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**Preliminary Open Loop Analysis of BFF
Models: Concentrating on low frequency
dynamics**

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1.0 INTRODUCTION

This working paper documents preliminary open loop analysis of the LM BFF models. These models were delivered to STI from UMN under a different contract.

The focus for this study is on the rigid body dynamics which are in the lower frequency range. This vehicle has high coupling between rigid body and flexible dynamics so traditional classic rigid body modes do not exist. Regardless, the low speed models do exhibit some behavior familiar to traditional aircraft dynamic modes (e.g., short period, phugoid, dutch roll, roll subsidence, spiral).

2.0 PRELIMINARY MODEL ADJUSTMENTS

Bare Airframe Dynamics

First, the actuator and sensor dynamics were residualized out so all that remained was the bare airframe, which has 148 states. These states consist of 10 rigid body states (Lateral, Plunge, Roll, Pitch, Yaw, and derivatives), 64 flexible structural states (32 modes and derivatives), and 74 unsteady aerodynamic states. It is noted that there is no heave state and derivative (which would be forward velocity). Without forward velocity there should be no phugoid mode. Despite this, a longitudinal mode that resembles phugoid was found as shown in the analysis below.

Additional Model Outputs

New attitude outputs were added. From the model state descriptions,¹ states 19, 20, and 21 have been defined as the rigid body roll, pitch, and yaw. These have been interpreted to be the rigid body attitude mode shapes. Units are unknown but these states were added to the available outputs of the system.

Control Allocation

The vehicle has 8 trailing edge control surfaces. For the purposes of open loop studies, allocation was defined to provide pitch and roll effectors similar to elevator and aileron. A simple allocation was defined where differential deflection of the outer surfaces provided aileron and a collective deflection of the middle surfaces (next outer) provided elevator.

3.0 OPEN LOOP ANALYSIS

Analysis was conducted by observing system open loop poles, Bode plots, and pole-zero maps as shown below.

3.1 V = 40 knots Model

System Poles

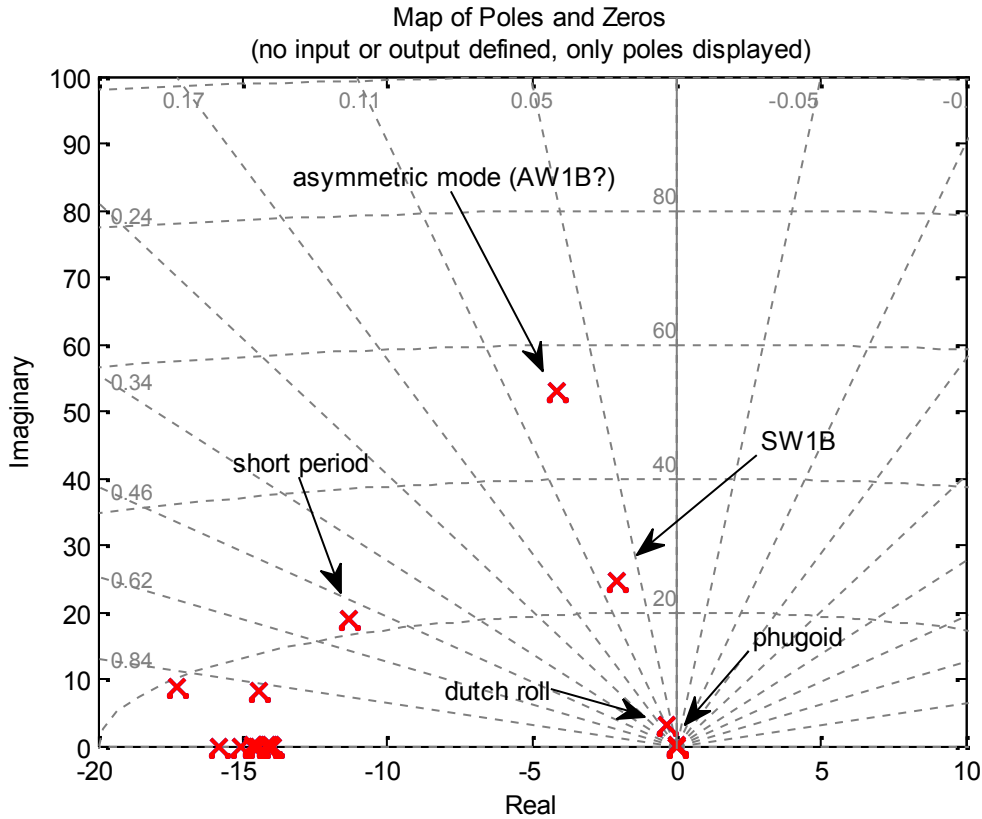


Figure 1: Open loop system poles: focus on low frequency.*

The modes are labeled based on analysis of the system Bode and root locus plots (see below). As mentioned above, the model does not include a forward velocity state so it is unclear how a phugoid is present. Nevertheless, a low frequency 2nd order pole is present in the longitudinal dynamics and has been labeled phugoid. It is noted that since this vehicle has highly coupled rigid body and flexible dynamics, traditional rigid body modes will not exist but the modes labeled represent the modes that closest resemble traditional rigid body aircraft modes. Table 1 displays the identified “rigid-body-like” modes with the wet SW1B mode.

Table 1: System “rigid-body-like” poles.

