Analysis of the Stability Augmenation System of An Aircraft (Sj30) in Flight Turbulence

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Abstract

The article analyzed the Stability Augmentation System (yaw damping) of Syberjet 30 aircraft in turbulent conditions using High Level programming Language. The yaw damper significantly reduced the short-period lateral-directional motion of the aircraft in turbulent air resulting in both the ride and the flying qualities. There was no significant improvement in the pilot's overall performance of the Instrument Landing System (ILS) approach task. The aileron-to-rudder interconnect was found to be effective in compensating for adverse aileron yaw, and turns could be made easier and more accurately. An increase in the intensity of the lateral motions of the airplane in turbulent was experienced when the autopilot system was used alone. The autopilot performance in turbulent was significantly improved when the system was used with the yaw damper. It will therefore be recommendable to the aeronautical sector to use the yaw damper to improve the autopilot performance in turbulence.

Keywords: Instrument Landing System (ILS); Stability Augmentation System (SAS); Yaw Damping; Autopilot; Control Augmentation system(CAS); Automatic Control System (ACS);

I. INTRODUCTION

The approach to aircraft stability and control analysis has evolved round the concept of the aircraft regarded as an aerodynamic system whose behaviour is predominantly determined by its aerodynamic properties. This concept has to, a large extent, influenced such formal choices as the definition of the preferred system of axes and of the stability derivatives.

When flying an aircraft, the pilot needs to control it. The controls can be done either by human (Pilot) or by a computer in which the latter is more often much easier, safer, more efficient and more reliable. The computer is preferred as it has much higher reaction velocity than a human pilot; not subjected to concentration losses and fatigue and then more accurately knows the state the aircraft is in. Computers can handle huge amounts of data better and also do not need to read a small indicator to know, for example, the velocity or the height of the aircraft. There are, however, some downsides to the use of the Computer. That is, computers are only designed for certain flight envelopes. When the aircraft is outside of the flight envelope, the system cannot really operate the aircraft anymore. For such situations, human pilots are still needed.

Previously, aircraft's mechanical systems known as Flight Control Systems(FCS) were made up of cables and pulleys, which helped in surface controls by giving the necessary deflection to control it. This new era of development of technological development has brought into play the fly-by-wire in which electrical signals are sent to the controlled surfaces by flight control computer. In this way the aircraft is controlled by the computer in a process known as Automatic Flight Control.

The Flight control system consists of three important parts namely:

(a) Stability Augmentation System (SAS): augments the stability of the aircraft by using the control surface to make the aircraft more stable (yaw damping);

(b) Control Augmentation System (CAS): a helpful tool for the pilot to control the aircraft by keeping the current direction of the aircraft.

(c) Automatic Control System (ACS): automatically controls the aircraft by calculating the roll angle of the aircraft that is required to stay on a given path and ensures the roll angle is achieved.

The system of stability axes has served well in all aspects of aircraft stability work, in particular as it permits the partial aerodynamic derivatives to be isolated with ease in experimental techniques.

The increase in wing loading and the trend to a more elongated inertia distribution, gyroscopic forces and moments exerts an increasing influence on the dynamic behavior of the modern aircraft. An example is the inertia cross coupling. Two conclusions that have been drawn from the analytical work on inertia coupling [1] may be noted as being potentially significant for aircraft stability analysis in general:

(i) Analysis of the dynamics of aircraft with relatively large inertia is simplified by principal inertia axes rather that stability axes as reference system;

(ii) The inertia distribution becomes a dominating factor in determining the aircraft stability.

This paper aimed at analyzing and validating conditions in the controlling of the stability on an aircraft by using the control surface (yaw damping) and stability criteria application in Matlab with graphs in the form of control system.

