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Airplane loss of control problem: Linear controllability analysis

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ABSTRACT

The controllability analysis for airplane flight dynamics is very crucial in upset/loss-of-control situations. Conventional airplanes are normally equipped with so redundant control authority. That is, an airplane might experience a loss of one or more control surfaces and remain controllable. As such, the aim of this paper is to investigate common upset situations and to explore the limits of controllability using linear analysis tools with emphasis on analysis of Thrust-only Flight Control Systems (TFCSs) where all the hydraulic systems are lost. Based on those analyses, the necessity of nonlinear controllability analysis for such situations is discussed.

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1. Introduction

Control loss of an airplane, known in literature as loss-of-control, is a serious problem whose repercussions can be catastrophic. Luckily, conventional airplanes may still be controllable if one or more control surfaces fail. For example, if an airplane lost all of its control surfaces due to hydraulic failure, it may still be controllable by manipulating the engines thrust forces. There are two common incidents in history that support such a fact. In 1989, the United Airlines Flight 232 DC-10 aircraft lost flight control surfaces due to hydraulic pressure loss because of a failure in its tail-mounted engine. However, the crew managed to control the airplane until they reached an airport. Nevertheless, the aircraft lost balance just before touchdown leading to a wing-tip crash into the run way, which in turn, led to the aircraft breaking apart. But 185 people survived out of the 296 on board. The 2003 DHL A300-B4 aircraft incident is another example. The aircraft was hit by a ground-to-air missile during initial climb right after takeoff from Baghdad airport. As such, all hydraulics were lost within few seconds. However, the crew managed to land the airplane safely using only thrust controls. Of course, there are other examples of flight control failures where the crew could not avoid the worst case scenario such as the 1974 Turkish Airlines Flight 981. The DC-10 aircraft lost the cargo door, which leads to a damage in the control cables. The aircraft crashed a minute later and none of the 346 people on board survived.

The above incidents among others invoked design and analysis of a thrust-only flight control system (TFCS) or a propulsion controlled aircraft (PCA). These systems have been investigated in the 1990s by Burcham et al. [5,6] and Tucker [20] at NASA Dryden Flight Research Center. They developed a computer-assisted engine control system, implemented and tested it on the F-15 fighter aircraft and the MD-11 transport aircraft. In his study of the 2003 DHL A300-B4 aircraft incident, Lemaignan [13] analyzed the applicability of TFCSs. More recently, Yamasaki et al. [22], at Mitsubishi Heavy Industries, developed a TFCS system for the Boeing 747-400 and validated it by testing in a domed simulator.

On the other hand, Wilborn and Foster [21], at Boeing Company and NASA Langley Research Center, presented a quantitative measures for loss-of-control in commercial transport aircraft. They presented five envelopes relating to airplane flight dynamics, aerodynamics, structural integrity, and flight control use that can reliably identify key Loss-of-control characteristics. Also, Kwatny et al. [12] presented a nonlinear analysis for aircraft loss-of-control. They examined the ability to regulate an aircraft around stall points with emphasis on impaired aircraft and presented some examples using NASA's generic transport model.

The objective of this paper is to formulate the airplane loss of control (LOC) into a controllability framework. It is understandable that controllability of a linearized model is not necessary. That is there exists a class of systems that are linearly uncontrollable but nonlinearly controllable, see for example Sec. 3.1 in Ref. [17]. However, the linear analysis should be performed first because of its sufficiency. Then nonlinear analysis should be employed in the cases where the linear analysis fails. Therefore, the current effort is to perform linear controllability analysis for some LOC cases (e.g., no elevator) and identify situations where nonlinear analysis

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is required. A successive effort will be to discuss nonlinear controllability and apply it to these situations.

In this work, a linear decoupled six-degrees-of-freedom flight dynamic model is considered. Controllability of the linearized model about the cruise equilibrium is assessed at no-elevator, no-aileron, no-rudder, and no-thrust situations. In particular, the landing-approach problem using TFCS is analyzed. Also, the concerns raised by Lemaignan [13] and Nguyen et al. [16] are addressed. Finally, LOC situations that necessitate nonlinear controllability analysis are provided for a successive effort.

