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Proposal to Use Reaction Jets for Variable Stability Airplanes

Brijesh Kumar* and S. Pradeep†
Indian Institute of Science, Bangalore 560 012, India

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Introduction

A TOTALLY new concept of control mechanism for a variable stability airplane (VSA) is proposed. The use of cold air jets to generate the required forces and moments when the variable stability systems (VSS) is engaged is envisaged. Feasibility analysis is provided for a medium-transport base airplane, which is conceived as a three-degree-of-freedom VSA platform.

A preliminary study was carried out to examine the approximate magnitude of the required thrust that is sought from the reaction jets or thrusters. This Technical Note puts forward two different analytical studies in support of the concept. The first analysis involves matching of stability and control derivatives of the host airplane with that of the other simulated airplanes. The second analysis involves simulation of other dihedral angles.

A preliminary feasibility study suggests that air-thruster-based VSS is a viable proposition. However, it also gives rise to a set of design issues that must be addressed comprehensively before commencing any experimentation.

Background

For over half a century of design and development of VSS, nearly all VSA have made use of conventional hydraulic actuation of control surfaces [1,2]. Apart from generating forces and moments as desired by the control laws, conventional aerodynamic surfaces also generate undesirable loads that must be eliminated or contained by the control laws to avoid motion discrepancies that otherwise creep in when VSS is engaged [3]. These discrepancies, both in nature and degree, affect the dynamic response of the airplane, and the measures adopted to minimize them tend to make control laws fairly complex [4]. Because the VSS is a closed-loop control system, the complexity of the entire system also builds up.

The alternative is to design and incorporate completely new systems that generate only the required forces and moments with relatively absent or minimal interaction effects, thereby ensuring frivolous or no drifts in stability-derivative matrices. Within the domain of established technical know-how, this Technical Note is intended to provide a possible solution by proposing to use responsive compressed air jets for generating the required forces and moments when the VSS is engaged for in-flight simulations.

Proposed Air-Thruster (Reaction-Jet)-Based VSS

Easy and simplistic modeling of the control laws and improved quality of simulation are the very objectives of this proposal. These objectives can be achieved only if the reaction jets do not produce unwanted loads by themselves. At low speeds and small deflections, aerodynamic control surfaces generate negligible undesirable loads. However, in high-speed-flight regimes or for large deflections, these loads are no longer negligible, and if the VSS cannot effectively compensate for them, it cannot be engaged to produce an acceptable in-flight simulation. This leads to a compromised flight envelope when the VSS can be engaged. Reaction jets, on the other hand, will not pose constraints on the VSS in this regard. The envisaged VSS retains the established architecture sans the hydraulic actuation systems for control surfaces that will be used only for normal flight operations of the host airplane. When the VSS is engaged, actuation of control surfaces will be disconnected using a safety trip mechanism, and a pneumatic control system powered by air bleeding from the engine core or individual thrusters will support air thrusters placed on the host airplane at preidentified suitable locations.

However, the proposed pneumatic system also comes with a few design issues. Its ability to provide sustained mass flow rate and regulated total pressure would dictate the effectiveness of the reaction jets. It may also affect test duration. The dynamic response of the air jets to the valve actuation, the bandwidth of the pneumatic system, and the quasi-static nature of compressed air jets are likely to become decisive design issues.

This technique is being proposed for the "model-following" VSA platforms, and the operational procedures remain nearly the same. Although the evaluation pilot is flying the model simulated by the VSS computer, the safety pilot will stay in a hands-off-the-controls situation while ensuring that the flight operations remain within the prescribed safety limits of the host airplane. All pilot control inputs in the VSS-engaged condition will be fed into the VSS computer (on which the mathematical model of the subject airplane is solved), which will generate commands for the pneumatic system controllers governed by a set of control laws. Pneumatic system controllers will then generate control commands for the activation and regulation of reaction jets. Airplane motion sensed by the usual sensory suit and processed in the aircraft data unit will be fed back into the VSS computer to close the control loop. On completion of the simulation, the VSS will be disengaged and the safety pilot will repossess the conventional control-surface-based flight controls.

Preliminary Feasibility Analysis

To determine the order of magnitude of forces and moments required of the thrusters, a three-degree-of-freedom VSA platform was conceived from a medium-transport host airplane (subscript HA). The first analysis consisted of matching significant stability and control derivatives of the other three simulated airplanes (subscript SA). The second analysis was carried out to estimate the roll thrust required to simulate different dihedral angles on the host airplane.

