Flight Control System Development For the BURRO Autonomous UAV

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Abstract

Developing autonomous flying vehicles has been a growing field in aeronautical research within the last decade and will continue into the next century. With concerns about safety, size, and cost of manned aircraft, several autonomous vehicle projects are currently being developed; uninhabited rotorcraft offer solutions to requirements for hover, vertical take-off and landing, as well as slung load transportation capabilities. The newness of the technology requires flight control engineers to question what design approaches, control law architectures, and performance criteria apply to control law development and handling quality evaluation. To help answer these questions, this paper documents the control law design process for Kaman Aerospace's BURRO project.

Kaman Aerospace is currently developing the Broad area Unmanned Responsive Resupply Operations (BURRO) aircraft for the United States Marines. The BURRO is an adaptation of the existing K-MAX external lift helicopter (Figure 1), manufactured by Kaman, which will be capable of both remotely-piloted flight and autonomous waypoint navigation. The overall mission scenario consists of a remotely-piloted takeoff controlled by a ground operator followed by a smooth hand-off and transition to autonomous hover. Once in autonomous mode, the aircraft will proceed to fly to a number of pre-programmed GPS waypoints and hover at each to allow pickup or delivery of cargo pallets on a multi-hook carousel. The deliveries will be made to off-shore ships (Figure 2) or to forward-deployed troops in high-threat environments. Upon delivery BURRO will autonomously return to its point of origin and hover, awaiting transition back to remotely-piloted control for landing.

The K-MAX is a medium weight class, external lift cargo helicopter designed specifically for vertical-reference flying with slung loads (Figure 3). It is a twin main rotor, no tail rotor design with the main rotors in an overlapping, intermesher arrangement known as a "synchropter". The intermesher arrangement provides exceptional lift capability (the maximum certified hook load exceeds the helicopter's standard gross takeoff weight) with little transmission/gearing requirements. The extremely narrow fuselage permits clear vertical view of the load when operating in its normal piloted missions. This permits precision placement of the load.

The K-MAX uses two teetering main rotors with bearingless blades. All collective and cyclic control is achieved by using the Kaman servo-flap to elastically twist the blade spar. The low disc loading and low downwash of the synchropter creates low autorotation sink rates, low acoustic signatures, and a relatively comfortable environment for the ground load-handling crews.

This paper will describe the approach taken to design control laws and develop math models which will be used to convert the manned K-MAX into the BURRO autonomous rotorcraft. With the ability of the K-MAX to lift its own weight (6000 lb) the load significantly affects the dynamics of the system; the paper addresses the additional

design requirements for slung load autonomous flight. The approach taken in this design was to: 1) generate accurate math models of the K-MAX helicopter with and without slung loads, 2) select design specifications that would deliver good performance as well as satisfy mission criteria, and 3) develop and tune the control system architecture to meet the design specs and mission criteria.

An accurate math model was desired for control system development. The Comprehensive Identification from Frequency Responses (CIFER®) software package was used to identify a linear math model for unloaded and loaded flight at hover, 50 kts, and 100 kts. The results of an eight degree-of-freedom CIFER®-identified linear model for the unloaded hover flight condition are presented herein, and the identification of the two-body slung-load configuration is in progress.

There are several distinct dynamic characteristics of the K-MAX intermeshing rotor system that are not seen in single rotor configurations. The typical pitch rate to lateral input (q/δ_{lat}) and yaw rate to collective input (r/δ_0) coupled responses are absent, while there is greater coupling between roll rate to pedal input (p/δ_p) than in typical single rotor configurations. Another distinction becomes apparent in the modeling of the dynamic inflow. The standard coning and dynamic inflow equations do not adequately capture the vertical responses (A_z/δ_0 and W/δ_0) for the intermeshing rotor. A correction factor was implemented in the dynamic inflow equation to better capture the vertical response. Bode plots show the agreement of the model and flight-test frequency responses for hover (Figure 4). Time verification of doublet response for model and flight test data also agree (Figure 5). The time response verification demonstrates that the identified model does a good job of capturing the dynamics of the K-MAX and is well suited for control law development.