Mode	Pole	Frequency (rad/s)	Damping
phugoid	$-3.84\text{E-}6 \pm 8.77\text{E-}4j$	$8.77\text{E-}4$ (1.34E-4 Hz)	$4.38\text{E-}3$
short period	$-11.3 \pm 18.9j$	22.1 (3.52 Hz)	0.512
dutch roll	$-0.317 \pm 3.10j$	3.12 (0.50 Hz)	0.101
roll subsidence	??	-	-
spiral	$1.22\text{E-}3$	$1.22\text{e-}003$ (1.94E-4 Hz)	-1
wet SW1B	$-2.08 \pm 2.46j$	24.7 (3.93 Hz)	0.0841

* SW1B = symmetric wing 1st bending.

The roll subsidence mode is real, stable, and is believed to be somewhere near or above 25 rad/s. This vehicle has a high aspect ratio providing significant roll damping. Detailed investigation of the roll subsidence model was not conducted.

Bode Plots

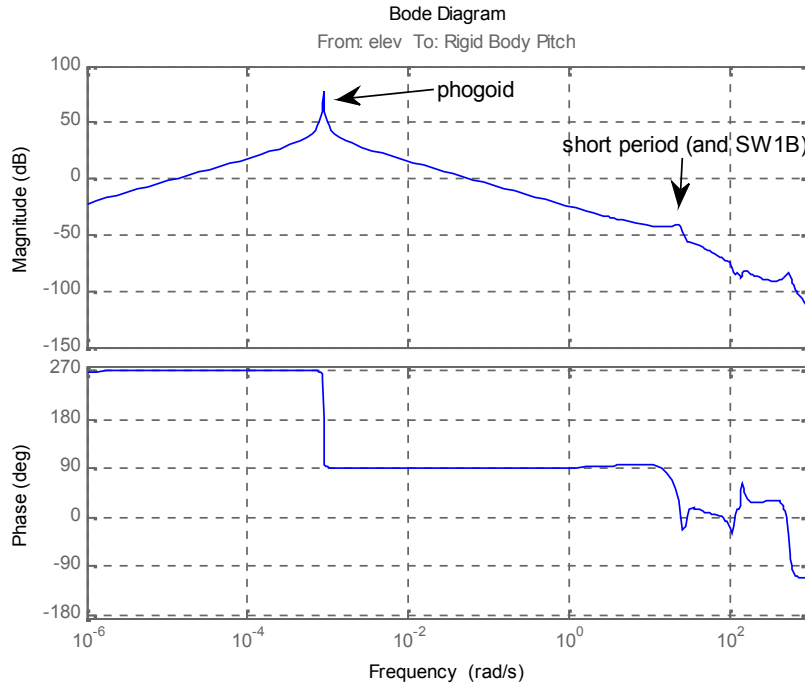


Figure 2: Pitch angle from elevator.

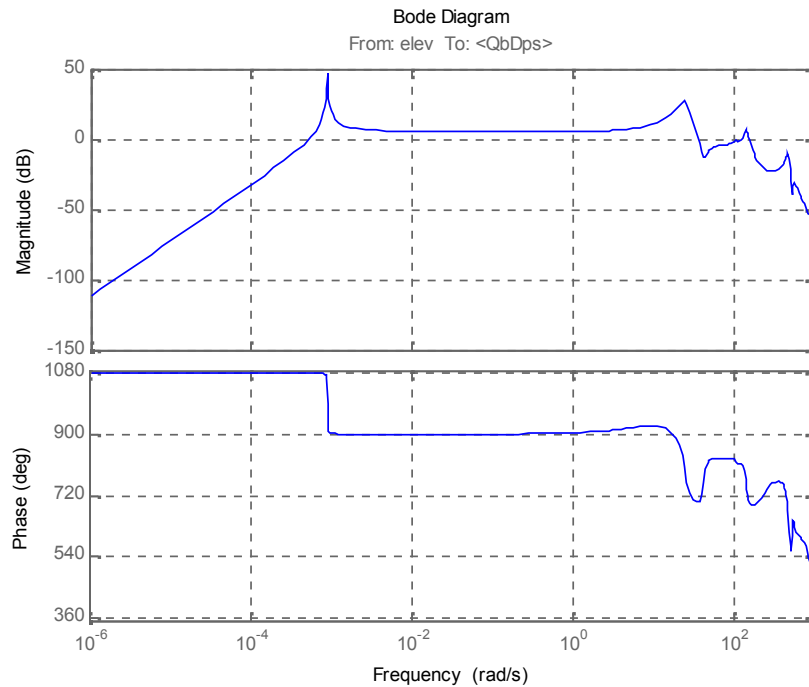


Figure 3: Pitch rate from elevator.

