UNIVERSITI TEKNOLOGI MARA

Journal of Mechanical Engineering

An International Journal

Volume 10 No. 2 December 2013 ISSN 1823-5514

JOURNAL OF MECHANICAL ENGINEERING (JMechE)

Journal of Mechanical Engineering (ISSN 1823-5514) is published by the Faculty of Mechanical Engineering (FKM) and UiTM Press, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

Journal of Mechanical Engineering

An International Journal

Volume 10 No. 2 **December 2013** **ISSN 1823-5514**

Journal of Mechanical Engineering *Vol. 10, No. 2, 37-51, 2013*

Stability Augmentation for Longitudinal Modes of a Small Blended Wing-Body Aircraft with Canard as Control Surface

Rizal E. M. Nasir
Wahyu Kuntjoro
Flight Technology and Test Centre (FTTC)
Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia.

ABSTRACT

Failure to achieve satisfactory level for transient response of an aircraft in longitudinal motion – short period mode and phugoid modes – would mean poor flying and handling qualities leading to unnecessary pilot workload. This study proposes a stability augmentation system in longitudinal flying modes for steady and level flight at all airspeeds and altitudes within Baseline-II E-2 BWB's OFE. The main controlling component of this stability augmentation system is a set of canard. It must be able to compensate Baseline-II E-2 BWB poor transient responses' damping ratios so that good flying quality can be achieved. Observation from the transient responses of the unaugmented system signify high-frequency short-period oscillations with almost constant low damping ratio at an altitude, and low-frequency phugoid oscillation with varying damping ratio depending on airspeed. A conclusive behaviour of natural frequencies and damping ratios against dynamic pressure leads to the understanding on how dynamic pressure influences the flying qualities. Derivation of dynamic equations in terms of dynamic pressures enables one to design and device a feedback system to compensate poor flying qualities of the original unaugmented aircraft with conclusive relationship between important parameters and dynamic pressure are put in the overall dynamic equation. Two feedback gain systems, pitch attitude and pitch rate gains are scheduled based on dynamic pressure values and are combined into the aircraft longitudinal SAS. The proposed SAS has proven to be the suitable candidate for Baseline-II E-2 BWB as it is able to ensure Level 1 flying qualities, longitudinally.

Keywords: *Blended Wing-Body; Flight Dynamics; Flight Stability.*

ISSN 1823-5514

Introduction

Transient response of an aircraft in longitudinal motion can be caused by a change in control surface deflection. This response has two modes of oscillatory motion – short period mode (SP) and phugoid mode (P). The former is a highly damped, high-frequency oscillatory motion representing rotations about the centre of gravity. Phugiod mode is a lowly damped, low-frequency oscillatory motion representing vertical translation usually related to kinetic-potential energy interchange. Failure to achieve satisfactory level for both modes would mean poor flying and handling qualities that may lead to unnecessary pilot workload. MIL-F-8785C states quantitative specification requirements on measurement of flying and handling qualities of piloted aircraft. For short period and phugoid modes, these requirements lie in the value of their damping ratios. Table 1 shows damping ratio requirement for Category B flight. Only Level 1 flying quality is accepted for flight within Operational Flight Envelope (OFE) [1].

Table 1: Phugoid and short-period damping ratios requirement in accordance to MIL-F-8786C [1]

Flying quality	Phugoid	Short-Period (Cat. B)
Level 1	$\zeta_p \geq 0.04$	$0.3 \leq \zeta_{sp} \leq 2.0$
Level 2	$\zeta_p \geq 0$	$0.2 \leq \zeta_{sp} \leq 2.0$
Level 3	$T_2 \geq 55$ s	$0.1 \leq \zeta_{sp}$

Many studies in flight stability and control system for blended wing-body aircraft (BWB) focus on getting the best flying quality at design flight condition; such as at one particular cruising speed and altitude only or at landing speed, for example. There are, particularly for blended wing-body aircraft, various methods of flight dynamic stabilizations;

- Classical methods or calculus-based analytical solutions which usually identify the cause of instability or poor handlings and seek to rectify problems by resizing the control surface or moving the centre of gravity [2]. Established textbooks [3, 4] provide solutions and approaches to gain adequate flying quality with incorporation of simple feedback, feedforward or proportional-integral-differential controllers [5]. There are optimisation methods within this approach involving changing design parameters on the whole aircraft to tackle instability problems but with penalties on other aspect such as flight performance and payload capacity [6].