The K-MAX's slung load configuration consists of a single line with a hook attached to a trolley, which moves on a rail (Figure 6). The trolley allows the load-sling combination to swing about the c.g. in roll thus minimizing the coupling between load motion and roll attitude. The slung load hook and trolley designs were modeled with nonlinear and linear equations of motion. The linear equations are used in the CIFER® identified model of the slung load dynamics.

The Control Designer's Unified Interface (CONDUIT) software package was used as the flight control system development environment. CONDUIT facilitates access to MATLAB and Simulink, including the Controls Toolbox, and also provides additional design tools. After construction of an aircraft / control system model and initial selection of system gains, CONDUIT can be used to evaluate and tune the system to meet selected design specifications.

The 8-DOF identified model was implemented in Simulink; included in the Simulink model were transfer function representations of the aircraft's sensor dynamics, nonlinear actuator models (rate- and position-limited), and time delays associated with the digital flight control computer.

To meet the mission requirements, the control system architecture must provide for both direct control by a ground operator and indirect hands-off control by software performing waypoint guidance and navigation. The control architecture therefore provides basic stability and direct control functions through attitude command / attitude hold controllers (altitude rate command / altitude hold for the vertical channel), and separately implements translational velocity command / position hold controllers for use by the guidance and navigation software.

From the 8-DOF identified model, ideal constrained transfer functions were extracted for the on-axis responses to control inputs. The transfer functions were then used to design the attitude and altitude controllers. Following these designs, the velocity controllers were created for the longitudinal and lateral axes. The resulting controller designs were implemented in the Simulink model. To minimize the effects of coupling, control crossfeeds were calculated from the ratio of constrained response transfer function numerators. For the frequency range near crossover, the crossfeeds could be accurately represented by simple gains, and they were implemented as such in the Simulink model.

With the aircraft and control system modeled and baseline gains selected, performance could be evaluated and tuned using CONDUIT. An initial set of performance and handling-quality specifications were selected to ensure that the aircraft would be stable and exhibit reasonable handling characteristics when under control of the ground operator, in attitude/altitude command mode. The baseline results computed in CONDUIT are shown for the unloaded hover condition (Figure 7). CONDUIT was used to tune the system gains to meet the specifications; the results of tuning are shown (Figure 8).

FCS design is presently being conducted for the 50- and 100-knot forward flight conditions, both unloaded and with external slung loads, and in hover with a slung load. Additional specifications will be added to the CONDUIT case, to constrain the aircraft behavior during velocity command/waypoint navigation mode.

In conclusion, this paper will focus on the flight control design process for the autonomous BURRO project. The paper will examine the unique system identification requirements for an intermeshing rotorcraft with slung load. The paper will propose a set of manned rotorcraft specifications that also apply to autonomous rotorcraft. Lessons learned will be presented for control law development of autonomous helicopters with slung loads.