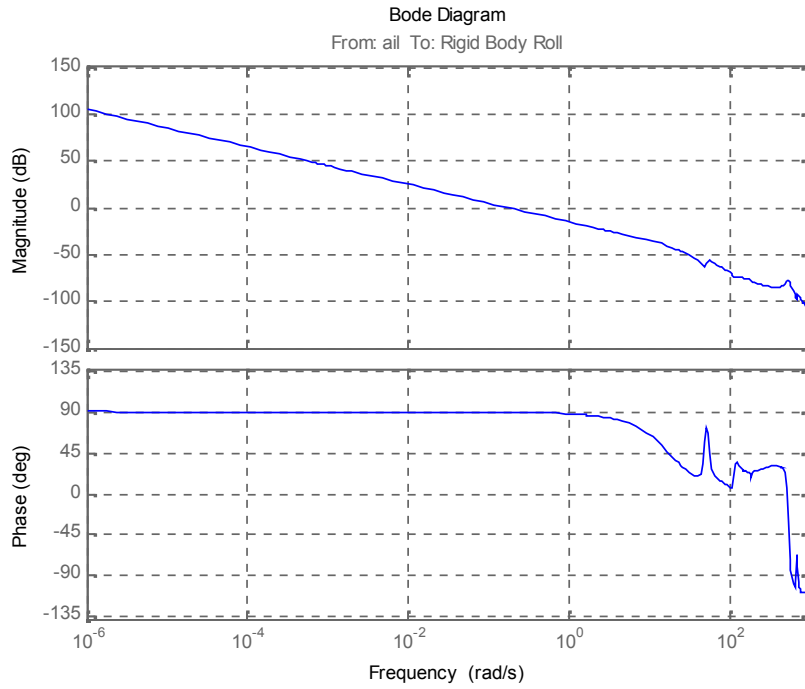


Figure 4: Roll angle from aileron.

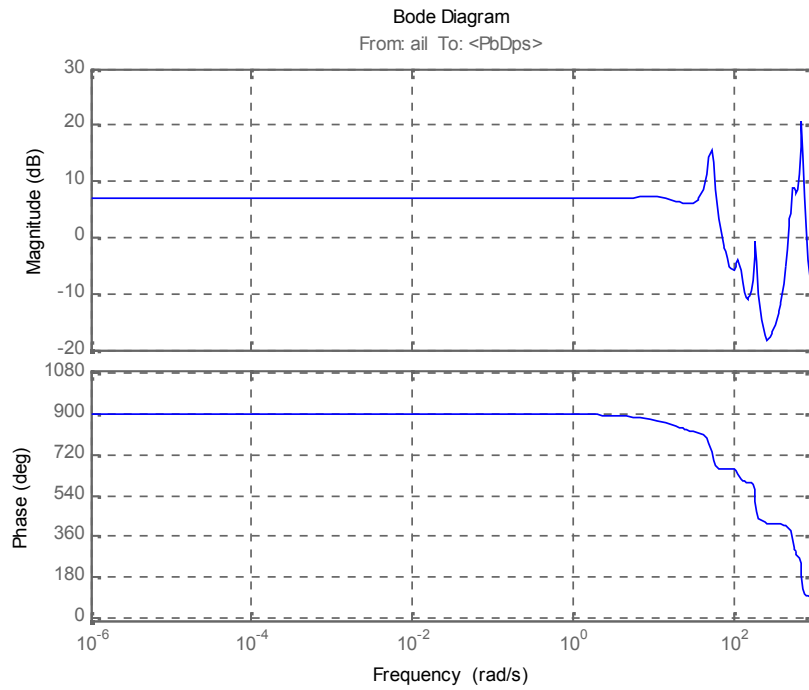


Figure 5: Roll rate from aileron.

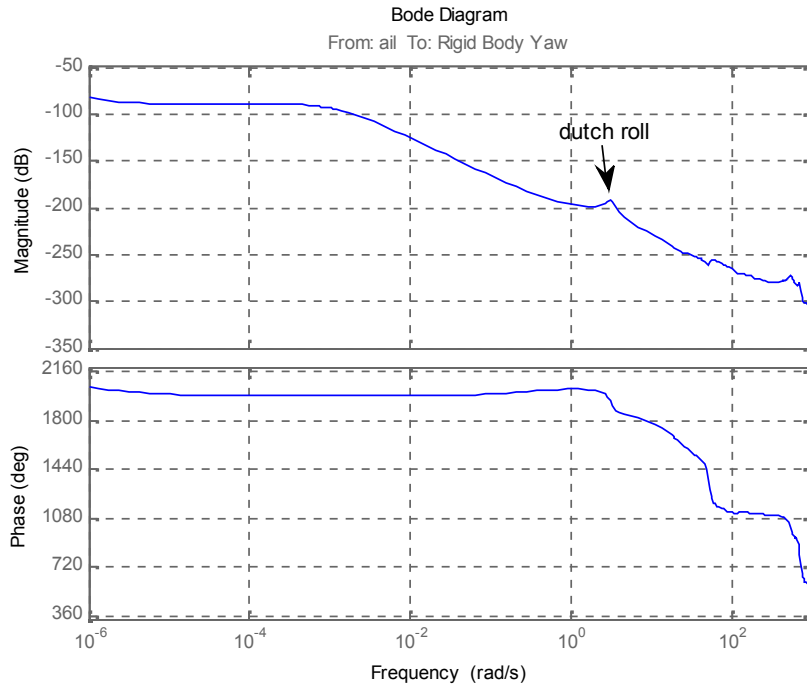


Figure 6: Yaw angle from aileron.