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*Doctoral Scholar, Department of Aerospace Engineering; brijesh@aero.iisc.ernet.in (Corresponding Author).

†Associate Professor, Department of Aerospace Engineering.

Stability and Control Derivative Analysis

To emulate or mimic the dynamic behavior of a subject or simulated airplane, the stability derivatives of the host airplane should be changed to match those of the simulated airplane. The thrusters must therefore compensate for the difference in these derivatives.

This analysis was carried out to examine the order of the required thrust that is demanded from the thrusters. Equations (1–11) indicate the thrust values that should be generated by the thrusters on the host airplane to match the important stability and control derivatives of a simulated airplane. Notations in all the equations, unless otherwise specified, are the popular standard adopted by Roskam [5].

Roll, pitch, and yaw thrusters were assumed to be tentatively "fixed" near the aerodynamic centers of the corresponding control surfaces, and the host and the simulated airplanes were considered to be flying under different flight conditions (see Table 1) under the standard atmosphere.

1) The roll thrusters' moment arm is $L_R = 6.2$ m.
2) The pitch thrusters' moment arm is $L_P = 6.6$ m.
3) The yaw thrusters' moment arm is $L_Y = 6.6$ m.

Matching Important Stability Derivatives

Case 1, matching C_{m_α}:

$$\frac{\partial}{\partial \alpha}[M_A] = C_{m_\alpha} q_1 S\bar{c}$$

Pitch-thruster requirement:

$$T_P = \frac{(C_{m_\alpha} \Delta\alpha q_1 S\bar{c})_{\mathrm{HA}} - (C_{m_\alpha} \Delta\alpha q_1 S\bar{c})_{\mathrm{SA}}}{L_P} \tag{1}$$

Case 2, matching C_{m_q}:

$$\frac{\partial}{\partial (q\bar{c}/2U_1)}[M_A] = C_{m_q} q_1 S\bar{c}$$

Pitch-thruster requirement:

$$T_P = \frac{(C_{m_q} \Delta q q_1 S\bar{c}/2U_1)_{\mathrm{HA}} - (C_{m_q} \Delta q q_1 S\bar{c}/2U_1)_{\mathrm{SA}}}{L_P} \tag{2}$$

Case 3, matching C_{l_β}:

$$\frac{\partial}{\partial \beta}[L_A] = C_{l_\beta} q_1 Sb$$

Roll-thruster requirement:

$$T_R = \frac{(C_{l_\beta} \Delta\beta q_1 Sb)_{\mathrm{HA}} - (C_{l_\beta} \Delta\beta q_1 Sb)_{\mathrm{SA}}}{L_R} \tag{3}$$

Case 4, matching C_{n_β}:

$$\frac{\partial}{\partial \beta}[N_A] = C_{n_\beta} q_1 Sb$$

Yaw-thruster requirement:

$$T_Y = \frac{(C_{n_\beta} \Delta\beta q_1 Sb)_{\mathrm{HA}} - (C_{n_\beta} \Delta\beta q_1 Sb)_{\mathrm{SA}}}{L_Y} \tag{4}$$

Case 5, matching C_{l_p}:

$$\frac{\partial}{\partial (pb/2U_1)}[L_A] = C_{l_p} q_1 Sb$$

Roll-thruster requirement:

$$T_R = \frac{(C_{l_p} \Delta p q_1 Sb/2U_1)_{\mathrm{HA}} - (C_{l_p} \Delta p q_1 Sb/2U_1)_{\mathrm{SA}}}{L_R} \tag{5}$$

Case 6, matching C_{n_p}:

$$\frac{\partial}{\partial (pb/2U_1)}[N_A] = C_{n_p} q_1 Sb$$

Yaw-thruster requirement:

$$T_Y = \frac{(C_{n_p} \Delta p q_1 Sb/2U_1)_{\mathrm{HA}} - (C_{n_p} \Delta p q_1 Sb/2U_1)_{\mathrm{SA}}}{L_Y} \tag{6}$$

Case 7, matching C_{l_r}:

$$\frac{\partial}{\partial (rb/2U_1)}[L_A] = C_{l_r} q_1 Sb$$

Roll-thruster requirement:

$$T_R = \frac{(C_{l_r} \Delta r q_1 Sb/2U_1)_{\mathrm{HA}} - (C_{l_r} \Delta r q_1 Sb/2U_1)_{\mathrm{SA}}}{L_R} \tag{7}$$