- Eunumerative and random search methods are approaches where they optimize by computing the objective function in every point of the search space [7] and popular algorithms include intelligent water drops optimization [8], Consensus-Based Bundle Algorithm (CBBA) [9], Model Predictive Control (MPC) or Receding Horizon Control (RHC) [10], Fuzzy-logic [11], Evolutionary Algorithm [12], Neural Network [13], Backstepping Technique [14], and Genetic Algorithm [15]

This study proposes a stability augmentation system (SAS) in longitudinal flying modes for steady and level flight at all airspeeds and altitudes within Baseline-II E-2 BWB's operational flight envelope (OFE). The main controlling component of this stability augmentation system is a set of canard, a control surface located in front of the wing. It must be able to compensate Baseline-II E-2 BWB poor transient responses' damping ratios so that good flying quality (short period and phugoid modes' damping ratios, $\zeta_{sp} = 0.7$ and $\zeta_p = 0.7$, respectively) can be achieved and exceeding the minimum and maximum required flying quality values (Table 1).

Assessment to its flight dynamics, particularly transient response from canard input, and its flying qualities for flight missions within its operational flight envelope (OFE) is needed in order to understand its behaviour with respect to airspeed and altitude. Hence, it is necessary to determine whether Baseline-II E-2 BWB aircraft satisfy the minimum reqirement for Level 1 flying quality. The assessment seeks to understand how short-period and phugoid modes' natural frequencies and damping ratios change with changing atmospheric conditions within its operational flight envelope (OFE) and intended missions. A stability augmentation system (SAS) is proposed as the result of this assesment. The control law behind the augmentation system shall be simple and easily understood. This begins with identifying the dynamic pressure as the main factor in determining flying quality thus also the design of stability augmentation system and its governing control law.

Longitudinal Flight Dynamics

General equations of motion for aircraft's flight dynamics begin with setting up dynamics parameters based on Figure 1. These forces, moments, velocities, rates and angles become the parameter basis of deriving flight equation of motion thus flight dynamic model of Baseline-II BWB's transient response behaviour with respect to canard deflection input.

Numerical values of derivatives, aerodynamic coefficients and flight response are calculated and computed for various cases ranging from Baseline-II's minimum airspeed to its maximum airspeed (due to maximum thrust limitation) and from sea level to maximum operational altitude of 30,000 feet. Five airspeeds and three altitudes are chosen to be included in the study, making

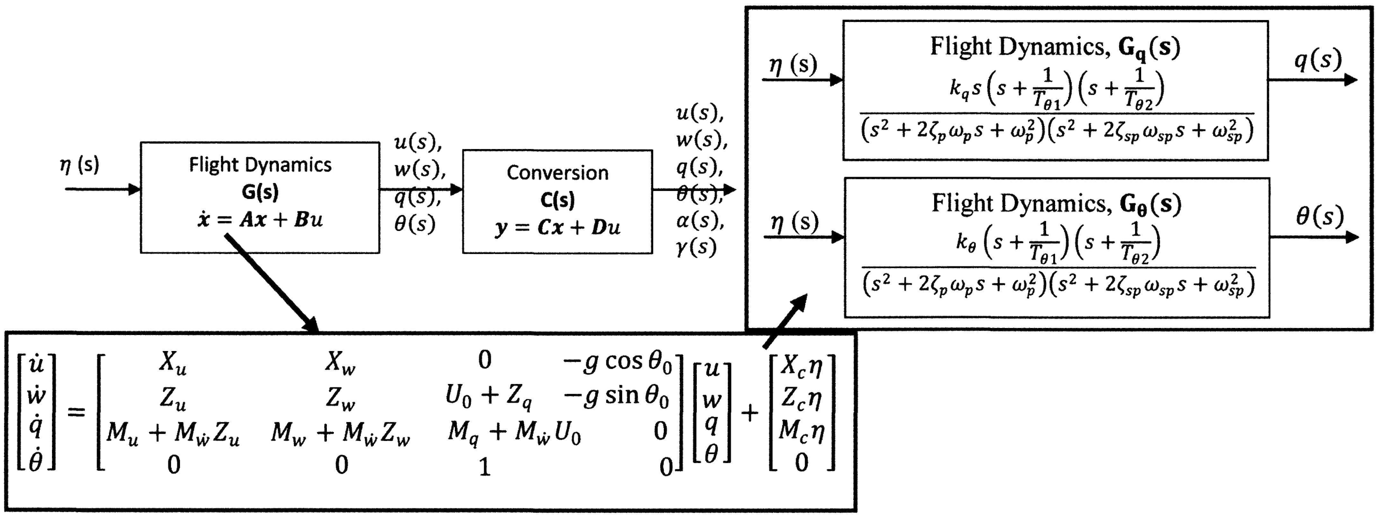

Figure 1: Above - Axes systems, forces, moments, velocities, angular velocities (rates) and angles. Below - Block diagram of Baseline-II E-2 BWB unaugmented longitudinal flight dynamics

a total of fifteen flight "points of study" within operational flight envelope limit. A simple performance study and evaluation has been conducted prior to this to determine Baseline-II's operational flight envelope. All these flight points of study are classified as Category B flight mission in MIL-F-8785C, or in short, steady and level cruise or steady climb. All atmospheric data is based on International Standard Atmosphere (ISA).