2. Linear controllability analysis

Controllability is defined as the ability to steer a given system from some configuration into another configuration in finite time. A linear time-invariant (LTI) system is written in the form

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) \tag{1}$$

where $\boldsymbol{x}$ is the state vector $(n \times 1)$, $\boldsymbol{u}$ is the control input vector $(m \times 1)$, $\boldsymbol{A}$ is the state matrix $(n \times n)$, and $\boldsymbol{B}$ is the input matrix $(n \times m)$. A necessary and sufficient condition for the controllability of the system (1) is that the $(n \times nm)$ controllability matrix

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{B} & \boldsymbol{A}\boldsymbol{B} & \boldsymbol{A}^2\boldsymbol{B} & \ldots. & \boldsymbol{A}^{n-1}\boldsymbol{B} \end{bmatrix} \tag{2}$$

to be of full rank (i.e. $\mathrm{rank}(\boldsymbol{C}) = n$) which is often denoted by Kalman rank condition [18].

Luckily, controllability of linear systems is constructive. That is, if the matrix $\boldsymbol{C}$ is of full rank, then the following relation provides a control input history that steers the system (1) from $\boldsymbol{x}_0$ at t_0 to $\boldsymbol{x}_1$ at t_1 [3, pp. 74–77]

$$\begin{aligned} \boldsymbol{u}(t) &= -\boldsymbol{B}'\,\boldsymbol{\Phi}'(t_0,t)\,\boldsymbol{W}^{-1}(t_0,t_1)\left(\boldsymbol{x}_0 - \boldsymbol{\Phi}(t_0,t_1)\,\boldsymbol{x}_1\right) \\ \boldsymbol{W}(t_0,t_1) &= \int_{t_0}^{t_1} \boldsymbol{\Phi}(t_0,t)\,\boldsymbol{B}\,\boldsymbol{B}'\,\boldsymbol{\Phi}'(t_0,t)\,dt \end{aligned} \tag{3}$$

where $(.)'$ denotes the transpose, $\boldsymbol{\Phi}$ is the state transition matrix which is defined as $\Phi(t_0,t) = e^{\boldsymbol{A}(t_0-t)}$. It should be noted that the control law (3) minimizes the integral $\int_{t_0}^{t_1} ||\boldsymbol{u}(t)||^2 dt$ of control energy needed for steering.

On the other hand, for nonlinear, control-affine system in the form

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \sum_{i=1}^{m} \boldsymbol{g_i}(\boldsymbol{x})u_i \tag{4}$$

where $\boldsymbol{f}(\boldsymbol{x})$ is the drift vector field (uncontrolled dynamics) and $\boldsymbol{g_i}(\boldsymbol{x})$ is the control input vector field associated with the control input u_i. Assume, without loss of generality, that $\boldsymbol{x}_0$ is an equilibrium point (i.e. $\boldsymbol{f}(\boldsymbol{x}_0) = 0$). A sufficient condition for the local controllability of the system (4) at $\boldsymbol{x}_0$ is that the linearization about $\boldsymbol{x}_0$, written as

$$\Delta\dot{\boldsymbol{x}} = \left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]\Bigg|_{\boldsymbol{x}_0} \Delta\boldsymbol{x} + \sum_{i=1}^{m} \boldsymbol{g_i}(\boldsymbol{x}_0)u_i \tag{5}$$

to be controllable. That is, the controllability matrix

$$\begin{aligned} \boldsymbol{C} = \Bigg[&\boldsymbol{g_1}(\boldsymbol{x}_0), \ldots, \boldsymbol{g_m}(\boldsymbol{x}_0), \left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]\Bigg|_{\boldsymbol{x}_0} \boldsymbol{g_1}(\boldsymbol{x}_0), \ldots, \left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]\Bigg|_{\boldsymbol{x}_0} \boldsymbol{g_m}(\boldsymbol{x}_0), \ldots \\ &\ldots, \left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]^{n-1}\Bigg|_{\boldsymbol{x}_0} \boldsymbol{g_1}(\boldsymbol{x}_0), \ldots, \left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]^{n-1}\Bigg|_{\boldsymbol{x}_0} \boldsymbol{g_m}(\boldsymbol{x}_0)\Bigg] \end{aligned} \tag{6}$$