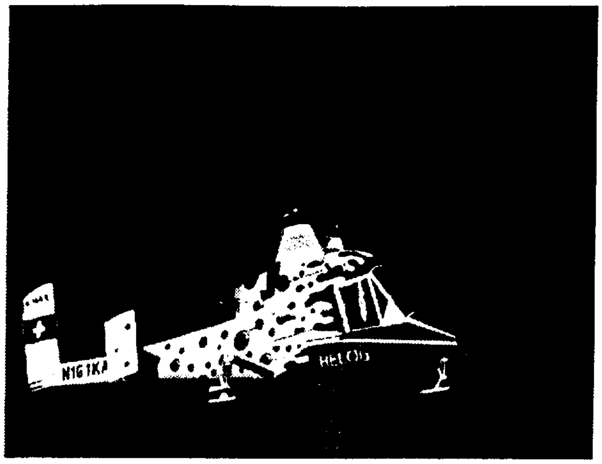

Figure 1. Kaman K-MAX

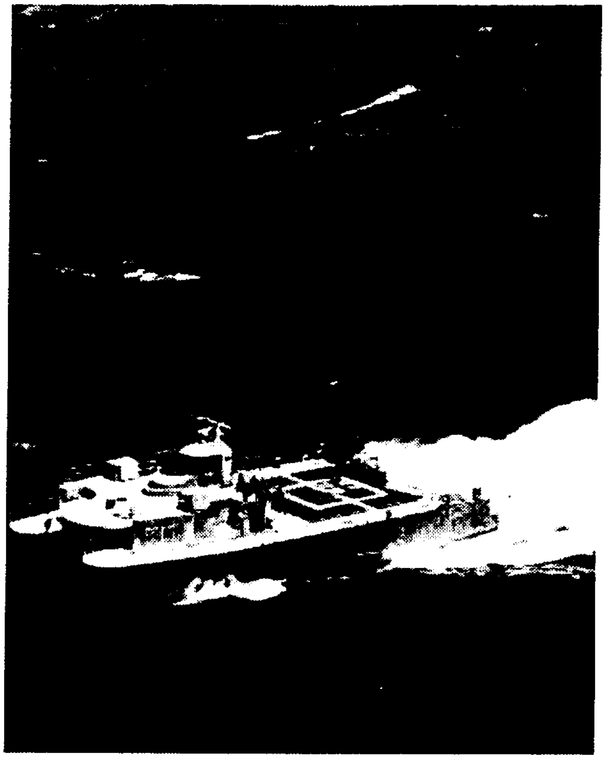

Figure 2. BURRO mission demonstration aboard SWATH vessel off the coast of Hawaii