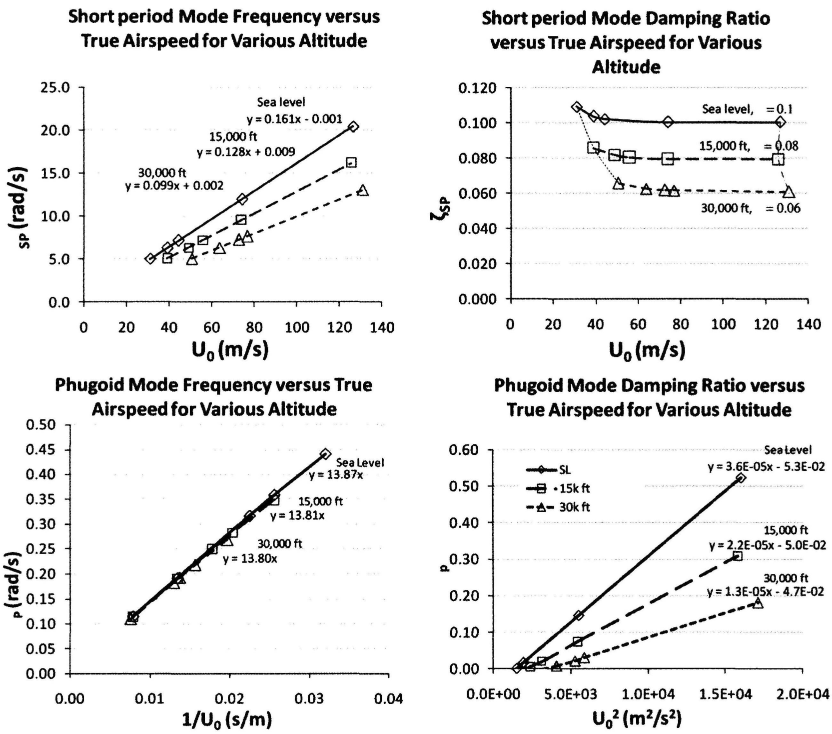

Figure 2: Short period and Phugoid natural frequencies and damping ratios plots against airspeed for various altitudes.

Observation from the transient responses of the unaugmented system signify high-frequency short-period oscillations with almost constant low damping ratio at an altitude, and low-frequency phugoid oscillation with varying damping ratio depending on airspeed (Figure 2). Short-period mode natural frequency of Baseline-II E-2 BWB changes linearly with respect to airspeed. Altitude alters the short-period natural frequency-airspeed slope. As altitude increases, the slope decreases. However, if one plots the natural frequency against equivalent airspeed, then the short-period mode natural frequency versus equivalent airspeed plots for all altitudes sit on the same linear line.

This indicates one thing; short-period natural frequency changes linearly with square root of dynamic pressure Q_o. The plots of ω_{sp} versus n/α for all altitudes and airspeed shows that Baseline-II E-2 BWB is within Level 2 flying qualities. Short-period mode damping ratio is almost constant at all airspeeds except at very low airspeed. This is due to high angle of attack that makes the pitch angle, hence the effect to gravity to force in x-direction, significant in increasing the damping ratio. As the altitude increases, the damping ratio decreases. Since the damping ratio of Baseline-II E-2 BWB is around 0.11 at sea level that makes its flying quality at the lower border of Level 3, the higher altitudes damping ratios are observed to be worsen making Baseline-II E-2 BWB's flying quality to be unsafe.

Phugoid natural frequency value is inversely proportional to airspeed; as airspeed increases, the natural frequency decreases. However, the natural frequency-airspeed curve plots remain the same for all altitude within its OFE. Phugoid's damping ratio changes almost parabolically with respect to airspeed and the slope of ζ_p versus U_o^2 also changes with altitude. Damping ratio increases as airspeed increases but the slope of this ζ_p versus U_o^2 decreases as altitude increases. In other words, ζ_p is inversely proportional to altitude h for the same airspeed U_o. Phugoid's damping ratio is generally good at Level 1 for most airspeed range within Baseline-II E-2 OFE except at low airspeed (especially at loitering airspeed where the lift-to-drag ratio is maximum) where the flying quality drops to Level 2 and Level 3 (unsatisfactory). Like short period natural frequency, phugoid mode damping ratio versus equivalent airspeed squared plots sits on the same linear line for all altitude within OFE indicating that the phugoid damping ratio is simply proportional to dynamic pressure.

Referring to Figure 3, Baseline-II E-2 BWB flight dynamics, especially when phugoid mode and short-period mode are taken into context, are generally stable in most area within its OFE except airspeeds near wing stall angle of attack (α = 13 deg.) where the phugoid mode is dynamically unstable ($\zeta_p \leq 0.0$) but still within Level 3 of flying quality. However, in all areas within the altitude-airspeed hodograph that represents Baseline-II E-2 OFE, not a single point of flight the aircraft is able to achieve Level 1 flying qualities for short-period modes! Short period mode seems to be more severe than the phugoid mode because the former cannot even reach level 2 flying quality where as the latter may have Level 2 and Level 1 flying quality within OFE. A compensation of some sort is needed to increase Baseline-II E-2 damping ratios to acceptable values in accordance to MIL-F-8785C.