to be of full row rank [17]. It is noteworthy to mention that this controllability matrix of the linearized system (5) is the analogue of the controllability matrix of the linear system (1), where $\left[\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right]\Big|_{\boldsymbol{x}_0}$ is the Jacobian matrix of the vector field $\boldsymbol{f}(\boldsymbol{x})$ evaluated at $\boldsymbol{x}_0$, which is equivalent to the matrix A in (1) and $[\boldsymbol{g_1}(\boldsymbol{x}_0), \ldots, \boldsymbol{g_m}(\boldsymbol{x}_0)]$ is equivalent to the matrix B in (1).

3. Controllability analysis of linearized flight dynamics

In this section, the controllability analysis of the linearized system is performed. Since this linearization is performed at the cruise flight condition; i.e., the lateral velocity $v = 0$ as well as the rolling and yawing angular velocities $p = r = 0$, then the longitudinal and lateral dynamics are decoupled and their respective reduced-order models can be studied separately.

3.1. Longitudinal 4×4 flight dynamics model

The longitudinal 4×4 flight dynamics model for a rigid aircraft can be written as follows [15]

$$\begin{aligned} \begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} &= \begin{bmatrix} X_u & X_w & 0 & -g\cos\theta_0 \\ Z_u & Z_w & U_0 & -g\sin\theta_0 \\ M_u & M_w & M_q & -gM_w\sin\theta_0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} \\ &\quad + \begin{bmatrix} X_{\delta_e} & X_{\delta_t} \\ Z_{\delta_e} & 0 \\ M_{\delta_e} & M_{\delta_t} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \end{aligned} \tag{7}$$

where u and w are the forward and normal velocity perturbations of the airplane center of gravity from the equilibrium state along the longitudinal and normal body axes, respectively. The body pitching angle and angular velocity are θ and q, respectively. U_0 and θ_0 are the cruise forward speed and pitching angle, respectively and g is the gravitational acceleration. The longitudinal control inputs are the elevator deflection δ_e and thrust control input δ_t. The parameters X_u, X_w, Z_u, Z_w, M_u, M_w, M_q, X_{δ_e}, X_{δ_t}, Z_{δ_e}, M_{δ_e}, and M_{δ_t} are stability and control derivatives at the cruise condition.

The rank of the controllability matrix for this system is calculated using Eq. (2) and found to be **four** which ensures linear (and hence nonlinear) controllability for the system at hand. In case of a failure in the elevator system or loss of regulation in the engine system, the control input matrix $\boldsymbol{B}$ becomes $[X_{\delta_t}\ 0\ M_{\delta_t}\ 0]'$ or $[X_{\delta_e}\ Z_{\delta_e}\ M_{\delta_e}\ 0]'$, respectively. However, in either case, the rank of the controllability matrix is found to be also **four**, which means that the airplane remains controllable even if the elevator or engine fails.

In order to verify the existence of a steering control input history in the case of elevator or engine loss, we use the longitudinal flight dynamic characteristics of the DELTA aircraft (a paradigm model for a very large, four-engined, cargo jet aircraft) from [14, pp. 561–563], at the flight condition (sea-level cruising at $U_0 = 75$ m/s and $\theta_0 = \alpha_0 = 2.7°$). It is preferred over a particular airplane type (e.g., B747, A320) for its general representation for a whole class of airplanes. However, it should be noted that the presented analysis is transferable to any class. The stability and control derivatives of such an airplane at the stated flight condition are given as:

$$m = 300{,}000\ \text{kg},\ X_u = -0.02,\ X_w = 0.1,$$

$$Z_u = -0.23,\ Z_w = -0.634,$$

$$M_u = -2.55 * 10^{-5},\ M_w = -0.005,\ M_q = -0.61,$$

$$X_{\delta_e} = 0.14,\ Z_{\delta_e} = -2.9,$$

$$M_{\delta_e} = -0.64,\ X_{\delta_t} = 1.56,\ M_{\delta_t} = 0.0054.$$

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