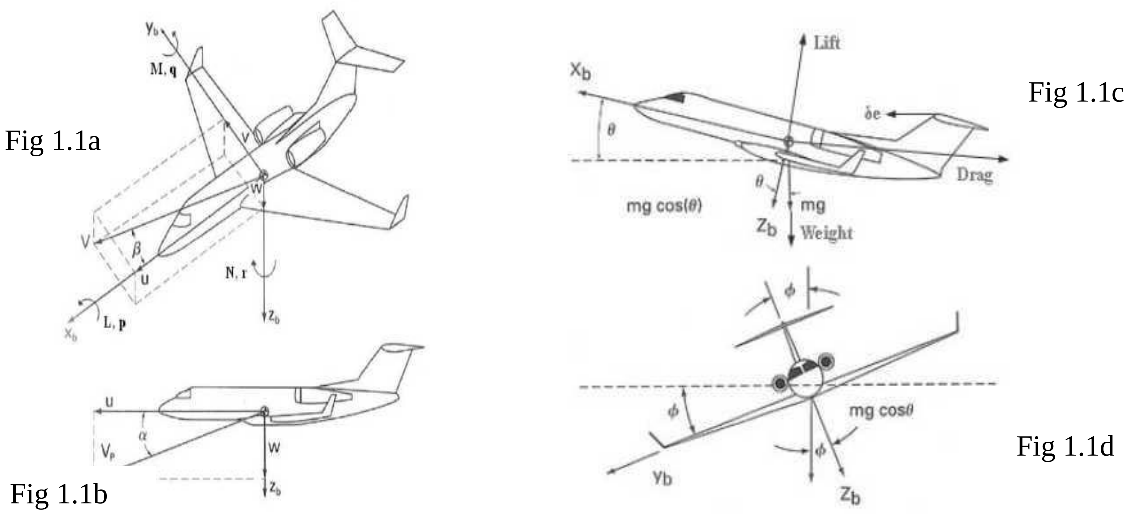

Figure 1.1a, 1.1b, 1.1c and 1.1d (Vertical array)

These figures in vertical array above show a Body-fixed frame of reference where figure 1.1a -Banking, figure 1.1.b -Pitching down, figure 1.1c-Pitching up and figure 1.1d-Rolling

Where ψ is the aircraft heading angle, θ and α are the angle of attack (pitch up and pitch down angle respectively), ϕ is roll angle. Whenever aircraft faces turbulence, one or more of these angles are affected. P, Q, and R are angular rates about roll, pitch and yaw axes respectively while J_x, J_y, and J_z are their respective aerodynamics moment components with u, v, w- the velocities components of the aircraft relative roll, pitch and yaw axis of aircraft.

II. REVIEW OF RELATED LITERATURE

There are a number of research publications on this subject, however the data available did not discuss analytical stability using high level programming Language, as this research has done.

This research seeks to critically analysis the Stability Augmentation System (SAS)-yawing damping when an aircraft is in flight.

The paper categories related information into:

a) **Longitudinal command stability augmentation system** design for unstable aircraft using flying and handling qualities specifications was presented by Mansor and co-workers(2015) at an International Conference on Computing, Control, Networking, Electronics and Embedded Systems Engineering (ICCNEEE).

The study demonstrated a practical approach in designing a longitudinal command stability augmentation system for unstable combat aircraft. The unaugmented aircraft was originally in unstable configuration in order to gain fast response for agility. The flight control system was designed in compliance with MIL-F-8785C and Gibson Criterion for the corresponding flight case. The design case study was based on pitch rate command control system using I controller. The design evaluation was based on time response analysis of simulated results using Matlab and Simulink. The pole-placement method was used to determine the augmented feedback gain. Second order actuator dynamics model was introduced to ascertain its effect on overall design. The designed case study offered a better understanding, an easier and practical approach implementation based on aircraft longitudinal pitch rate command.

b) Designing Stipulated Gains of Aircraft Stability and Control Augmentation Systems for Semiglobal Trajectories Tracking was investigated by Mohamed and co-workers (2014).