The overall trend of damping ratios (short period and phugiod modes) can be summarized by only two equations that represent the behavior. Airspeed, be it true or equivalent, is measured by a set of pitot-static tube that actually measures dynamic pressure Q_o (unit: Pa) which is a function of airspeed and air density where $Q_o = P_{pitot} - P_{static} = 0.5\rho_o U_o^2 S$. P_{pitot} and P_{static} are pressures

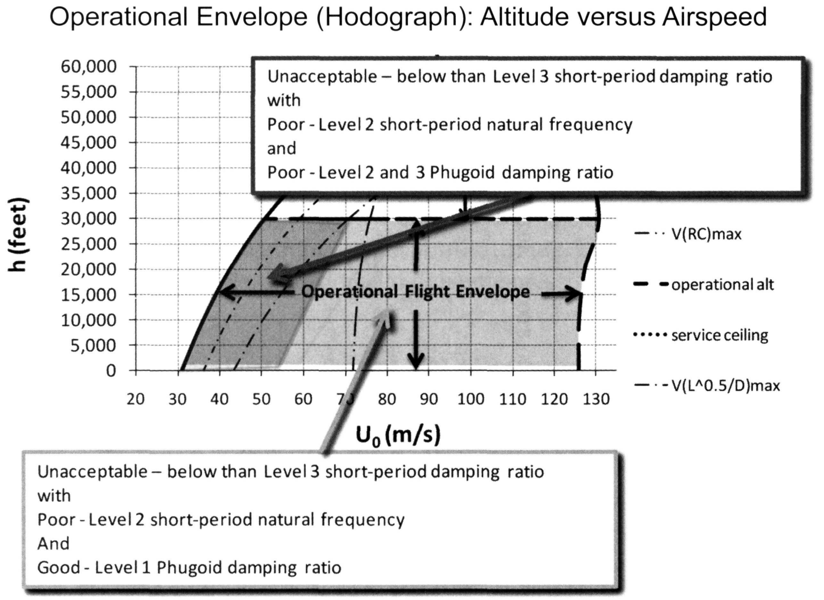

Figure 3: Critical region of flying quality within OFE – Baseline-II E-2 BWB

measured on pitot tube and static tube respectively. ρ_o is the true air density while U_o is true airspeed. Since the pitot-static tube's pressure bellows and mechanism are usually being calibrated at sea level then the airspeed measured is known as equivalent airspeed, U_{Eo}. Since there are variations of climate condition (for example, air pressure) for sea level all over the world, then a standard (ISA) has been established to fixed the sea level static air pressure to 101.3 kPa with standard air density of 1.225 kg/m^3 and temperature of 15 deg. Celscius. In this way, aircraft's aerodynamics, flight dynamics and performance can be monitored and controlled easily because flying, in simple terms, is all about pressure. The reason for coming up with dynamic pressure-air density-airspeed relationship is to show that it is practical to design a longitudinal flight stability augmentation system that uses static and stagnation pressures, a combination of these would become dynamic pressure, on an aircraft. In the end, the objective in this section is to come up with common relationship between flying qualities and dynamic pressure.

A conclusive behaviour of natural frequencies and damping ratios against dynamic pressure (Figure 4) leads to the understanding on how dynamic pressure influences the flying qualities. Short-period mode undamped natural frequency at all altitude within Baseline-II E-2 BWB's OFE is proportional to the square root of dynamic pressure ($\omega_{sp} \cong 0.207Q_o^{0.5}$). It is hard to conclude the behaviour short-period mode damping ratio at all altitude with respect to dynamic pressure. It can if the damping ratio is combined with its undamped

