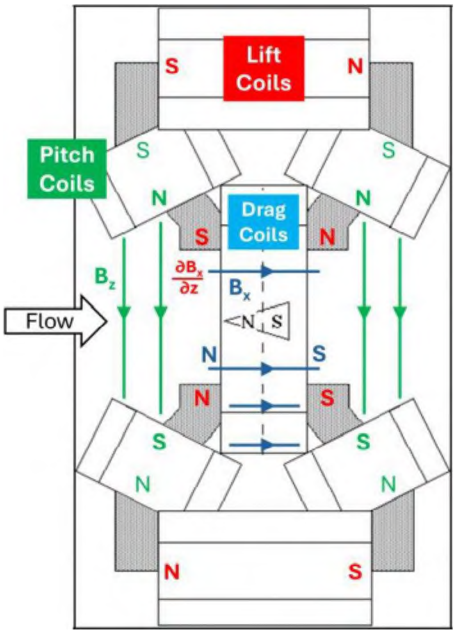

Fig. 3 Schematic showing the layout of the casings/coils and magnetic fields, with the magnetised model in the centre.

Since the device has a vertical plane of symmetry, lateral stability is achieved by strategic placement of ferromagnetic material to absorb some of the magnetic field, creating a local maximum in the test region. The tunnel flow damps any lateral oscillation and the magnetising field is sufficient to eliminate any model yawing motion.

The coils are made from 1.6 mm diameter solid copper. These are housed in cast casings through which liquid water is passed as a coolant, thereby enabling continuous operation in the vacuum environment of the LDT test section. Hollow conductors were not used in the original design, likely because they either were not widely available at the time and/or they cannot be made small enough to give the large number of turns required to achieve the desired number of Ampere-turns for the limited reliable supply of current achievable at the time.

The present task of refurbishing and recommissioning the MSBS has exposed some issues with old designs, detailed in the following section. This task was made further difficult by the lack of documentation and accessible expertise in the device that remains since its conception in the 1970s.

3. Refurbishing and Recommissioning Efforts – Current status

The initial task was to take apart the device, beginning with an inspection of the water cooling system, then separating the casings, removing the cores, and inspecting the coils.

The water cooling system tubing was filled with deposits accumulated over the years, and plenty of deposition and corrosion in casings, causing damage to some electrical connections (see Figures 4a and 4b). The excessive corrosion and residue deposition in the casings was diagnosed to likely be the result of galvanic corrosion at the screw and at the crimp connections as well as the use of insufficiently pure water for cooling. To mitigate these risks in the future device:

- Casings are being redesigned to use appropriate feedthroughs to pass current directly to the coils, eliminating any crimps;
- External tubing of the cooling system will have larger internal diameters to reduce pressure losses in the fluid;
- Cooling system will use Galden instead of water. Galden is a chemically inert corrosion resistant fluorocarbon coolant with good dielectric properties typically used in high power systems such as transformers and the electromagnets in fusion reactors [9].

Removing cores from centres of the casings was difficult due to rusting and fusing of the individual laminated sheets, indicating possible coolant leakages in some of the casing assemblies. The initial design of the cores suggested that dovetailing the laminate parts enabled easier disassembly - in its current state, the opposite was true, friction between the dovetails and