The aim of the investigation was to provide a simple procedure to select the controller gains for an aircraft with a largely wide complex flight envelope with different source of nonlinearities. The stability and control gains were optimally devised using genetic algorithm. Thus, the gains were tuned based on the information of a single designed mission. This mission was assigned to cover a wide range of the aircraft's flight envelope. For more validation, the resultant controller gains were tested for many off-designed missions and different operating conditions such as mass and aerodynamic variations. The results show the capability of the proposed procedure to design a semi global robust stability and control augmentation system for a highly maneuverable aircraft such as F-16. Unlike the gain scheduling and other control design methodologies, the proposed technique provided a semi-global single set of gains for both aircraft stability and control augmentation systems. This reduced the implementation efforts. The proposed methodology was superior to the classical control method which rigorously required the linearization of the nonlinear aircraft model of the highly maneuverable aircraft by eliminating the sources of non linearities.

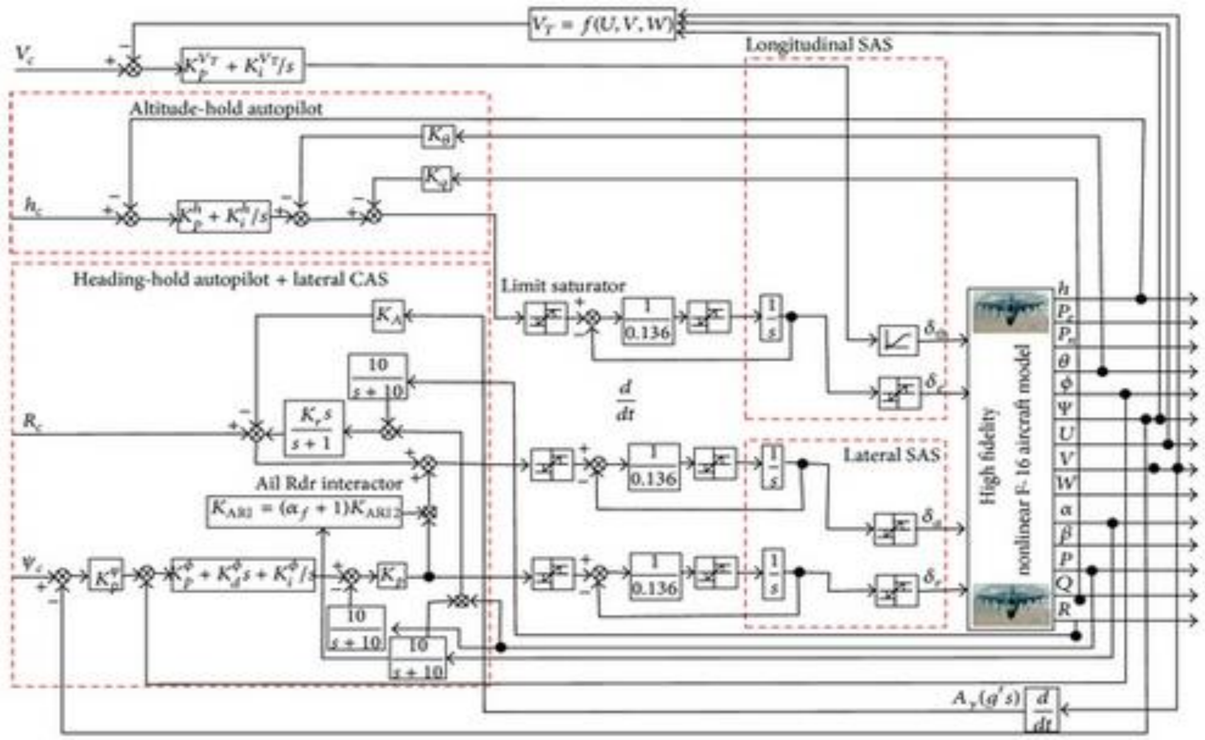

Figure 1.2 Block diagram of Overall system with autopilot, SAS, and CAS.

C) **Selection of Optimal Stability Augmentation System Parameters for a High Performance Aircraft Using Pitch Paper Pilot was investigated by Denaro et al (2015).**

Pitch paper pilot was a computer program which yields pilot parameters for a pitch tracking task and predicts the pilot rating of the aircraft handling qualities. Using Pitch Paper Pilot, optimal SAS gains were selected for the fixed form Stability Augmentation System of a high performance aircraft with structural bending. This aircraft was described in the Design Challenge to the 1970 Joint Automatic Control Conference. The final augmented aircraft responses compared favorably with desired normal acceleration response envelopes. The pilot model in Pitch Paper Pilot was modified in this study to include pilot lag and remnant which results in greater rating accuracy, although a few cases still show room for improvement.