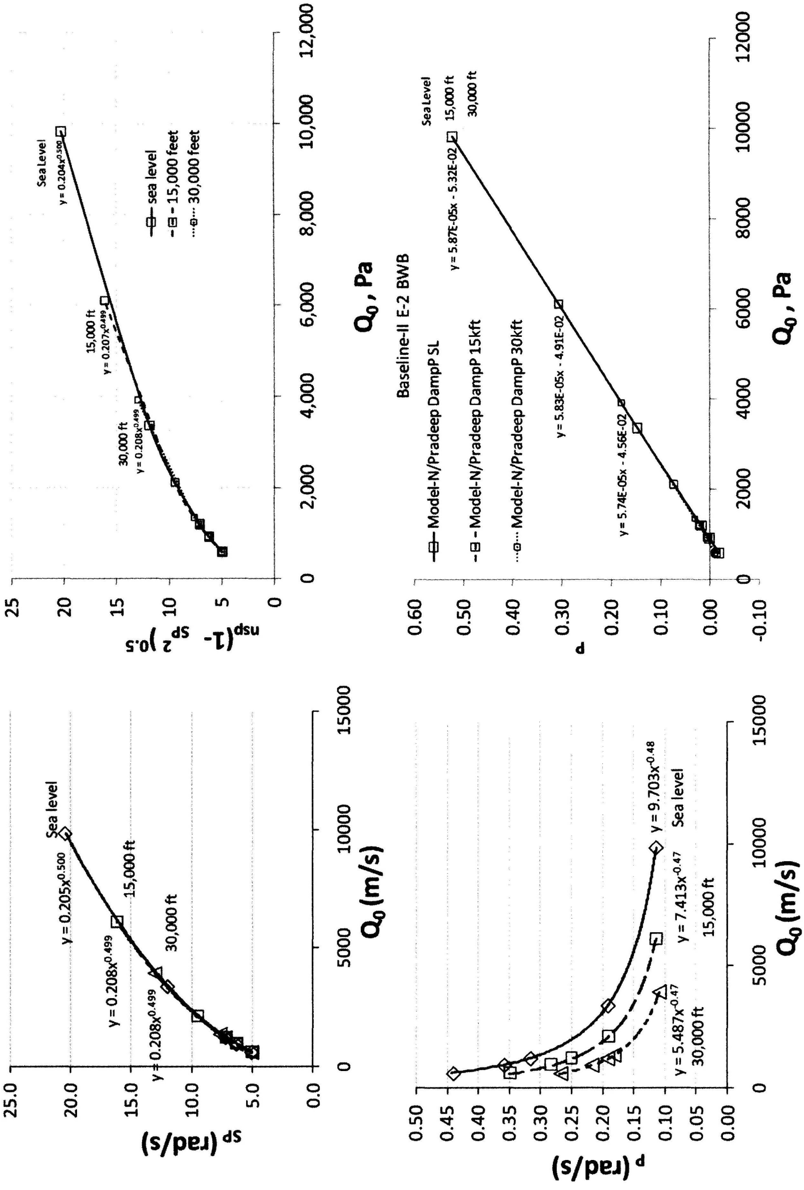

Figure 4: Baseline-II E-2 BWB natural frequencies and damping ratios plots against dynamic pressure

natural frequency to become damped natural frequency where $\omega_{dsp} \cong \omega_{sp}(1 - \zeta_{sp}^{2})^{0.5} \cong 0.206Q_o^{0.5}$. Meanwhile, the short-period mode half damping coefficient (c/2 $= \zeta_{sp}\,\omega_{sp}$) is represented by $\zeta_{sp}\,\omega_{sp} \cong 0.02Q_o^{0.5}$. Both damped natural frequency and half damping coefficient for short-period mode relationship for all altitude within OFE shows that they are also proportional to the square root of dynamic pressure. Therefore, Baseline-II E-2 BWB's short-period mode damping ratio for all altitude within OFE is approximated at 0.1.

Phugoid mode damping ratio at all altitude within Baseline-II E-2 BWB's OFE is linearly proportional to dynamic pressure where $\zeta_p \cong 0.000058$