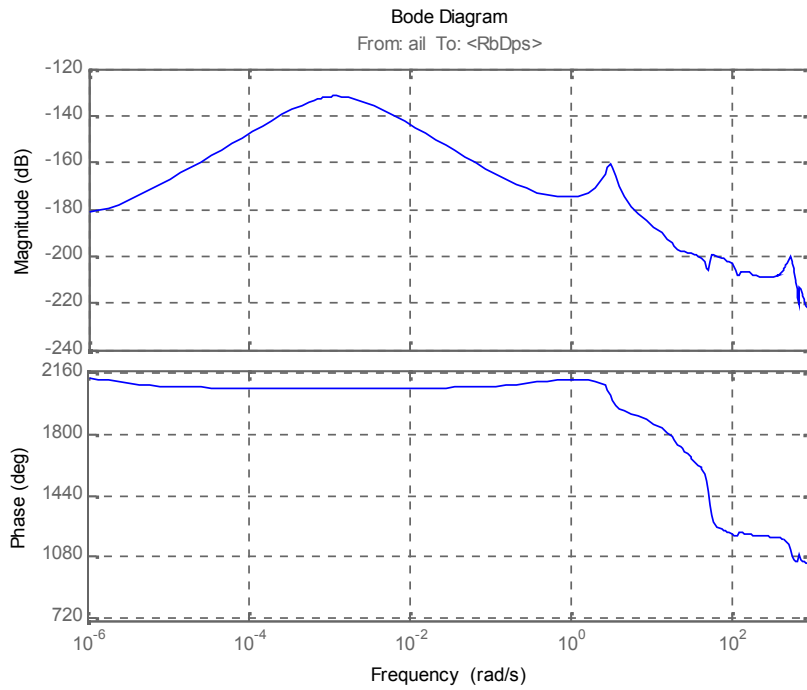


Figure 7: Yaw rate from aileron.

Pole-zero maps

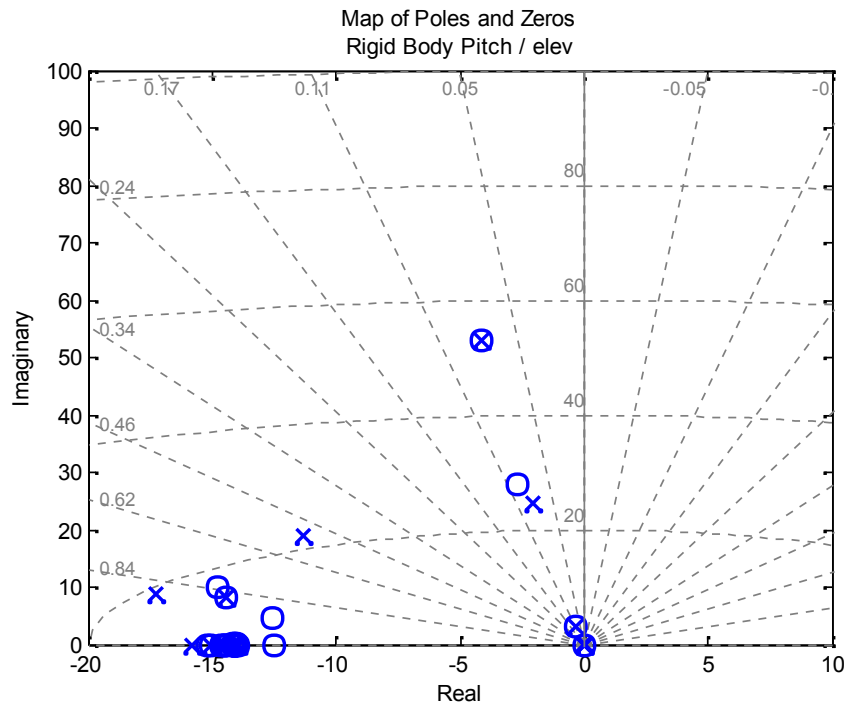


Figure 8: Pitch angle from elevator.

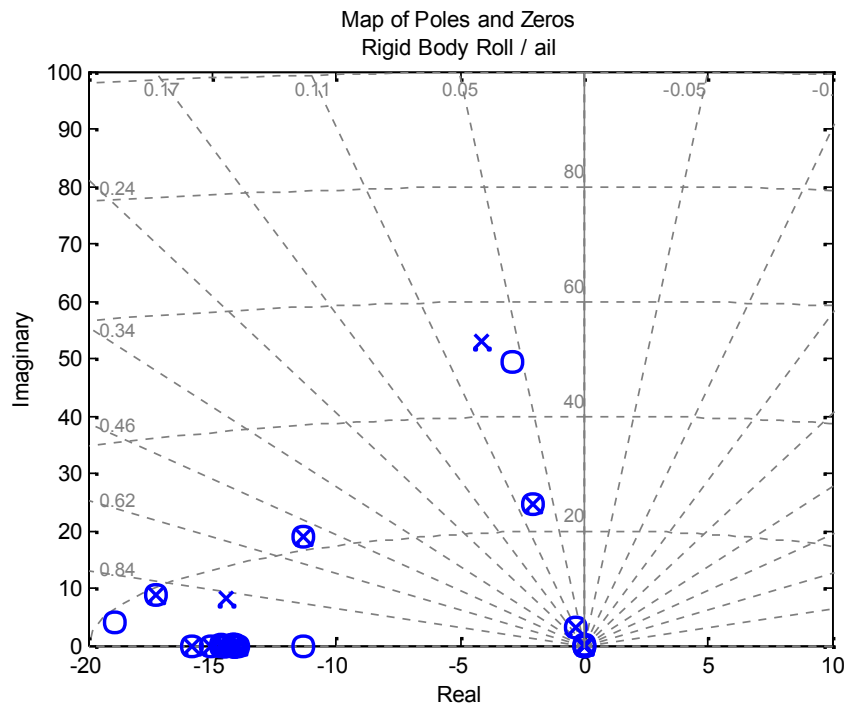


Figure 9: Roll angle from aileron.