D) Stability Augmentation Systems for Jet Trainer Aircraft was done by Bogdan Dobrescu (2015)

Stability augmentation for jet trainer aircraft requires damping of oscillations in the Dutch roll mode. The implementation of stability augmentation systems depends on the aircraft flight controls design. This paper presented the architecture and implementation of a yaw damper on the IAR–99 aircraft, which has unassisted mechanical controls, without the need for major modifications to the local structure and without affecting other onboard systems. The system ensures stability augmentation in the Dutch roll mode, improving aircraft safety and performance. Numerical simulations show that the system can achieve the damping of Dutch roll oscillations at Level 1 for all flight conditions.

III METHODOLOGY

The aircraft model chosen for this research was based on an existing aircraft (Syberjet 30) which without the Stability Augmentation System (SAS), is almost impossible to fly the aircraft because of the sensitivity of the response of the aircraft for the given control surface deflections. To analyze the stability augmentation system, the information required were the states of the aircraft at any instance. These include the angular positions (roll, pitch and yaw) and also the rate of change of the angular position at any time. The information was fed into the SAS module. The inputs given by the joystick were the demanded roll rate and the demanded pitch rate. The demanded roll rate and the demanded pitch rate were fed into a high Level Programming language that calculated the demand pitch and demand roll during every step then relied on another function that used classical control method to determine state of aircraft at that instance.

When an aircraft has a low speed at a high altitude, the Dutch roll properties of the aircraft deteriorate. To prevent this, a yaw damper is used. An overview of this system can be seen in Figure 1.3 below. Yaw damper receives its input (feedback) from the yaw rate gyro and then sends a signal to the rudder servo. The rudder then moved in such a way that the Dutch roll damped much more quickly than usual. As a designer, the yaw damper can only be influenced. How the other systems work as well, however, need not be known. It is usually assumed that the model of the aircraft is known. (Or the one that is derived in the Flight Dynamics course could be used).

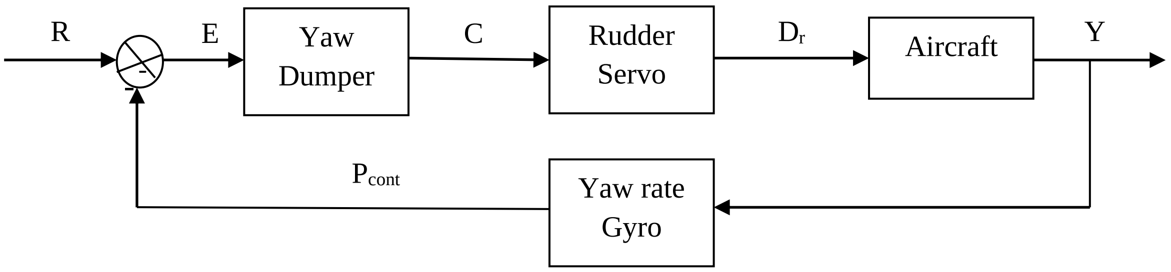

Figure 1.3 Block diagram of feedback control system

Where: R, E, C, Dr, Y and P_{cost} are the related functions in the frequency(s) domain.

Yaw Rate Gyro:

Gyros are generally very accurate in low frequency measurements, but not so good in high frequency regions so the model of the gyro is a low pass filter, given by the equation 1.1

$$H_{gyro}(s) = 1/(s + \omega_{br}) \qquad 1.1$$

The gyro break frequency ω_{br} (above which the performance starts to decrease) is quite high. In fact, it is usually higher than any of the important frequencies of the aircraft [3]. Therefore, the gyro was simply modeled as H(s) = 1. In other words, it was assumed that the gyro is sufficiently accurate.

