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THRUST MEASUREMENT USING SHAPIRO PROBE

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Abstract
A shapiro probe is a probe used to measure the total pressure at the exit of the nozzle. A shapiro probe is usually mounted at the end of the nozzle. When the air flows, a bow shock is formed in front of the shapiro probe. Assuming that, the shock is formed in front of the probe (just before the shapiro probe),by using the measured total pressure after the shock and the static pressure before the shock, it will be possible to determine the nozzle exit Mach number which in turn will help find the thrust using the normal shock relations. Mostly thrust cells were used to measure the accurate thrust, however in order to use the thrust cells, a separate thrust stand has to be developed. Also, the mounting the thrust stand into the system is quite and costly, particularly if there is vaccum exhaust. The method helps overcome these difficulties method helps overcome these difficulties by using shapiro probe. All the pressure measurements were communicated to the DAS (data acquisition system).
Keywords: CFD, Data Acquisition System.

I. Introduction

The experiments were carried out for both the atmospheric and vaccum condition (7kpa) exhaust for both the nozzles. The vaccum condition has been monitored by a separate pressure transducer. In order to take schlieren pictures of the nozzle flow the schlieren setup has been arranged as shown in fig1.1 For various inlet pressure, the experiments were repeated and schlieren photos taken. Fig 1.2 & 1.33 clearly shows the bow shock including the normal shock portion of it formed in front of the shapiro probe. The experiments were repeated for various inlet pressures and for both atmospheric and vaccum (7kpa) exhaust for both the rectangular nozzle axisymmetric nozzle. The data were collected using DAS along with lab view software and stored in the computer. Two methods of calculating the nozzle exit mach number were used. The first method used the total pressure ratio across the normal shock and its termed as "Nor Shock" in the graph. The second method used the ratio of total pressure downstream of the normal sock and the upstream static pressure at he nozzle exit. The thrust calculated using this method is termed as "Shapiro" in the graph. The ideal thrust was calculated from the thrust formula mentioned earlier for the same inlet operating conditions and is termed as "Tideal" in the graph. From the results, the exit mach number has been calculated for various inlet pressures, from which, thrust has been calculated and compared with both the ideal and CFD thrusts.

$$\frac{P_{o2}}{P_1} = \left[\frac{k+1}{2} M_1^{\;2}\right]^{\frac{k}{k-1}} \left[\frac{k+1}{2kM_1^{\;2} - (k+1)}\right]^{\frac{1}{k+1}}$$

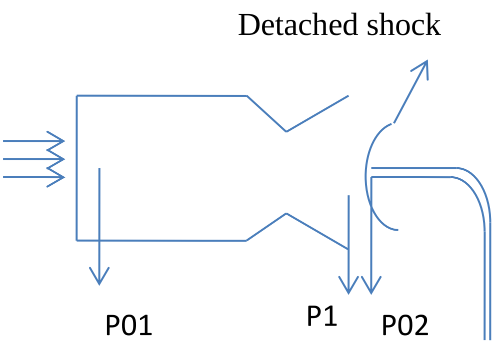

Fig 1.1 Thrust measurement using Shapiro

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If the pressure at the inlet is assumed to be constant throughout, that is no losses. Then, the normal shock relation between the upstream total pressure and downstream total pressure are used to find the Mach number and thrust.

$$\frac{P_{o2}}{P_{o1}} = \frac{\left[\frac{(k+1)M_1^{\,2}}{(k-1)M_1^{\,2}+2}\right]^{\frac{k}{k-1}}}{\left[1+\frac{2k}{k+1}(M_1^{\,2}-1)\right]^{\frac{1}{k-1}}}$$

where Po2- Downstream Total pressure
P1- Upstream Static pressure
M1 –Upstream Mach number

From the above equations Mach number can be calculated and for thrust the following equation is used.

Ae is the exit area.The thrusts we are calculating for various chamber pressures is for steady state only and has been validated with CFD results. The thrust for both rectangular nozzle and 2D Axisymmetric nozzles are calculated from the above equations and been plotted in a graph. The schematic diagram of the Shapiro probe setup is given in fig.1.2.

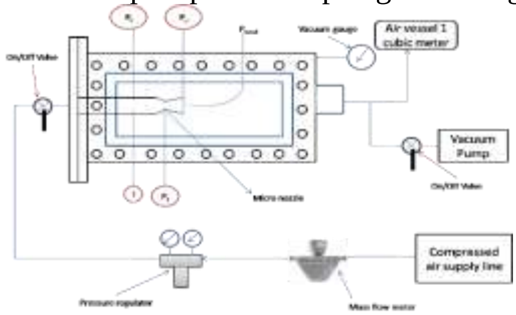

Fig.1.2 Test setup for Shapiro tube in vacuum condition

Fig.1.3 Flow in the 2D axisymmetric nozzle with Shapiro probe (P01=5 bar)

Fig.1.3 Flow in the rectangular nozzle with Shapiro probe mounted

The following graphs are plotted for various chamber pressures and for both vacuum condition of 0.07 bar and atmospheric exit conditions.