Case 8, matching C_{n_r}:

$$\frac{\partial}{\partial (rb/2U_1)}[N_A] = C_{n_r} q_1 Sb$$

Yaw-thruster requirement:

$$T_Y = \frac{(C_{n_r} \Delta r q_1 Sb/2U_1)_{\mathrm{HA}} - (C_{n_r} \Delta r q_1 Sb/2U_1)_{\mathrm{SA}}}{L_Y} \tag{8}$$

Matching Important Control Derivatives

Case 9, matching $C_{m_{\delta_e}}$:

$$\frac{\partial}{\partial \delta_e}[M_A] = C_{m_{\delta_e}} q_1 S\bar{c}$$

Pitch-thruster requirement:

$$T_P = \frac{(C_{m_{\delta_e}} \Delta\delta_e q_1 S\bar{c})_{\mathrm{HA}} - (C_{m_{\delta_e}} \Delta\delta_e q_1 S\bar{c})_{\mathrm{SA}}}{L_P} \tag{9}$$

Table 1 Host airplane and simulated airplane data

Type	Civil medium transport (host airplane)	Four-seater light airplane (simulated airplane: SA 1)	Medium-weight business jet (simulated airplane: SA 2)	Small jet trainer (simulated airplane: SA 3)
Flight state	Cruise	Cruise	Power approach	High cruise
Altitude, km	6.1	1.5	Std. sea level	10.5
Weight, kN	48.94	11.76	57.82	17.8
Speed, m/s	135.4	66.75	51.8	178.0
Wing area, m^2	25.36	16.16	21.37	12.63
Span, m	13.84	10.91	10.36	8.0
MAC, m	1.95	1.5	2.13	1.65

Case 10, matching $C_{n_{\delta_r}}$:

$$\frac{\partial}{\partial \delta_r}[N_A] = C_{n_{\delta_r}} q_1 S b$$

Yaw-thruster requirement:

$$T_Y = \frac{(C_{n_{\delta_r}} \Delta\delta_r q_1 S b)_{\mathrm{HA}} - (C_{n_{\delta_r}} \Delta\delta_r . q_1 S b)_{\mathrm{SA}}}{L_Y} \tag{10}$$

Case 11, matching $C_{l_{\delta_a}}$:

$$\frac{\partial}{\partial \delta_a}[L_A] = C_{l_{\delta_a}} q_1 S b$$

Roll-thruster requirement:

$$T_R = \frac{(C_{l_{\delta_a}} \Delta\delta_a q_1 S b)_{\mathrm{HA}} - (C_{l_{\delta_a}} \Delta\delta_a q_1 S b)_{\mathrm{SA}}}{L_R} \tag{11}$$

where S is the wing planform area and q_1 is the local steady-state dynamic pressure.

Typical thrust required on the thrusters corresponding to each case of matching the derivative are shown in Fig. 1, which provides an idea of the magnitude of thrust required on the thrusters. All the thrust values are below 10 kN. Higher thrust demand on the pitch thrusters to simulate C_{m_α} and $C_{m_{\delta_e}}$ can be attributed to the greater differences in pitching moments. Thrust requirement to simulate C_{m_q}, C_{n_β}, C_{n_p}, C_{l_r}, C_{n_r}, and $C_{n_{\delta_r}}$ are below 2 kN.

In a similar fashion, extreme cases can be examined to arrive at the maximum thrust values for which all the thrusters must be designed.

Dihedral Matching Analysis

Another preliminary study to simulate other dihedral angles on the host airplane was performed to gauge the magnitude of the required roll thrust. The host airplane, a low-wing configuration with a 4-deg geometric dihedral, was subjected to various positive sideslip angles to change its effective dihedral (thereby simulating another dihedral). The effective dihedral on the main wing changes owing to corresponding changes in the effective angle of attack. A simple mathematical argument can be given as follows to arrive at the required thrust values.