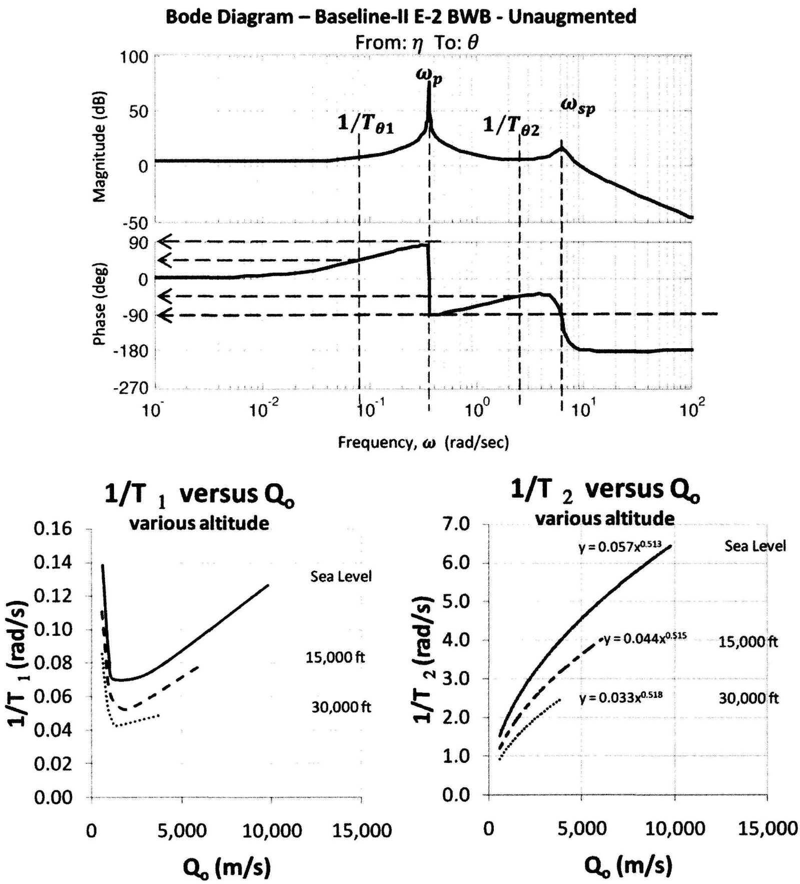

Figure 5: Example of bode plots (magnitude and phase angle of pitch angle θ versus canard input frequency ω_c) for unaugmented Baseline-II E-2 BWB longitudinal dynamics and its corresponding phase lead frequencies versus Q_o for various altitudes.

Q_o -0.05. Other parameters such as phugoid undamped natural frequency ω_p, phugoid mode half damping coefficient $\zeta_p \omega_p$, phase change frequencies $1/T_{\theta 1}$ and $1/T_{\theta 2}$ and internal gain k_θ found from Baseline-II E-2 BWB flight dynamic data, transfer functions and frequency response (Bode plot) are plotted against dynamic pressure (Figure 5). Mathematical representations of these parameters with respect to dynamic pressure are approximated from the plots. Routh-Hurwitz stability criterion is used to find out instability region in Baseline-II E-2 BWB longitudinal flight and found that phugoid mode suffers dynamic instability at low dynamic pressure. The finding also confirms transient response's analyses that Baseline-II E-2 is dynamically unstable at low airspeed.

Longitudinal Stability Augmentation

Despite many sophisticated flight control techniques, a classical approach is still relevant. Derivation of dynamic equations in terms of dynamic pressures enables one to design and device a feedback system to compensate poor flying qualities of the original unaugmented aircraft with conclusive relationship (behaviour) between important parameters (damping ratios, frequencies, phase change frequencies) and dynamic pressure are put in the overall dynamic equation. Two simple feedback systems, namely pitch attitude feedback consists of gain K_q and pitch rate feedback consists of gain K_θ are studied separately. The former is devised to overcome Baseline-II E-2 BWB's extremely low and sometimes unstable phugoid mode damping ratio and the latter is devised to overcome poor damping ratio of the short-period mode oscillations. Analytical derivations of required pitch attitude feedback gain and pitch rate feedback gain were written to approximately represent the change of these feedback gains with respect to dynamic pressure.

The target damping ratios for both phugoid and short-period modes are not the minimum values of 0.04 and 0.3, respectively, as mentioned in the MIL-F-8785C but rather set to 0.7 for both modes. If one would have to design a SAS why would one settle for the minimum requirement if the augmentation architecture is able to provide good flying qualities? Damping ratio of 0.7 has small overshoot magnitude (around five percent) and fairly quick settling time meaning that Baseline-II E-2 may avoid overshooting to the dangerous angle of attack zone. Root locus plots for each flight cases chosen within OFE are analyzed to find suitable gains. The feedback gains found from the root locus plots are plotted against dynamic pressure to come up with estimated equations that computes feedback values at any given flight conditions within OFE. It was found that, in order to achieve a constant damping ratios of 0.7 for both short-period and phugoid modes at all altitude and airspeed – 1. The pitch rate feedback gain K_q must be scheduled to be inversely proportional