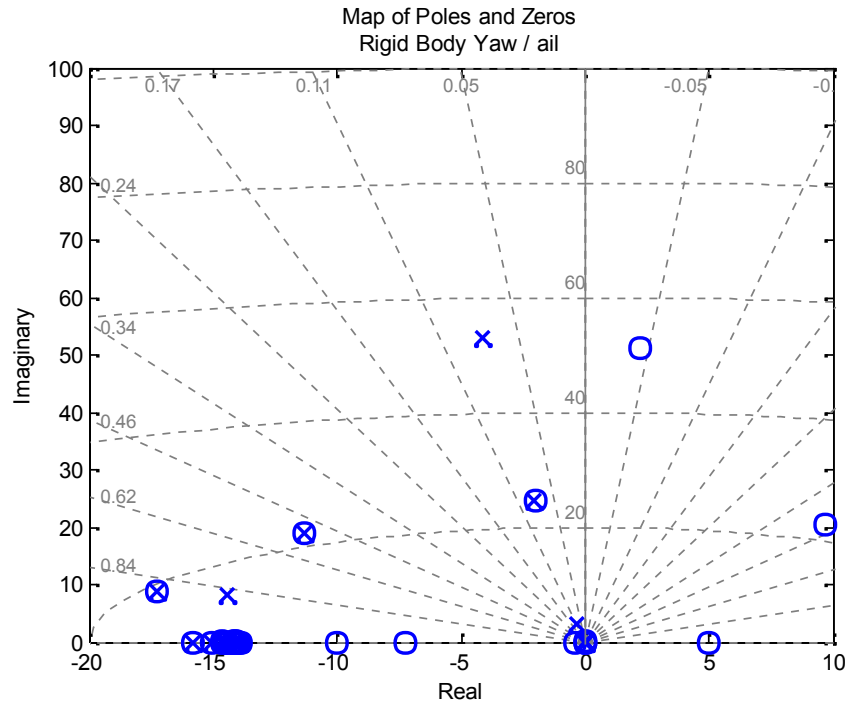


Figure 10: Yaw angle from aileron.

The following three pole-zero maps show low frequency detail. It is apparent that the complex mode (phugoid?) is indeed a longitudinal mode since it is not exactly cancelled by a zero in u_e while it is canceled in w/u_a and ξ/u_a . The real modes are almost mirrored about the imaginary axis and are canceled by zeros in u_e and w/u_a but are not canceled by zeros in ξ/u_a . This suggests that one of them could be the spiral mode.

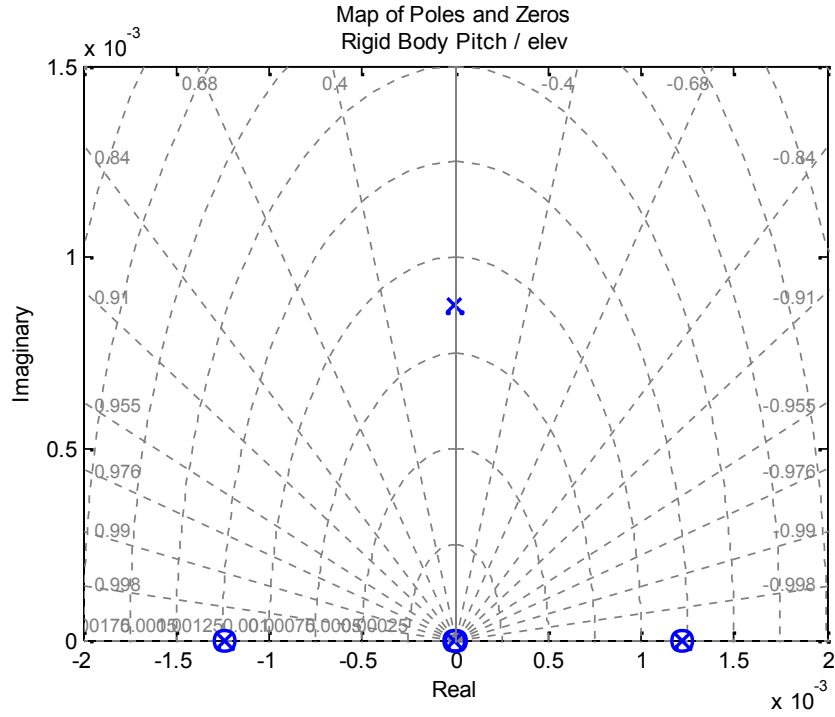


Figure 11: Pitch angle from elevator, low frequency detail.