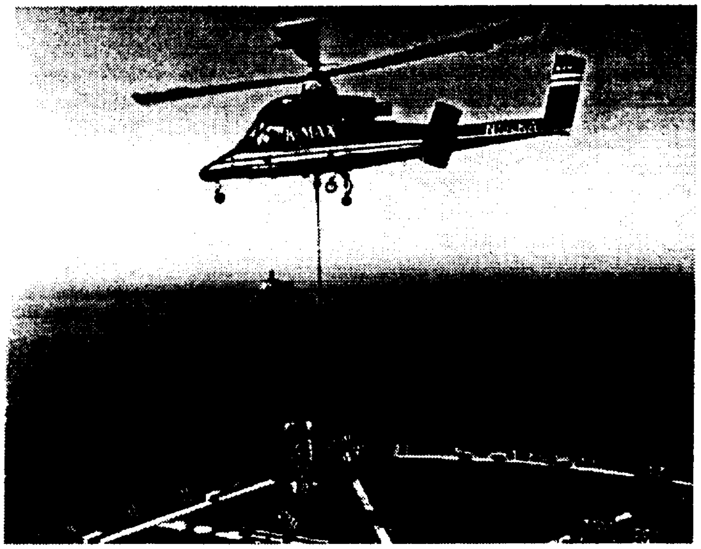

Figure 3. K-MAX performing BURRO mission demonstration

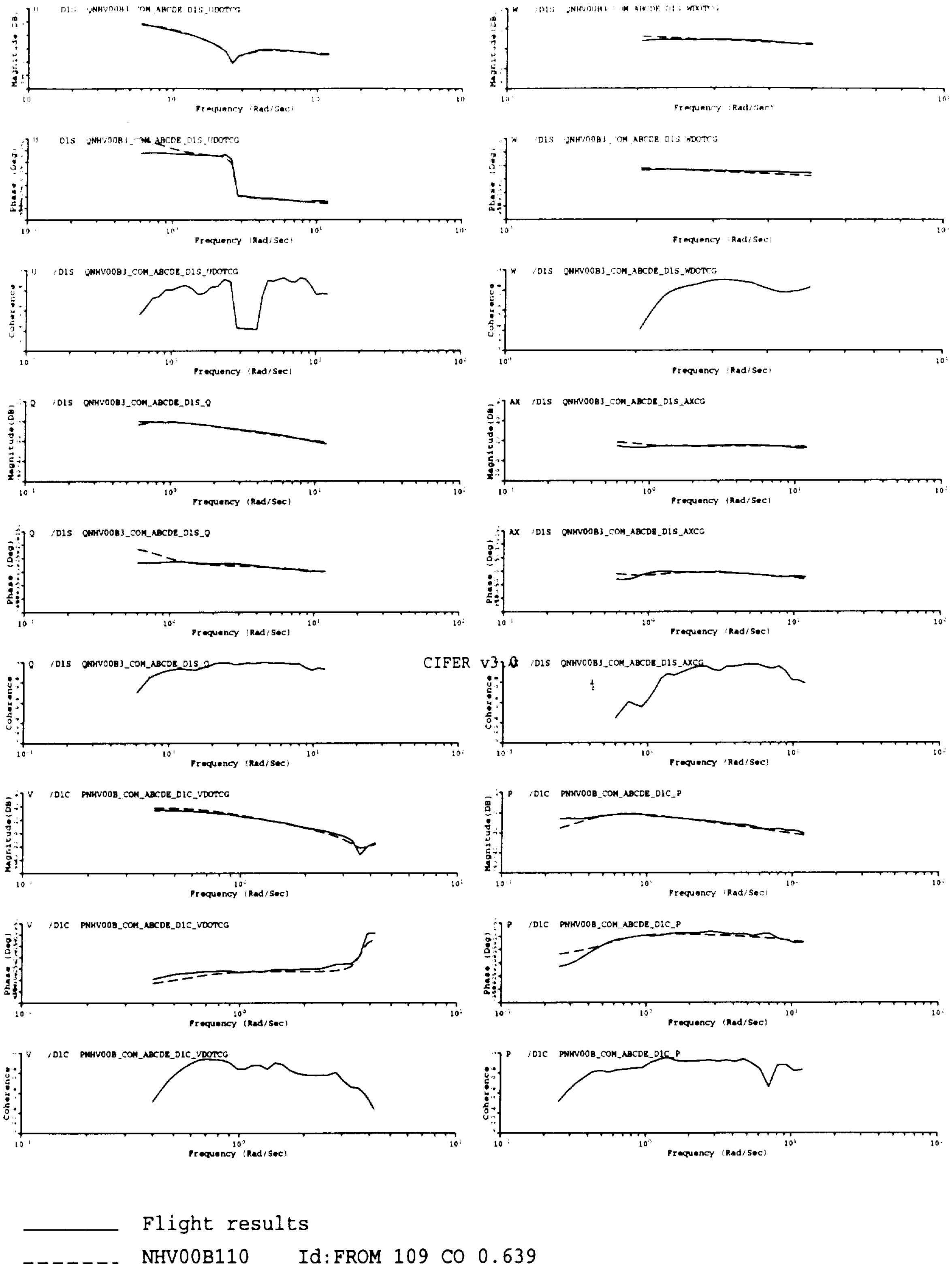

Figure 4. Comparison of CIFER-identified model and flight-test frequency responses (hover, unloaded)