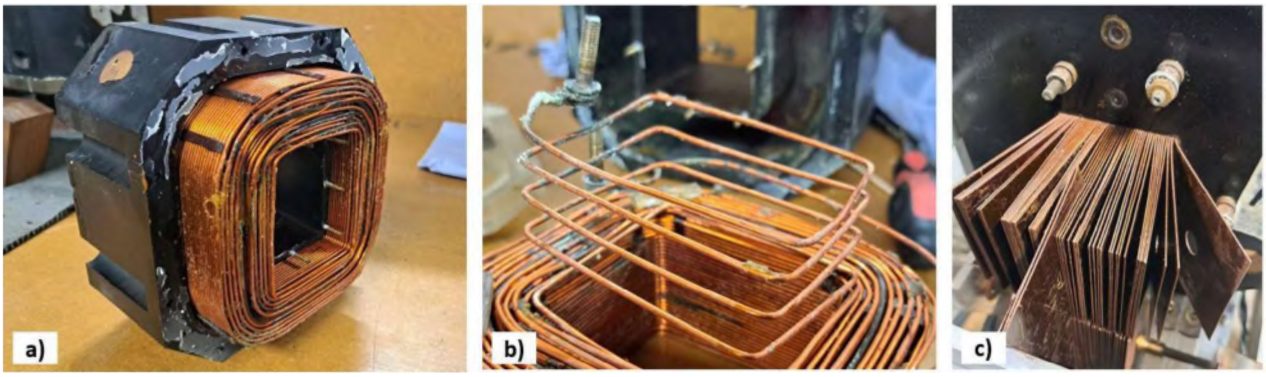

Fig. 4 Disassembly of the Oxford 3-DoF MSBS. (a): An opened casing showing the packaged coils. (b): Close-up showing deposition and corrosion on the coils and at the screw connection which forms the electrical terminal for the passage of current to the coils across the casing barrier. (c): Close up of the laminates that make up the core, with a small amount of rusting and forcibly splayed out to enable disassembly of the dovetail joint.

laminates meant some joints could not be taken apart without destroying the laminates (see Figure 6). Further, it is highly likely that subtle changes in the geometry of the cast casings, due to differential pressures across the walls, resulted in lift casings gripping very tightly to the core. Ultimately, to fully disassemble the balance, the cores were hammered out, destroying some of the casings in the process. Presently, new cores are being redesigned and manufactured by Tesla Engineering Ltd. The redesign maintains the dimensions of the original cores, but the laminates are bonded together such that each horseshow is assembled from three "blocks".

The copper coils themselves were found to be in decent condition (except for the corroded connections), with the enamel coating offering adequate protection alongside its initial purpose of insulating the individual turns from each other. Benchtop tests of continuity, resistance and inductance were conducted with the aid of Tesla Engineering Ltd to assess the state of each coil. A pulse test was, in which a pulse of electricity is passed through the coil and the returning signal monitored, was also conducted. This test assesses the integrity of the insulation between turns and the integrity of the coils themselves. Consider the below figures: Figure 5 shows the results of the pulse test of a pitch coil; this is a good result, showing a steadily decaying alternating voltage signal. In comparison, Figure 6 shows the result for one of the drag coils; this is a failed test indicating insufficient coil condition. This would not have been detected in a continuity test or resistance test. A diagnosis for this faulty coil has not yet been reached, though it is almost certain that the coil will need replacing.

Concurrently, work has been ongoing on migrating the system from a completely analogue control system to a computer-controlled system. A system architecture has been designed, shown in Figure 7, showing the interconnection between various MSBS and tunnel component. The original block diagrams produced by Haslam-Jones [5] will be implemented in MATLAB Simulink and deployed on National Instruments Veristand software, enabling control at near real-time speeds of up to lkHz. New AE Techron 7796 and 7224 power amplifiers were purchased to power the MSBS, with remote control capability. Work on the new system architecture continues.

4. Conclusion

The current Oxford MSBS has been used extensively in the late 20th century to conduct force measurements and flowfield surveys at hypersonic rarefied conditions. After sitting mothballed for the last 20 years, work has begun on refurbishing and recommissioning the device. Progress continues, with a first operation of the system targeted for Q1 2025.

Fig. 5 Pulse test of a pitch coil, showing a good result.

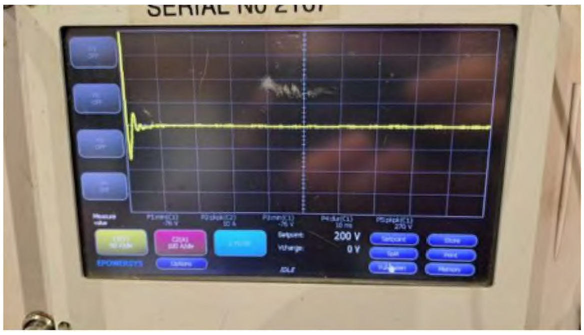

Fig. 6 Pulse test of a drag coil, showing a bad result.