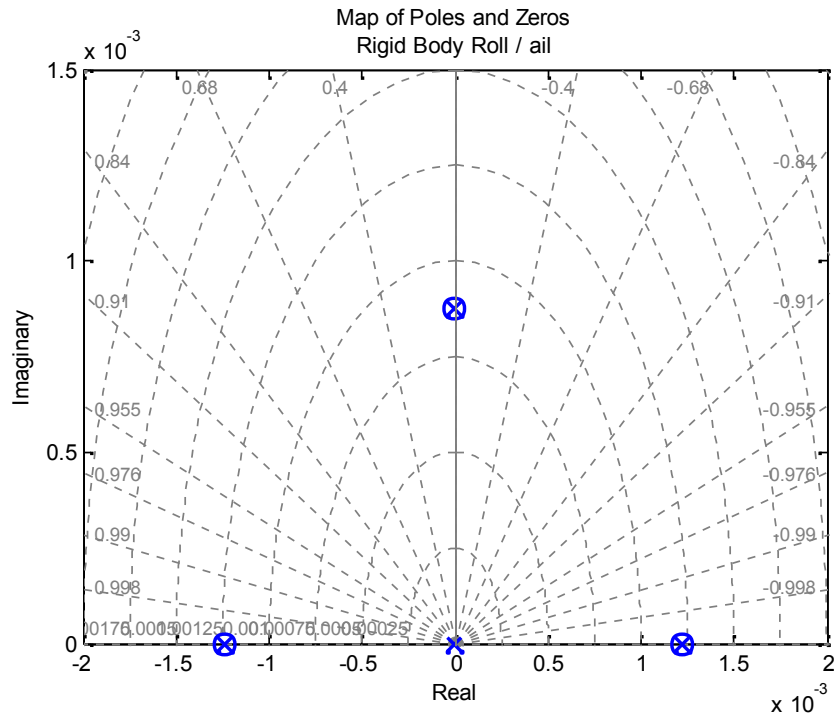


Figure 12: Roll angle from aileron, low frequency detail.

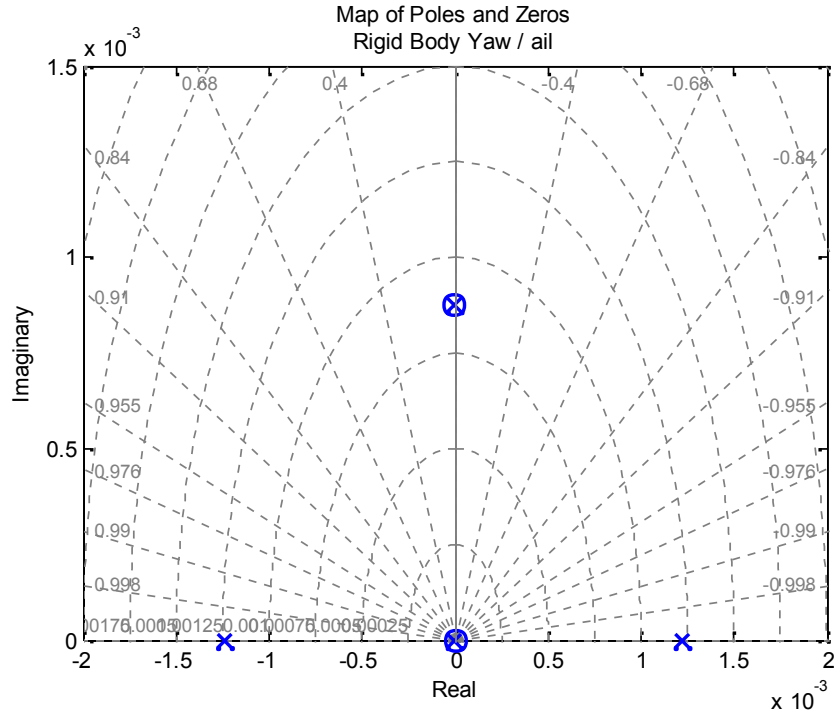


Figure 13: Yaw angle from aileron, low frequency detail.

Modal element magnitude

The following plots display the relative magnitude of mode shape elements (taken from eigenvectors of the system A matrix). Only the rigid body states and the SW1B are shown. The identified rigid body modes are shown as well as the wet SW1B mode.