If the airplane is assumed to have been subjected to positive sideslip, the angle of attack on the starboard wing increases, whereas it decreases on the port wing by the same amount:

$$\alpha = \beta\Gamma + \alpha_\circ \tag{12}$$

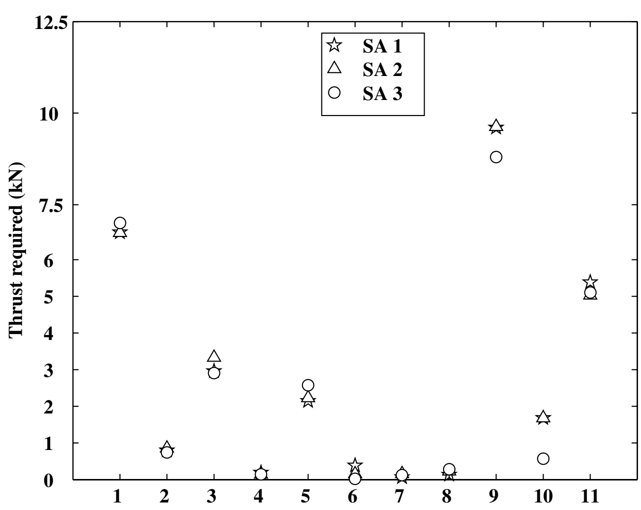

Fig. 1 Thrust requirements to simulate/match the stability and control derivatives of other airplanes.

where α_o is the angle of attack on wings when $\beta = 0$. The change in angle of attack can be given by

$$\Delta\alpha = \beta\Delta\Gamma$$

Note that $\Delta\Gamma = |\Gamma_{\mathrm{SA}} - \Gamma_{\mathrm{HA}}|$, where $\Gamma_{\mathrm{HA}} = 4$ deg.

The change in the lift coefficient is

$$\Delta C_L = C_{L_{\alpha_w}} \Delta\alpha \tag{13}$$

where $C_{L_{\alpha_w}}$ is the lift curve slope for the host airplane. The lift reduces on the starboard wing, whereas it increases on the port side by the same amount, thereby creating a rolling moment that is given by

$$M = (\Delta L)d \qquad M = (q_1 S \Delta C_L)d \tag{14}$$

where ΔC_L is the change in the lift coefficient, d is the distance between the line of action of the lift vectors acting on the starboard and port wing, and y is the spanwise separation between roll thrusters.

To simulate a different dihedral for another airplane, the roll thrusters must produce a moment M, which is given by $M = yT_R$.

Therefore, the thrust required is equal to

$$T_R = \frac{q_1 S \Delta C_L d}{y} \tag{15}$$

Roll-thrust values obtained using Eq. (15) are well below 4 kN when the dihedral was simulated up to 6 deg for varying amounts of positive sideslip (see Fig. 2). Roll-thrust values were also obtained under different flight conditions to produce a change in the effective dihedral by 3 and 4 deg for sideslip angles of 5 and 10 deg, respectively (see Figs. 3 and 4).

This analysis provided us with an estimate of magnitude of the thrust required on roll thrusters. Higher roll thrust is required to simulate a greater amount of dihedral at any test point in the flight envelope. To simulate a particular dihedral at a given test altitude, demand for roll thrust increases rapidly with increasing flight speed. On the other hand, when the airspeed is held constant, the requirement for roll thrust to simulate a particular amount of dihedral decreases at higher altitudes.

Design Concerns

Designing and testing a well-controlled pneumatic system to power the reaction jets will be the major assignments. The integration of this system with the rest of the VSS would help to determine the safety protocol for the VSS-engaged flight modes.

The proposed pneumatic system also comes with new design-related issues. Its ability to provide sustained mass flow rate with

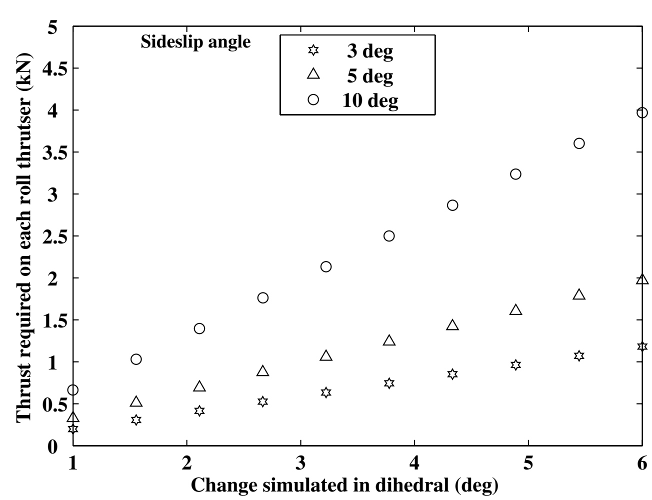

Fig. 2 Roll-thrust requirement to simulate other dihedral angles ($\Delta\Gamma = 1$–6 deg) on the host airplane in cruise conditions.