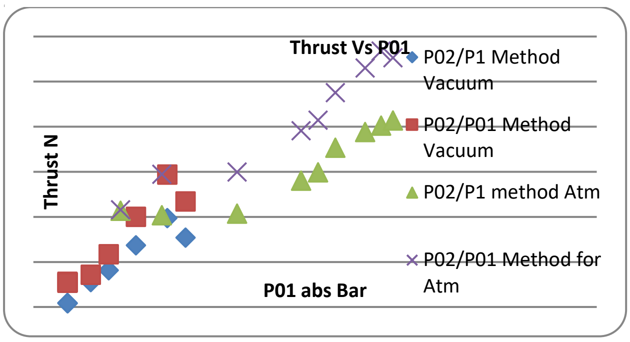

Fig.1.4 for 3D rectangular nozzle thrust Vs Pchamber For 2D axisymmetric nozzle

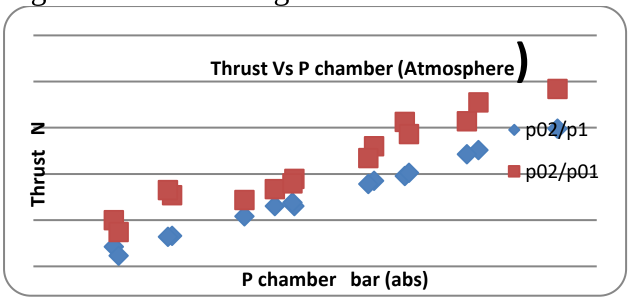

Fig.1.5 Thrust Vs Pchamber (Atmosphere)

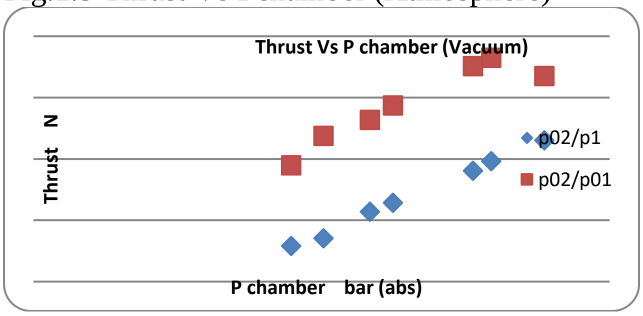

Fig.1.6 Thrust Vs Pchamber (Vacuum)

II. Validation with CFD

The thrusts calculated for various chamber pressures using Shapiro tube has been compared with the thrusts calculated from Computational Fluid Dynamics (CFD) analysis under same operating conditions. The ratio of thrust by Shapiro to thrust by CFD is calculated and plotted for various chamber pressures.

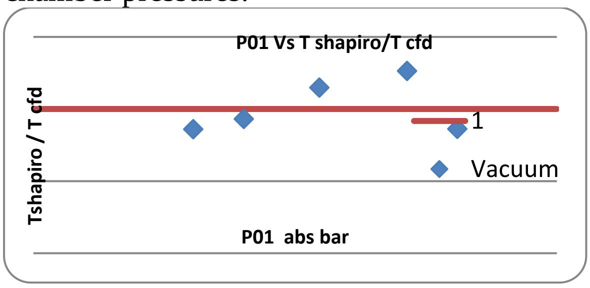

Fig.1.7 For 3D rectangular Nozzle (P01 Vs TShapiro/TCFD)

The CFD analysis for axisymmetric nozzle is currently running for various chamber pressures. Once the analysis is over, the thrust by Shapiro for Axisymmetric nozzle will be compared with the CFD results and will be plotted against various chamber pressures.