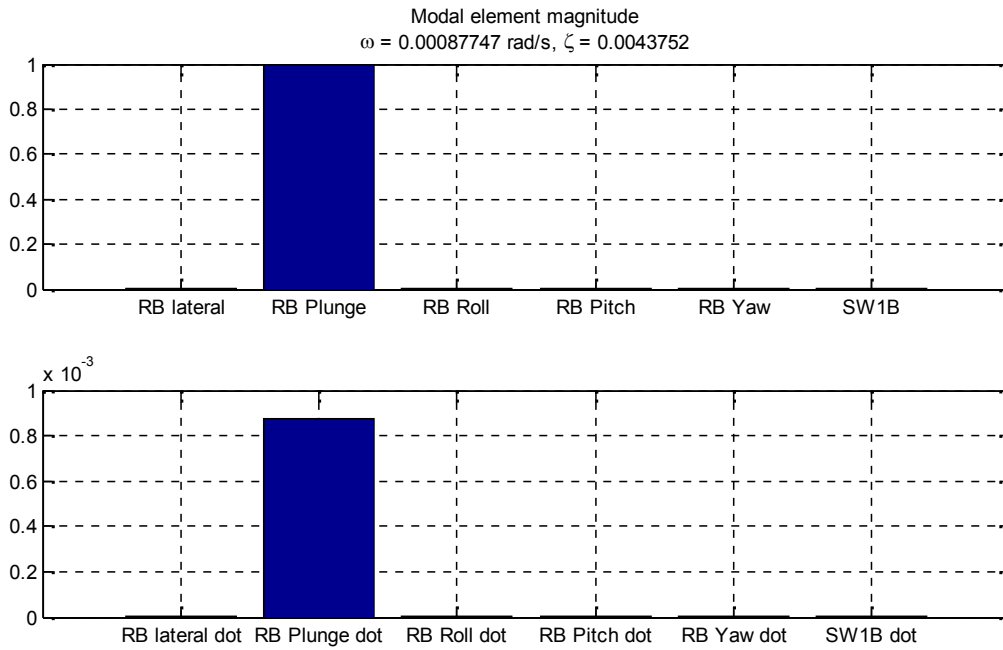


Figure 14: Phugoid mode state magnitudes.

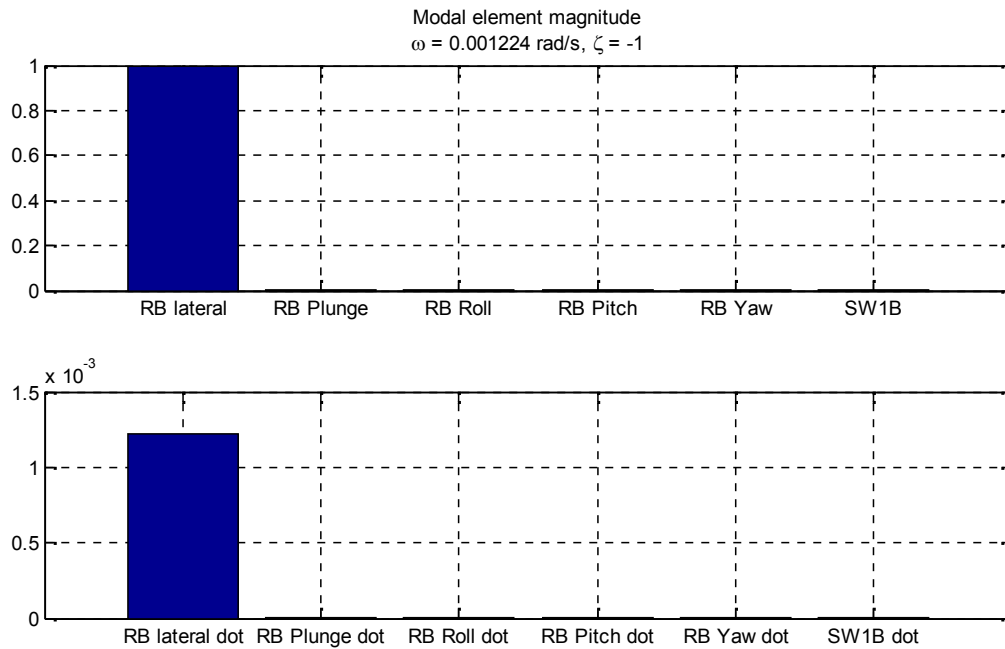


Figure 15: Spiral mode state magnitudes.

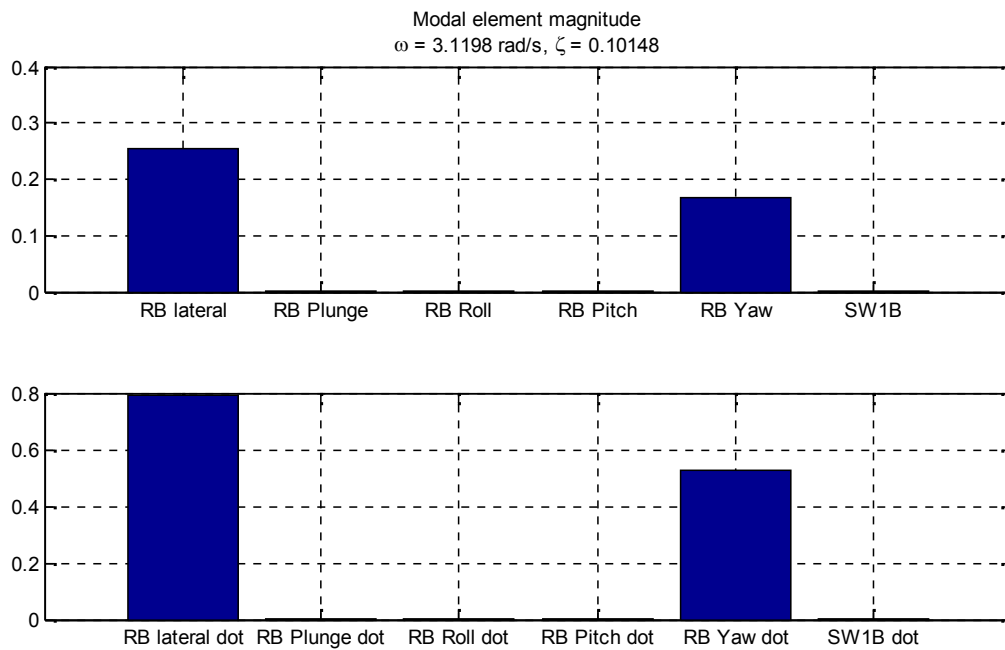


Figure 16: Dutch roll mode state magnitudes.