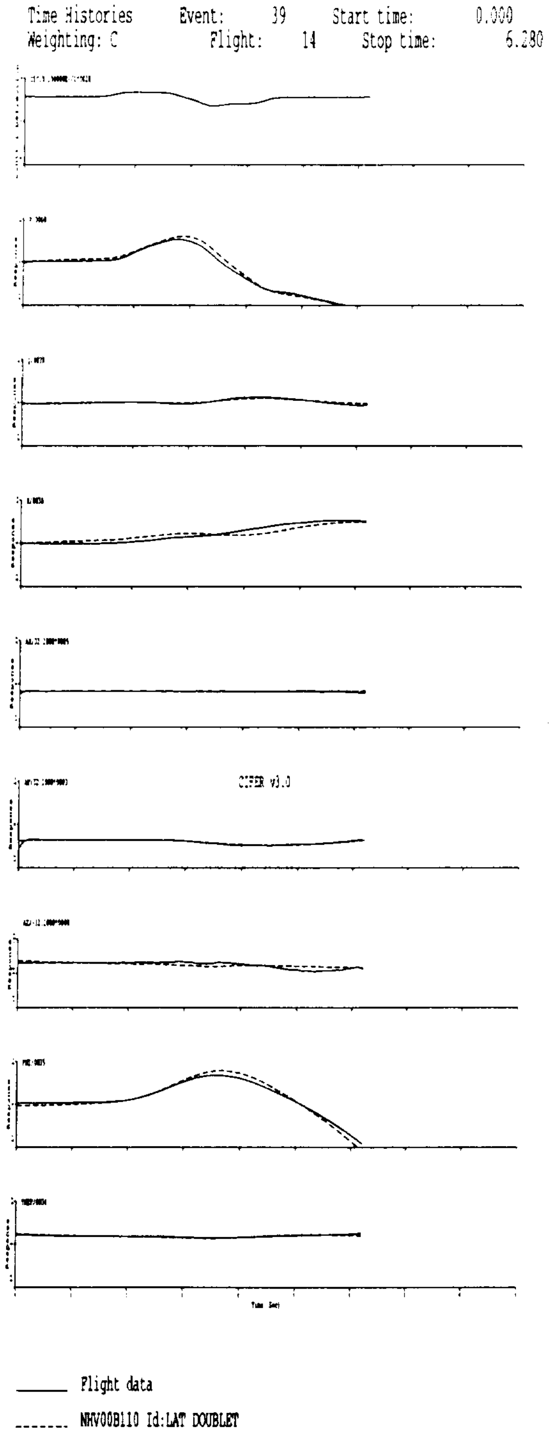

Figure 5. Time response verification of CIFER-identified model (hover, unloaded)

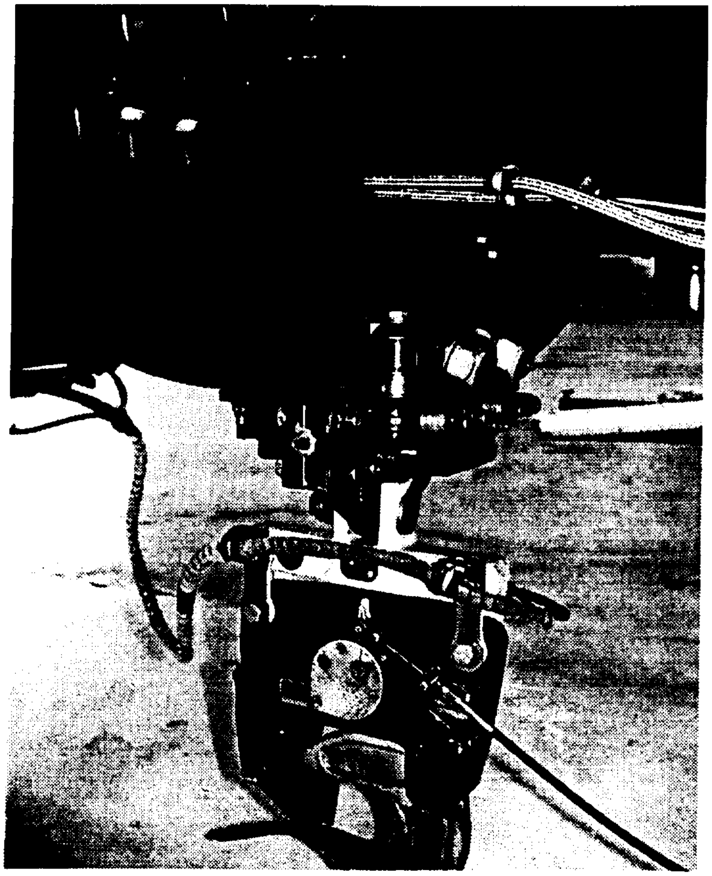

Figure 6. K-MAX hook and trolley configuration.