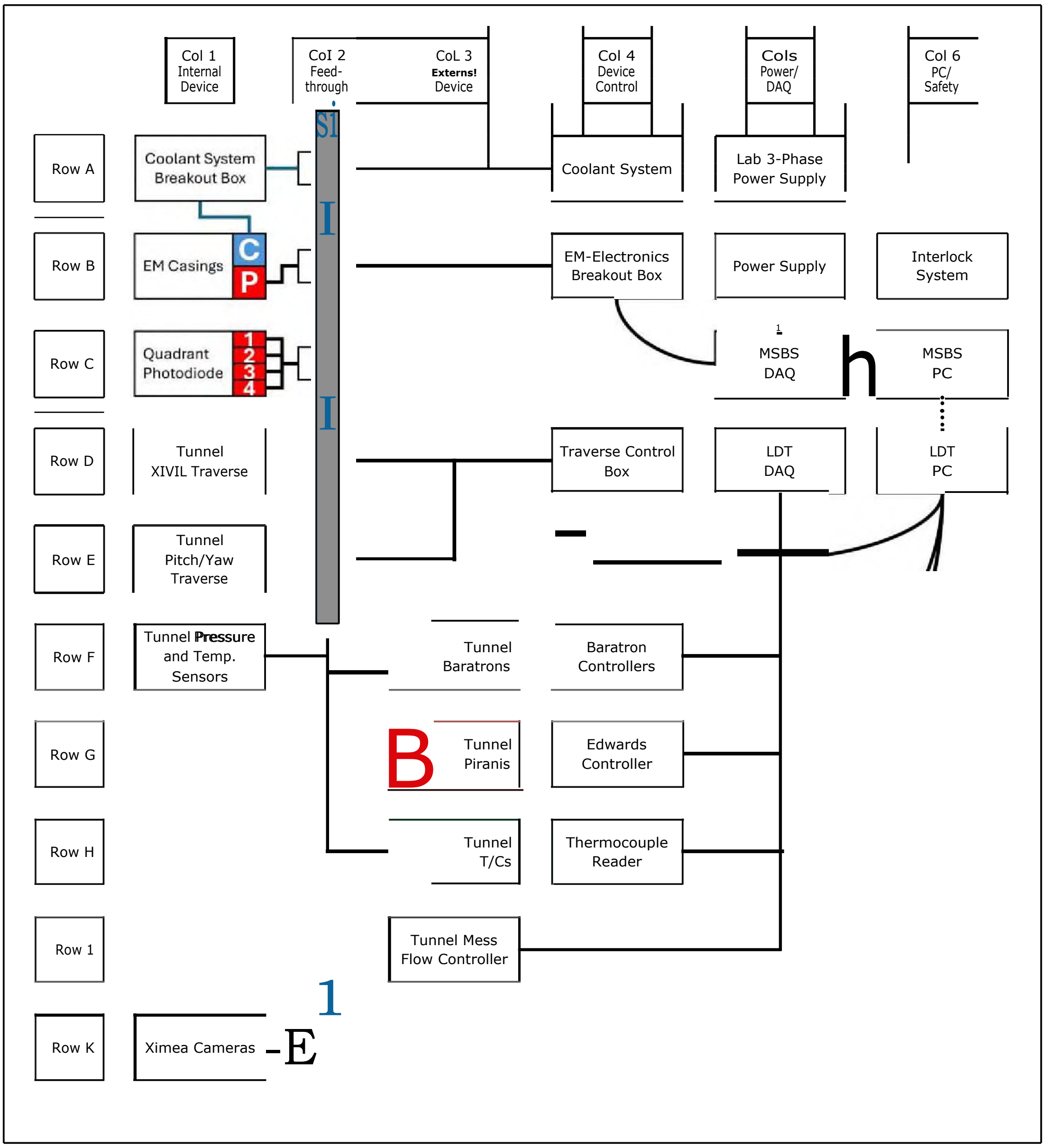

Fig. 7 System Architecture design of LDT and MSBS.

Acknowledgements

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