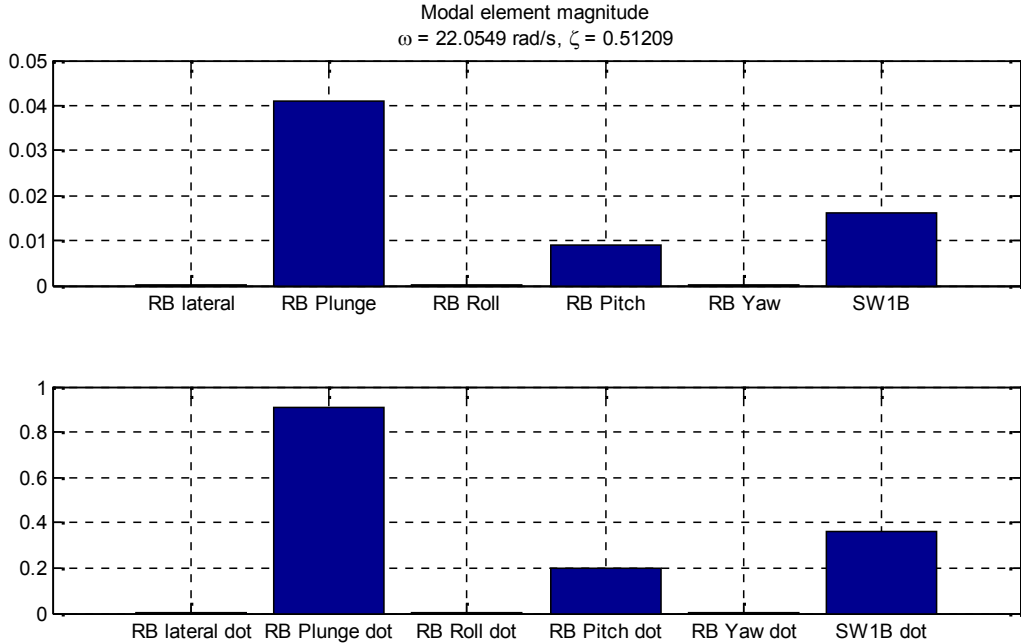


Figure 17: Short period mode state magnitudes.

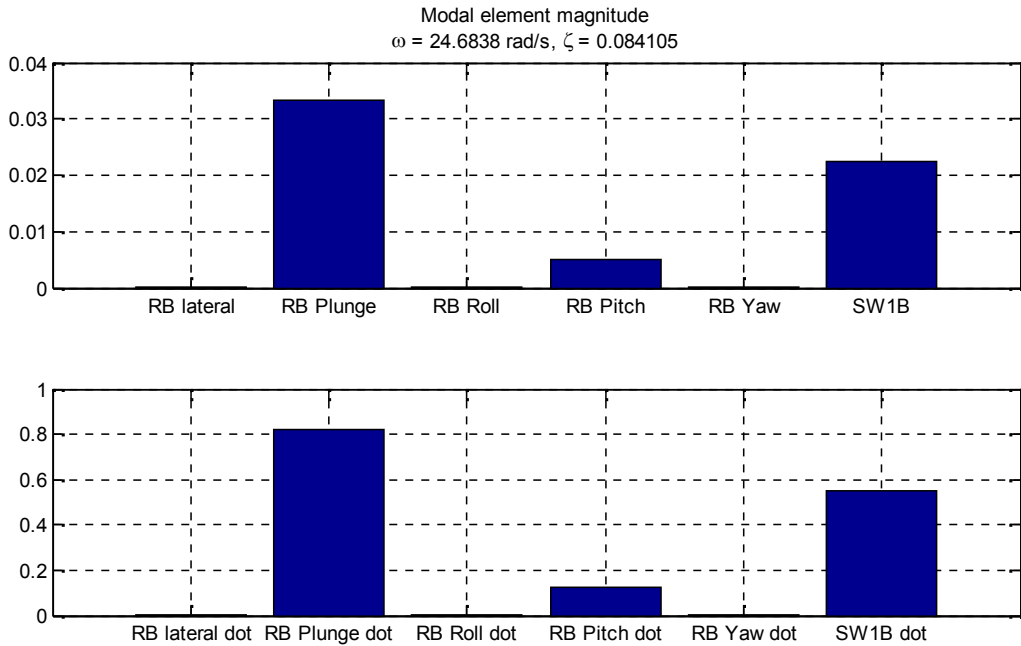


Figure 18: Wet SW1B mode state magnitudes.

4.0 CONCLUSIONS

This analysis reveals that the low frequency dynamics for the lower speed models display “traditional aircraft-like” behavior for the most part. This suggests that classic control design will be effective to some degree for stability augmentation. There are some unanswered questions regarding the low frequency phugoid mode. Since the model does not contain a heave state (and its derivative), a traditional phugoid

should not be present (traditional phugoid is due to mainly forward velocity and pitch attitude). Nevertheless, a low frequency complex pole exists in the longitudinal dynamics that has been labeled phugoid in the above analysis. This mode is due to mainly plunge and its derivative. Further investigation of the low frequency longitudinal dynamics is recommended to address this behavior.

REFERENCES

- ¹ “state names.xlsx,” Excel file delivered with the BFF model database.