The rudder servo Actuator

Actuators are always a bit slow to respond therefore lags behind the input. The Rudder was modeled as a lag transfer function, like

$$H_{servo}(s) = K_{servo}/(1 + T_{servo}\, s) \qquad 1.2$$

The time constant T_{servo} depends on the type of actuator installed for example slow electric actuators have $T_{servo} \approx 0.2$ while fast hydraulic actuators, $T_{servo} \approx 0.05$ to 0.1. This time constant (or equivalently, the servo break frequency $\omega_{brservo}$) can be very important. If it turns out to be different than expected, the results can also be very different, therefore investigation was done to see what happens if T_{servo} varies a bit. The SJ30 uses a Rudder bias system (integrated autopilot), hence electric actuators $T_{servo} \approx 0.25$. [3]

Yaw damping

The yaw damper reduces the yaw rate, but shouldn't always try to keep the yaw rate at zero. In this case, the pilot has hard time to change the heading of the aircraft. Thus, a reference yaw rate r was supplied to the system. This yaw rate was calculated from the desired heading rate ψ' by using

$$r = \psi' \cos\theta \cos\phi \qquad 1.3$$

In this equation, θ is the pitch angle and ϕ is the roll angle. Both of them thus need to be known. Alternatively, it was assumed that the aircraft is in a horizontal steady turn. In this case, we have

$$L\sin\phi = mg\sin\phi/\cos\phi = mU\psi' \Rightarrow \psi = (g/Us)\phi \qquad 1.4$$

In this equation, U is the forward velocity of the aircraft, assuming ϕ is small such that tan ϕ =ϕ) and that transformed the equation to the frequency domain (by replacing ψ' with $s\psi$).

If r is unknown, the system was made to work by incorporating a washout circuit (which is much less expensive) into the controller, being

$$H_{washout}(s) = \tau s/(\tau s + 1) \qquad 1.5$$

This causes the yaw damper to fight less when a yaw rate is continuously present. In other words, the system 'adjusts' itself to a new desired yaw rate. The time constant r is quite important. For too high values, the pilot will still have to fight the yaw damper. But for too low values, the yaw damper itself does not work, because the washout circuit simply adjusts too quickly. A good compromise is often achieved at τ = 4s. [5]

A yaw damper transfer function may have proportional (P), integral (PI) and derivative (PID) action. If the rise time is reduced, proportional action applies. If the steady state error needs to be reduces, an integral action is added. And if the transient response needs to be reduced (e.g. to reduce overshoot) a derivative action is applied. In this way, the right values of K_p, K_I and K_D can be selected.

Sometimes, the optimal values of the gains K_p, K_I and K_D differ per flight phase. In this case gain scheduling can be applied. The gains then depend on certain relevant parameters, like the velocity U and the altitude h. In this way, every flight phase will have the right gains.[6]

The various parameter for the SyberJet 30, given below were fed into the simulation model to obtain the data for analysis.

Cruising speed: U = 560mph =901km/h;

Maximum Flight height h_{max} = 49,000ft;

Tservo (electric) =0.25sec

Acceleration due to gravity: g =9.81m/s^2 =32ft/s^2;

Roll angle, ϕ = ± 21^o =0.367rad;

Yaw rate limit, Q_{lim}= 1.047rad/s;

Time constant, t = 4.0 sec;

Pitch angle, θ = ± 25^o = 0.436 rad;

Coefficient on Rudder (Actuator), Kservo = 1.4; [7],[8], [9] and [10]

For a transient response to be reduced (Reduce overshoot), the conditions of a Proportional Integrated Derivative (PID), PID gain, K_D taken as 100,000in-Ib sec/rad/s =45359.237kg sec/rad/sec[11]:

Then

Transfer Function for Yaw rate gyro, $H_{gyro}(s) \approx 1$;
Transfer Function for Rudder servo, $H_{servo}(s) = K_{servo}/(T_{servo}\, s + 1) = 1.4/(0.25s + 1)$;
Transfer function for washout, $H_{washout}(s) = \Gamma s / (\Gamma s + 1) = 4s^2/(4s^2 + 1)$;
Transfer function for closed loop,

$$G_{closed\ loop}(s) = H_{washout}(s)\, H_{servo}(s)\, K_D \,/\, (1 + H_{washout}(s)\, H_{servo}(s)\, H_{gyro}(s)\, K_D)$$

$$G_{closed\ loop}(s) = \frac{4s^2/(4s^2+1) * 1.4/(0.25s+1) * K_D}{[1 + (4s^2/(4s^2+1) * 1.4/(0.25s+1) * 1 * K_D)]}$$

$$G_{closed\ loop}(s) = \frac{5.6\, K_D\, s}{[(s^3 + (4.25 + 5.6K_D)s^2 + 0.25s + 1)]}$$

$$G_{closed\ loop}(s) = \frac{2.54 \times 10^5\, s}{s^3 + 2.54 \times 10^5 s^2 + 0.25s + 1}$$

Which is in the form:

$$G_{closed\ loop}(s) = \frac{G(s)}{1 + G_{open\ loop}(s)}$$

Where,

$$G_{open\ loop}(s) = s^3 + (4.25 + 5.6\, K_D)s^2 + 0.25s \qquad 1.6$$

Substituting $K_D = 45359.23$ in equation 1.6
Transfer Function for open loop,

$$G_{open\ loop}(s) = s^3 + 2.54 \times 10^5\, s^2 + 0.25s \qquad 1.7$$

Proving that the open system is stable implies the closed system is also stable:
There are different ways of proving this:

I) Routh-Huwitz stability criteria:

$G_{open\ loop}(s)$ is in the form: $a_3 s^3 + a_2 s^2 + a_1 s + a_0$ (third order system) 1.8
Where, $a_3 = 1$, $a_2 = 2.54 \times 10^5$, $a_1 = 0.25$ and $a_0 = 0$
Routh-Huwitz stability criteria says the system is stable if $a_n > 0$ where $n \geq 0$;
And $a_3 a_0 < a_1 a_2$
From the equation $a_0 = 0$ did not hold, although $(a_3 a_0 = 0) < (a_1 a_2 = 6.35 \times 10^4)$ is satisfied, therefore system is unstable.

II) Jury stability criteria: for a given system G(s), if it satisfies the following conditions:

a) $G(s)|_{s=1} > 0$,
b) $G(s)|_{s=-1} > 0$, when n –even and $G(s)|_{s=-1} < 0$, when n-odd and
c) $|a_0| < a_n$; then system is stable.

From equation (1.8) of $G_{open\ loop}(s)$, where $a_3 = 1$; $a_2 = 2.54 \times 10^5$, $a_1 = 0.25$ and $a_0 = 0$;

a) $G_{open\ loop}(1) = 2.54 \times 10^5 > 0$, satisfied
b) $G_{open\ loop}(-1) = (-1)^3 + 2.54 \times 10^5 (-1)^2 + 0.25(-1) \approx 2.54 \times 10^5 > 0$, unsatisfied
c) $|a_0 = 0| < a_3 = 1$, satisfied;

Since not all conditions are satisfied, hence system is unstable.

III. RESULTS

After feeding the parameters into Matlab application software using Bode stability criteria as depicted, the obtained results is shown in figure 1.4:

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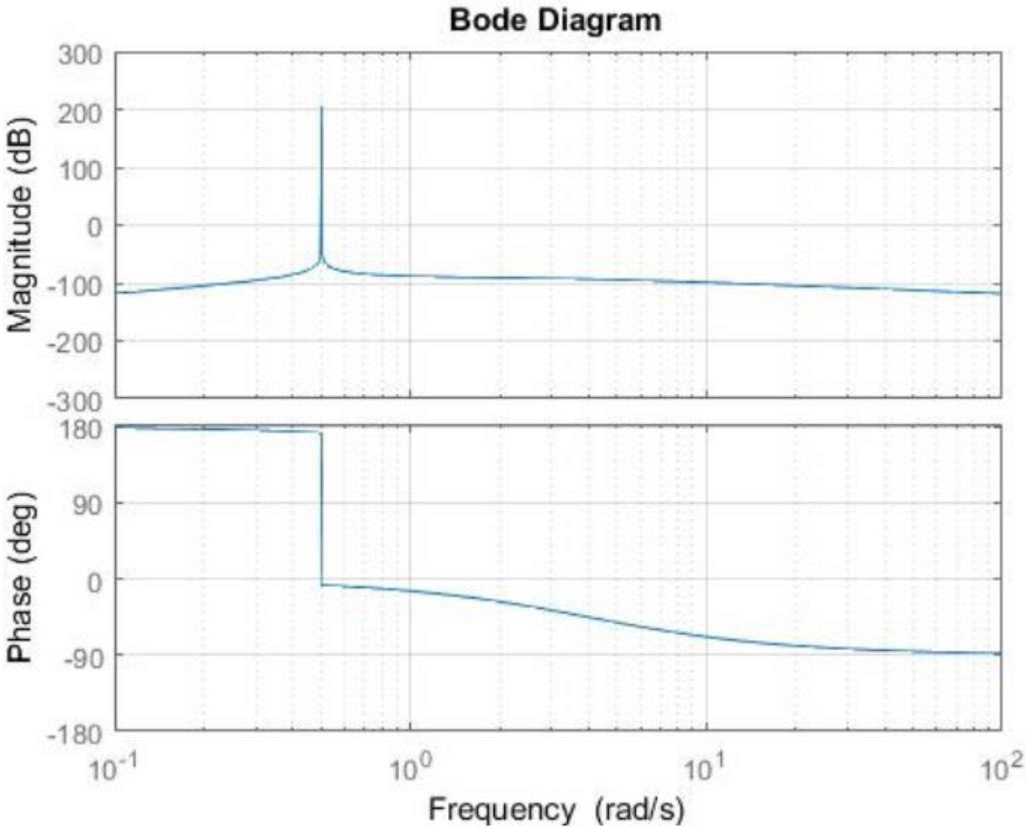

Figure 1.4 Graphical results from Matlab application software

IV.DISCUSSION

The Bode stability criterion provides a measure of the relative stability rather than merely a yes or no answer to the question, "Is the closed-loop system stable?"

Before considering the basis for the Bode stability criterion it is useful to review the General Stability Criterion:

A feedback control system is stable if and only if all roots of the characteristic equation lie to the left of the imaginary axis in the complex plane.

Before stating the Bode stability criterion, two important values come into play:

i) A critical frequency ω_c is defined to be a value of ω for which $\varphi_{OL}(\omega) = -180^\circ$.
This frequency is also referred to as a phase crossover frequency.

ii) A gain crossover frequency ω_g is defined to be a value of ω for which $AR_{OL}(\omega_g)=0$

Bode Stability Criterion: Consider an open-loop transfer function $G_{OL}=G$ that is strictly proper (more poles than zeros) and has no poles located on or to the right of the imaginary axis, with the possible exception of a single pole at the origin. Assume that the open-loop frequency response has only a single critical frequency ω_c and a single gain crossover frequency ωg. Then the closed-loop system is stable if $0 < AR_{OL}(\omega_c) < -12$dB. Otherwise it is unstable.

NB: $AR_{OL}(\omega) = 10 \log(|G(\omega)|)$, dB.

From the results, referring to the Phase vs Frequency graph in figure 1.4 above a phase angle of -180º known as the critical crossover phase helps to determine the critical frequency ω_c and according to Bode stability criteria this value is undefined from the graph. With ω_c being undefined, then refering to Magnitude of AR_{OL} (ω_c) in dB also becomes undefined thus falling below -12dB. As discussed above from Bodes stability criteria, the system would termed to be unstable.

V. CONCLUSION

It can be concluded the yaw damping of Syberjet 30 aircraft in turbulent conditions makes the system becomes unstable according to simulation results obtained. It becomes almost impossible to fly the aircraft due to the sensitivity of the response of the aircraft to the given control surface deflections. With the aid of a Stability Augmentation System (SAS) , the Syberjet 30 aircraft could be controlled to become stable during turbulence by automatically using the servo motor.

VI. RECOMMENDATION

It is therefore recommendable to the aeronautical sector to use the yaw damper to improve the autopilot performance in turbulence by means of the Servo motor which helps to control the movement of aircraft for stabilization.

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