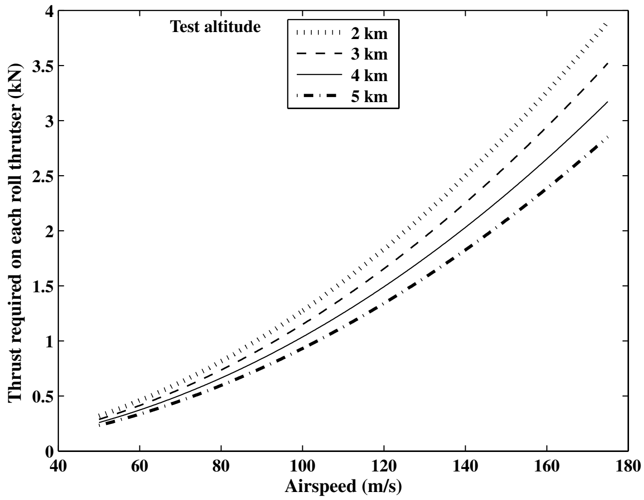

Fig. 3 Roll-thrust requirement to simulate $\Delta\Gamma = 3\,\mathrm{deg}$ for $\beta = 5\,\mathrm{deg}$ under different flight conditions.

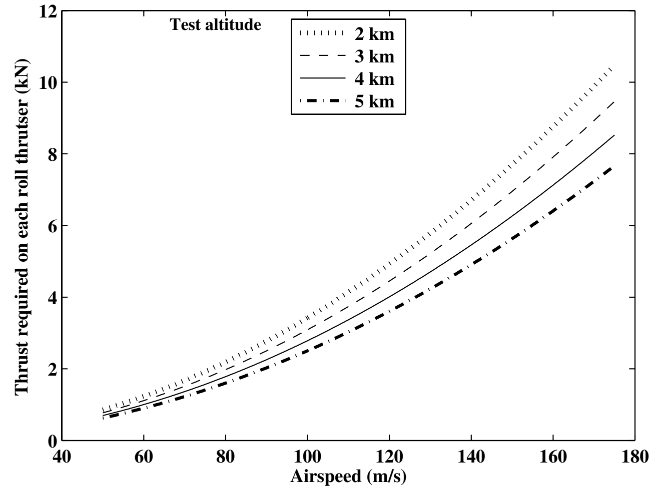

Fig. 4 Roll-thrust requirement to simulate $\Delta\Gamma = 4\,\mathrm{deg}$ for $\beta = 10\,\mathrm{deg}$ under different flight conditions.

regulated total pressure would dictate the effectiveness of the reaction jets and may also affect the test-duration limits. The dynamic response of the thrusters to the valve actuation has to be tested to achieve the desired bandwidth of the pneumatic system.

Therefore, the proposed system must satisfy the following set of design requirements: 1) highly responsive thrusters, 2) the ability of the thrusters to provide sustained thrust forces for long durations, and 3) fluctuation-free regulation of thrust forces.

These requirements will push the state of technology used in a few existing pneumatic systems of similar type. Highly responsive actuators, safety valves, and regulatory valves hold the key to the bandwidth requirements. The means adopted to generate compressed air should not affect the airplane state adversely due to their operations. Jet-discharge ambient conditions should also be considered as inputs to the VSS. Interaction of the pressurized air jet discharge and the airflow in the proximity of the thrusters must be examined for any adverse effect on the airplane performance. Finally, the quasi-static nature of a compressed air jet must be considered because the pneumatic system controllers will have to compensate for any deviation from the commanded thrust values.

Conclusions

The new system is believed to improve the operational safety level and system reliability and would be relatively easier to model.

The preliminary study, which was carried out to exhibit methodologies to arrive at the design thrust values, shows that the demanded thrust values will be on the order of a few kilonewtons or less. It was found that for the chosen host airplane, when engaged as a VSA platform with a simulation envelope big enough to cover the other three simulated airplanes, the pitch and roll thrusters should be designed to cater to the maximum thrust value of about 10 kN.

The operational requirements of the pneumatic system will give rise to a set of critical design issues pertaining to the system controllability and bandwidth. It was also realized that such thruster-based VSS is best suited for airplanes from the medium-weight category. Nevertheless, a comprehensive experimental study for a full-scale prototype is required to establish and refine the VSS design.

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