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Trade-off design of measurement tap configuration and solving model for a flush air data sensing system ☆

YanBin Liu *, DiBo Xiao

College of Astronautics, Nanjing University of Aeronautics and Astronautics, 29 Yudao St., Nanjing 210016, China

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ABSTRACT

This paper presents a trade-off design scheme with consideration of the pressure-tap configuration and solving model for a Flush Air Data Sensing System (FADS). First, a mechanism model of FADS is built for the basic structure in order to transform the measured pressures to the required air data. Then, several iteration algorithms are introduced for FADS to obtain the converging results of the solving model. Furthermore, four kinds of the pressure-tap configurations are designed in the relation to the basic structure, and the issues on the iteration convergence and modeling errors are discussed to analyze the compromise relations between the pressure-tap configuration and solving model. Lastly, a simulation example is applied to verify the feasibility of this proposed scheme, and at the same time some suggestions in the real application are provided for FADS.

1. Introduction

The Flush Air Data Sensing System (FADS) is developed with the increasing demands on the flight control system, such as the more accurate attitude tracking and holding, more rapid command response and multi-task switching [1]. Accordingly, the operation performances of the sensors will enhance in accordance with matching such complicated control goals. In practice, the angle of attack and sideslip angle tend to be difficult to precisely measure due to the uncertain and unknown disturbances induced by the flight itself [2]. On the other hand, these angles are important for the accurate attitude control determining the flight performances of the advanced airplane. Thus, the development of FADS is essential to satisfy the challenging flight tasks [3].

Recently, FADS is used for some high performance airplanes such as F-18, X-43A, and X-31. For example, the hypersonic vehicle X-43A combined FADS with the inertial system so as to hold the anticipated angle of attack which is critical for the scramjet operation [4]. More importantly, the previous devices for measuring the flight attitude cannot be adopted for the hypersonic vehicle because of the high surface temperature, as a result, the application of FADS becomes a critical event to implement the hypersonic flight task. In principle, the expected air data can be gotten using FADS which can transform the pressure signals to the resulting parameters, including the dynamic and static pressure, flight Mach, and airflow angles [5]. Nevertheless, the established model of FADS is highly nonlinear and strong coupling, and this makes that the numerical solutions are difficult to obtain rapidly [6]. Thus, some iteration algorithms are developed for meeting the computing requirements. In particular, the least squares method and three point mean are respectively applied for F-18 and X-33 to acquire the air data, while guaranteeing the fast convergence and good calculation precision [7]. In addition, the neural network and look-up methods are adopted to improve the real-time solving characteristics for FADS [8]. Apart from the solving model and iterative algorithms, there are also some other important aspects that need to be paid an attention, such as the fault diagnosis and data calibration [9]. Furthermore, the relations between the measure-tap layout and solving model should be carefully discussed to optimize the overall performance of FADS.

Based on this, this paper will study the compromise design problem with respect to the pressure-tap configuration and solving model in order to understand the intrinsic properties of FADS and to grasp the contradictory relationship between the system complexity and satisfactory performance. There are three aspects of this design problem have to be addressed. This first question involves the solving model and algorithms for the basic structure to build the relations between the pressure inputs and parameter outputs. The second problem relates to the compromise analysis based on the different configurations, while considering the

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* Corresponding author.
E-mail address: nuaa_liuyanbin@139.com (Y. Liu).

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modeling errors and iterative convergence. The third aspect deals with the feasible simulation to test the effectiveness of the proposed methods, and to obtain the valuable results from the viewpoint of the real application.

2. Measurement theory and solving algorithm for a flush air data sensing system

In this paper, we consider the following structure of FADS, shown in Fig. 1.

Fig. 1 demonstrates the basic layout of the measurement taps where there exist five measurement taps which can obtain the surface pressures. Theoretically, the flush air data sensing system is used to acquire the flight states and environment parameters based on the measured pressures of the surface taps. To this end, the pressure for any surface tap $p(\theta)$ can be expressed as [10]

$$p(\theta) = q_c(\cos^2\theta + \varepsilon\sin^2\theta) + P_\infty \tag{1}$$

where q_c and P_∞ represent the dynamic pressure and static pressure, respectively; θ, called the airflow incidence angle, is defined as the angle between the surface normal direction and flow velocity vector direction for any surface tap. In (1), The shaped pressure coefficient ε needs to be calibrated with the flight Mach M_∞, angle of attack α, and sideslip angle β using the experimental methods, provided by [11]

$$\varepsilon = f(\alpha, \beta, M_\infty) \tag{2}$$

In addition, θ is the related function with respect to the angle of attack and sideslip angle, given as [12]

$$\cos\theta = \cos\alpha\cos\beta\cos\lambda + \sin\beta\sin\phi\sin\lambda + \sin\alpha\cos\beta\cos\phi\sin\lambda \tag{3}$$

where ϕ and λ are the circumferential angle and cone angle for any measurement tap, respectively. For (1), according to the isentropic flow method and Rayleigh Pitot tube formula, the relation between the flight Mach and dynamic and static pressure is approximately determined by [13]

$$\frac{q_c}{P_\infty} = \begin{cases} \left[1 + \frac{\gamma-1}{2}M_\infty^2\right]^{\frac{\gamma}{\gamma-1}} - 1 & M_\infty \leqslant 1 \\ \frac{\left[\frac{\gamma+1}{2}M_\infty^2\right]^{\frac{\gamma}{\gamma-1}}}{\left[\frac{2\gamma}{\gamma+1}M_\infty^2 - \frac{\gamma-1}{\gamma+1}\right]^{\frac{1}{\gamma-1}}} - 1 & M_\infty > 1 \end{cases} \tag{4}$$

where γ is the specific heat ratio. Obviously, the angle of attack, sideslip angle, dynamic and static pressure can be obtained by solving the resulting model of FADS which is constituted with (1)–(4). However, the solving model of FADS is highly nonlinear and depends on the experimental results, so how to get the required parameters from such complicated model becomes a critical work for FADS to satisfy the application demands. To this end, some solving methods are developed for FADS, including the least squares method, three-point method, look-up table method and so on [14].