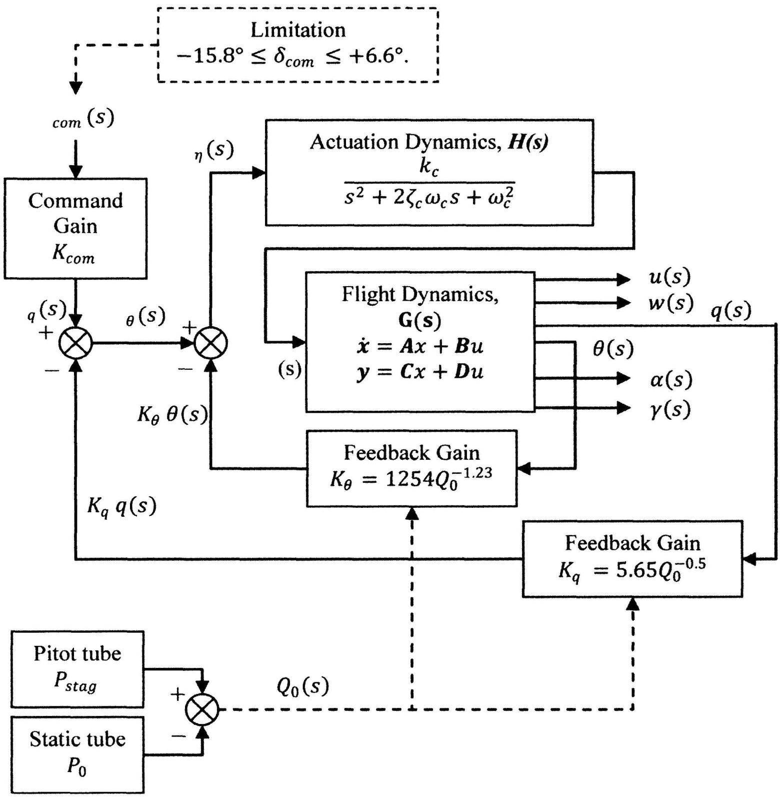

Figure 6: Proposed SAS for Baseline-II E-2 BWB

to the square root of dynamic pressure where $K_q = 5.6502Q_0^{-0.5}$, 2. The pitch attitude feedback gain K_θ must be scheduled to be inversely proportional to the dynamic pressure to the power of 1.23 where $K_\theta = 1254Q_0^{-1.23}$. These two equations are part of the governing control law for the stability augmentation system. The equations governing the feedback gain values with respect to dynamic pressure can be assumed to be some sort of mechanical-electrical signals conversion mechanism. The response that becomes the feedback to the augmentation system is also converted to electrical signal within the feedback gain mechanism.

The two feedback gain systems are combined to become a complete proposed stability augmentation system (SAS) as shown in Figure 6. Analytical approximation equations have proven that the augmentation system changes the behaviour of Baseline-II E-2 BWB aircraft to have both short-period and phugoid mode damping ratios of around 0.6 to 0.7 ($0.6 < \zeta_{sp} < 0.7$) and 0.7 to 0.8 ($0.7 < \zeta_p < 0.8$) respectively. The proposed SAS is then

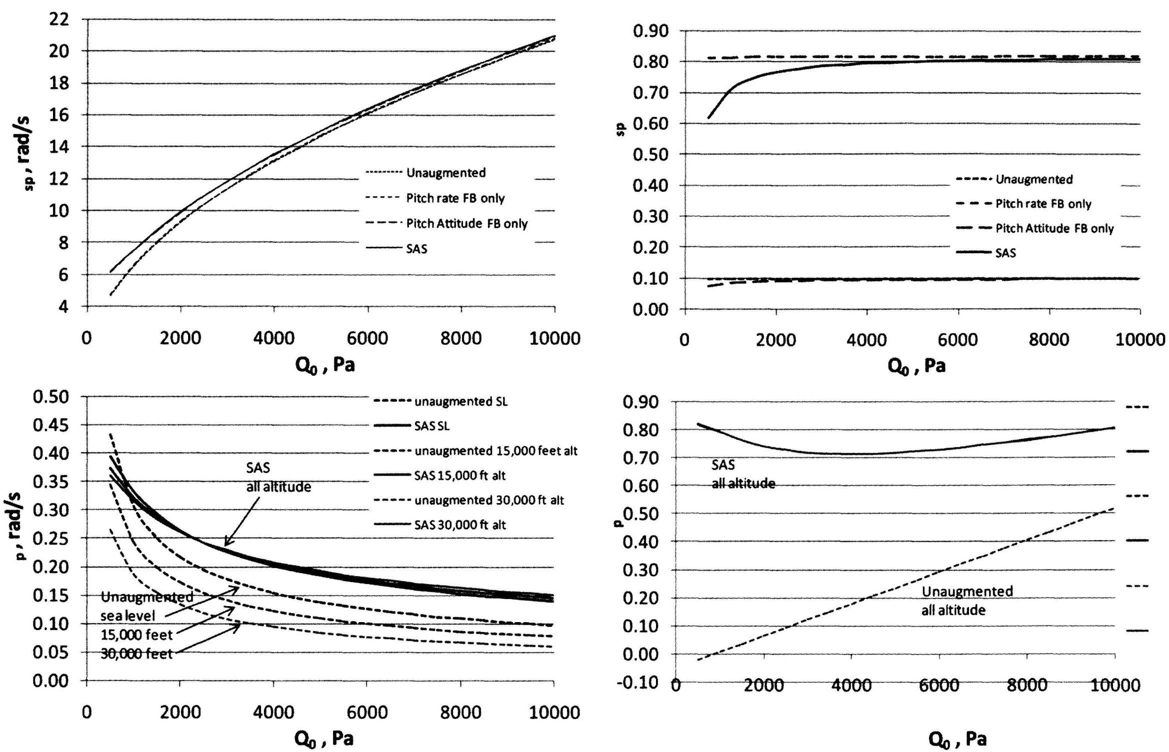

Figure 7: Short-period and Phugoid modes' natural frequencies and damping ratios – comparisons between SAS and unaugmented aircraft.

being simulated in SIMULINK for all fifteen flight cases and the results are not far from prediction from analytical equations. Three cases are simulated per flight mission – 1. Pitch rate feedback only (pitch attitude feedback is turned off), 2. Pitch attitude feedback only (pitch rate feedback is turned off) and 3. Complete stability augmentation system consists of both pitch rate and pitch attitude feedbacks (SAS) – and these are compared with the unaugmented behaviour discussed in previous section.