III. Schilieren

Schlieren imaging has also been taken for both the nozzles with shapiro probe mounted. Schlieren imaging is a method to visualize density gradient variations in transparent media. The classical implementation of an optical schilieren systems uses light from a single collimated source shining on, or from behind, a latest object. Variations in refractive index caused by density gradients in the fluid distort the collimated light beam. This distortion creates a spatial variation in the intensity of the light, which can be visualised directly with a shadowgraph system in flow of uniform density this will simply make the photograph half as bright. and parts which have been focused in an area covered by the knife edge are blocked. The result is a set of lighter and darker patches corresponding to positive and negative fluid density gradients in the direction normal to the knife edge. When a knife edge is used, the system is generally referred to as schlieren system, which measures the first derivative of density in the direction of the knife edge. If a knife edge is not used, the system is generally referred to as shadowgraph system, which measure the second derivative of density.for all the pressures and exit conditions (both vacuum and atmospheric), schlieren pictures have been taken. From the schieren pictures, it is easy to visualize the bow shock in front of the shapiro probe. On closer look, the assumption of the shock being normal just in front of the shapiro has been justified from the following figures.fig 4 &5 repreents variation of thrust with respect to variation of thrust with respect to various inlet pressures for both the rectangular nozzle and axisymmetric nozzle for vaccum and atmospheric conditions respectively. Thrust calculated by both the methods (using normal shock relation and shapiro probe) have been plotted for both thenozzles in the above graphs along with the ideal thrust. From the above graph, it is clear that the thrusts calculated using shapiro probe equation are quite close to the ideal thrust calculated using isentropic relations. Th thrust calculated using the normal shock relations are somewhat diverging from the ideal thrust.

IV. Conclusion

Thrusts were determined for both the nozzles and have been compared with the theorectical thrust values. It has been found that the thrusts calculated using shapiro probe are close to the ideal thrust. This behaviour is repeated for both the nozzles and for both atmospheric and vacuum exit conditions. However, the thrusts calculated using normal shock relations were foun to be differ considerably from the ideal thrust.

References

[1] Roberts, G., Calmer, R., et al., “multi-dimensional Cloud-aERosol Exploratory Study using RPAS (mCERES): Bottomup and top-down closure of aerosol-cloud interactions,” EGU General Assembly Conference Abstracts, Vol. 18, 2016, p. 6530.
[2] Bevacqua, G., Cacace, J., Finzi, A., and Lippiello, V., “Mixed-Initiative Planning and Execution for Multiple Drones in Search and Rescue Missions.” ICAPS, 2015, pp. 315–323.
[3] “SHERPA Project,” june 2016.
[4] Bronz, M. and Hattenberger, G., “Design of A High-Performance Tailless MAV Through Planform Optimization,” 33rd AIAA Applied Aerodynamics Conference, AIAA, 2015, pp. eISBN–978. 5Nio, J., Mitrache, F., Cosyn, P., and Keyser, R. D.,
[5] “Model Identification of a Micro Air Vehicle,” Journal of Bionic Engineering, Vol. 4, No. 4, 2007, pp. 227 – 236.
[6] Valavanis, K. P. and Vachtsevanos, G. J., Handbook of Unmanned Aerial Vehicles, chap. UAV Modeling, Simulation, Estimation, and Identification: Introduction, Springer Netherlands, Dordrecht, 2015, pp. 1215–1216.
[7] Simsek, O. and Tekinalp, O., “System Identification and Handling Quality Analysis of a UAV from Flight Test Data,” AIAA Atmospheric Flight Mechanics Conference, AIAA SciTech, AIAA 2015 , 2015.
[8] Edwards, D., “Performance Testing of RNR’s SBXC Using a Piccolo Autopilotd,” Tech. rep., 2007.

[9] Bronz, M. and Hattenberger, G., "Aerodynamic Characterization of an Off-the-Shelf Aircraft via Flight Test and Numerical Simulation," AIAA Flight Testing / Ground Testing Conference, Washington, DC , AIAA, June 2016.
[10] Stoll, A. M., Bevirt, J., Moore, M. D., Fredericks, W. J., and Borer, N. K., "Drag Reduction Through Distributed Electric Propulsion," Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia, 16-20 June 2014.
[11] Brisset, P., Drouin, A., Gorraz, M., Huard, P.-S., and Tyler, J., "The paparazzi solution," MAV2006, Sandestin, Florida, 2006.
[12] Hattenberger, G., Bronz, M., and Gorraz, M., "Using the Paparazzi UAV System for Scientific Research," IMAV 2014, International Micro Air Vehicle Conference and Competition 2014 , Delft, Netherlands, Aug. 2014, pp. pp 247–252.
[13] Hattenberger, G., Drouin, A., and Bronz, M., "Electric Propulsion System Characterization through Experiments," IMAV 2016, International Micro Air Vehicle Conference and Competition , Beijing, China, 2016.
[14] Edwards, D. J., "Autonomous Locator of Thermals (ALOFT) Autonomous Soaring Algorithm," Tech. rep., DTIC Document, 2015.
[15] Kahn, A. D. and Edwards, D. J., "Navigation, guidance and control for the CICADA expendable micro air vehicle," AIAA Guidance, Navigation, and Control Conf., 2012.