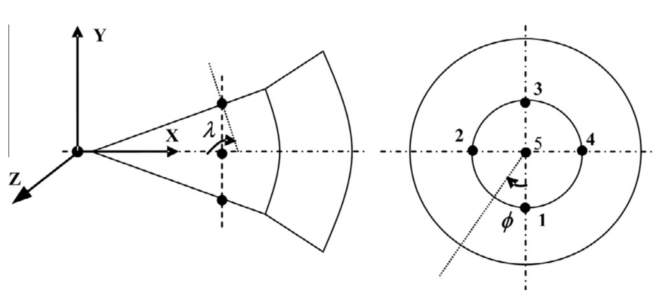

Fig. 1. Basic structure of FADS.

First, the three-point method is used to estimate the angle of attack and sideslip angle based on these pressures gotten for the measurement taps in Fig. 1 [15]. They are expressed by

$$\alpha = \begin{cases} \frac{1}{2}\tan^{-1}\frac{A}{B} & |\alpha| \leqslant 45^\circ \\ \frac{1}{2}\left(\pi - \tan^{-1}\frac{A}{B}\right) & |\alpha| > 45^\circ \end{cases} \tag{5}$$

$$\beta = \begin{cases} \tan^{-1}\left(-\frac{B'}{2A'} \pm \sqrt{\left(\frac{B'}{2A'}\right)^2 - \frac{C'}{A'}}\right) & A' \neq 0 \\ \frac{1}{2}\tan^{-1}\frac{C'}{B'} & A' = 0 \end{cases} \tag{6}$$

$$\begin{cases} A = \left(\Gamma_{kj}\sin^2\lambda_i + \Gamma_{ik}\sin^2\lambda_j + \Gamma_{ji}\sin^2\lambda_k\right) \\ B = \Gamma_{kj}\cos\lambda_i\sin\lambda_i\cos\phi_i + \Gamma_{ik}\cos\lambda_j\sin\lambda_j\cos\phi_j + \Gamma_{ji}\cos\lambda_k\sin\lambda_k\cos\phi_k \end{cases} \tag{7}$$

$$\begin{cases} A' = \Gamma_{kj}b_i^2 + \Gamma_{ik}b_j^2 + \Gamma_{ji}b_k^2 \\ B' = \Gamma_{kj}a_ib_i + \Gamma_{ik}a_jb_j + \Gamma_{ji}a_kb_k \\ C' = \Gamma_{kj}a_i^2 + \Gamma_{ik}a_j^2 + \Gamma_{ji}a_k^2 \end{cases} \tag{8}$$

$$\begin{cases} \Gamma_{ij} = -\Gamma_{ji} = P_i - P_j \\ \Gamma_{jk} = -\Gamma_{kj} = P_j - P_k \\ \Gamma_{ki} = -\Gamma_{ik} = P_k - P_i \end{cases} \tag{9}$$

where i, j and k are the number of the different measurement taps, given in Fig. 1. In fact, for each measurement tap, the acquired angle of attack and sideslip angle is slightly different due to the influence induced by the local airstream. In turn, based on the measured values of any three taps, we can solve the according results in terms of (5)–(9), and the average value of these results are considered as the expected angle of attack and sideslip angle. Once the angle of attack and sideslip angle are identified, the following work is to identify the shaped pressure coefficient ε.

Obviously, ε is expressed as a function of α, β and M_∞ in (2). To this end, the changes in α, β and M_∞ will lead to the different ε as a result that the nonlinear relation among them can be plotted as a resulting figure. As soon as ε is solved, the static and dynamic pressures are completely computed accordingly [15].

In addition to the three-point method, the least squares solving algorithm can be also used to identify the relationship between the acquired pressures of the measurement taps and solving data parameters. According to the fundamental model of FADS in (1)–(4), we have

$$p_i = F_i(\theta_i(\alpha, \beta), q_c, P_\infty, \varepsilon(\alpha, \beta, M_\infty(q_c, P_\infty))) = F_i(\alpha, \beta, q_c, P_\infty) \tag{10}$$

By using the Taylor expansion the linearization expression in (10) along with the given point $(\alpha^j, \beta^j, q_c^j, P_\infty^j)$ is approximately described as [16]

$$\begin{aligned} p_i \approx{}& F_i\left(\alpha^j, \beta^j, q_c^j, P_\infty^j\right) + \left(\frac{\partial F_i}{\partial \alpha}\right)_{(\alpha^j, \beta^j, q_c^j, P_\infty^j)}(\alpha - \alpha^j) \\ &+ \left(\frac{\partial F_i}{\partial \beta}\right)\Big|_{(\alpha^j, \beta^j, q_c^j, P_\infty^j)}(\beta - \beta^j) + \left(\frac{\partial F_i}{\partial q_c}\right)\Big|_{(\alpha^j, \beta^j, q_c^j, P_\infty^j)}(q_c - q_c^j) \\ &+ \left(\frac{\partial F_i}{\partial P_\infty}\right)\Big|_{(\alpha^j, \beta^j, q_c^j, P_\infty^j)}\left(P_\infty - P_\infty^j\right) \end{aligned} \tag{11}$$

After that, the least square method is used based on the Newton iterative principle, and the critical point for this method lies in the solutions with regard to some partial derivative matrices. Nevertheless, these partial derivatives result in the slow processing speed. To this end, the three points method can be merged into