Figure 7 shows that the short-period mode damping ratio for Baseline-II E-2 BWB with proposed SAS is slightly higher than 0.6 at near minimum airspeed and increases slowly as airspeed increases to its maximum of around 0.8 at its maximum airspeed. This is true for all altitudes within OFE. Therefore, all Category B steady and near level flight missions within Baseline-II E-2 BWB OFE has augmented short-period damping ratio of between 0.6 to 0.8 which puts it at Level 1 flying quality and exceeding minimum damping ratio of 0.3 in accordance to MIL-F-8785C. The phugoid mode damping ratio for Baseline-II E-2 BWB with proposed SAS is around 0.7 to 0.8 and is true for all altitudes within OFE and puts it at Level 1 flying quality and far exceeding minimum damping ratio of 0.04 in accordance to MIL-F-8785C.

Concluding Remarks

The proposed SAS has proven to be the suitable candidate for Baseline-II E-2 BWB as it is able to ensure Level 1 flying qualities, longitudinally. The logic behind gain scheduling for pitch rate and pitch attitude feedbacks is straightforward. The study of Baseline-II E-2 flight dynamics can be extended to include lateral-directional dynamics. Couplings between flight oscillation modes, including lateral-directional and longitudinal-lateral, shall be studied in detail.

Acknowledgment

Authors would like to express gratitude to Research Management Institute of Universiti Teknologi MARA (UiTM) for funding this research under RIF Grant. The gratitude is extended to the Faculty of Mechanical Engineering, UiTM for non-monetary support during the period of study.

References

[1] MIL-F-8785C: Flying Qualities of Piloted Airplanes. Military Standard, USAF.

[2] Jung, D.W. and Lowenberg, M.H. (2005). "Stability and control assessment of a blended-wing-body airliner configuration." AIAA Atmospheric Flight Mechanics Conference and Exhibition. San Francisco, California. 15-18 August 2005.

[3] Nelson, R. C. (1998). Flight Stability and Automatic Control, McGraw-Hill, Michigan.

[4] Cook, M.V. (2007). Flight Dynamics Principle, 2nd ed., Elsevier, Amsterdam.

[5] Panesi, R. and Mengali, G. "Flight control system design with loop-shaping approach through non-diagonal weights," The Aeronautical Journal. 113(1145): 447-458

[6] Martinez-Val, R., Perez, E., Puertas, J. and Roa, J. (2010). "Optimization of planform and cruise conditions of a transport flying wing," Proceedings of Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 224: 1243-1251.

[7] Teixeira, B. O. S., Torres, L. A. B., Iscold, P. and Aguirre, L. A. (2011). "Flight path reconstruction – a comparison of nonlinear Kalman filter and smoother algorithms," Aerospace Science and Technology. 15: 60-71.

[8] Duan, H. B., Liu, S. Q. and Wu, J. (2009). "Novel intelligent water drops optimization approach to single UCAV smooth trajectory planning," Aerospace Science and Technology. 13: 442-449.

[9] Bertucelli, L. F., Choi, H. L., Cho, P. and How, J. P. (2009). "Real-time Multi-UAV task assignment in dynamic and uncertain environments," AIAA Guidance, Navigation & Control Conference, Chicago, Illinois, August, 2009. AIAA-2009-5776.

[10] Zhang, Y., Rabbath, C. A. and Su, C. Y. (2008). "Reconfigurable control allocation applied to an aircraft benchmark model," Proceedings, 2008 American Control Conference, Seattle, Washington, June 11-13, 1052-1057.

[11] Roshanian, J., Hashemi, S. V. and Mehrabian, A. R. (2010). "Optimal gain-scheduled flight control system design using a new fuzzy clustering algorithm," Proceedings of Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 224: 403-415.

[12] Lee, D.S., Gonzales, L.F., Srinivos, K., Auld, D.J. and Periaux, J. (2007). "Multi-objective/multi-disciplinary design optimization of blended wing body UAV via advanced evolutionary algorithms." 45th AIAA Aerospace Science Meeting 2007. Reno, Nevada. Jan 8-11th. 2007, 296-316.

[13] Pashilka, A. A., Sundarajan, N. and Sarachandran, P. (2006). "A fault-tolerant neural aided controller for aircraft auto-landing" Aerospace Science and Technology, 10: 49-61.

[14] Li, C.Y., Jing, W.X. and Gao, C.S. (2009). "Adaptive backstepping-based flight control system using integral filters." Aerospace Science and Technology 13: 105-113.

[15] Fantimutto, R., Guglieri, G. and Quagliotti, F. (2005). "Flight control system design and optimization with genetic algorithm." Aerospace Science and Technology, 9: 73-80.