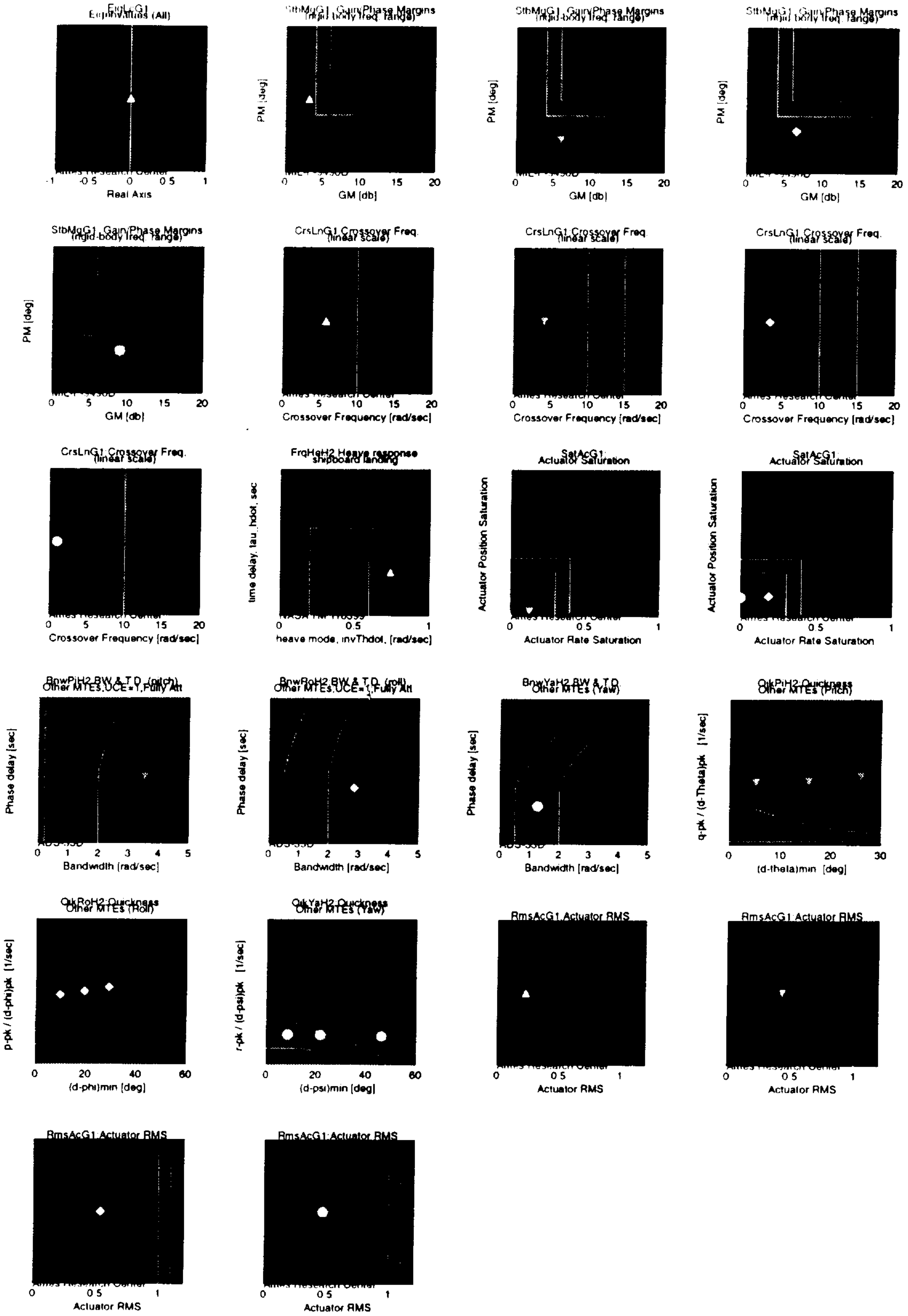

Figure 7. Baseline CONDUIT specifications

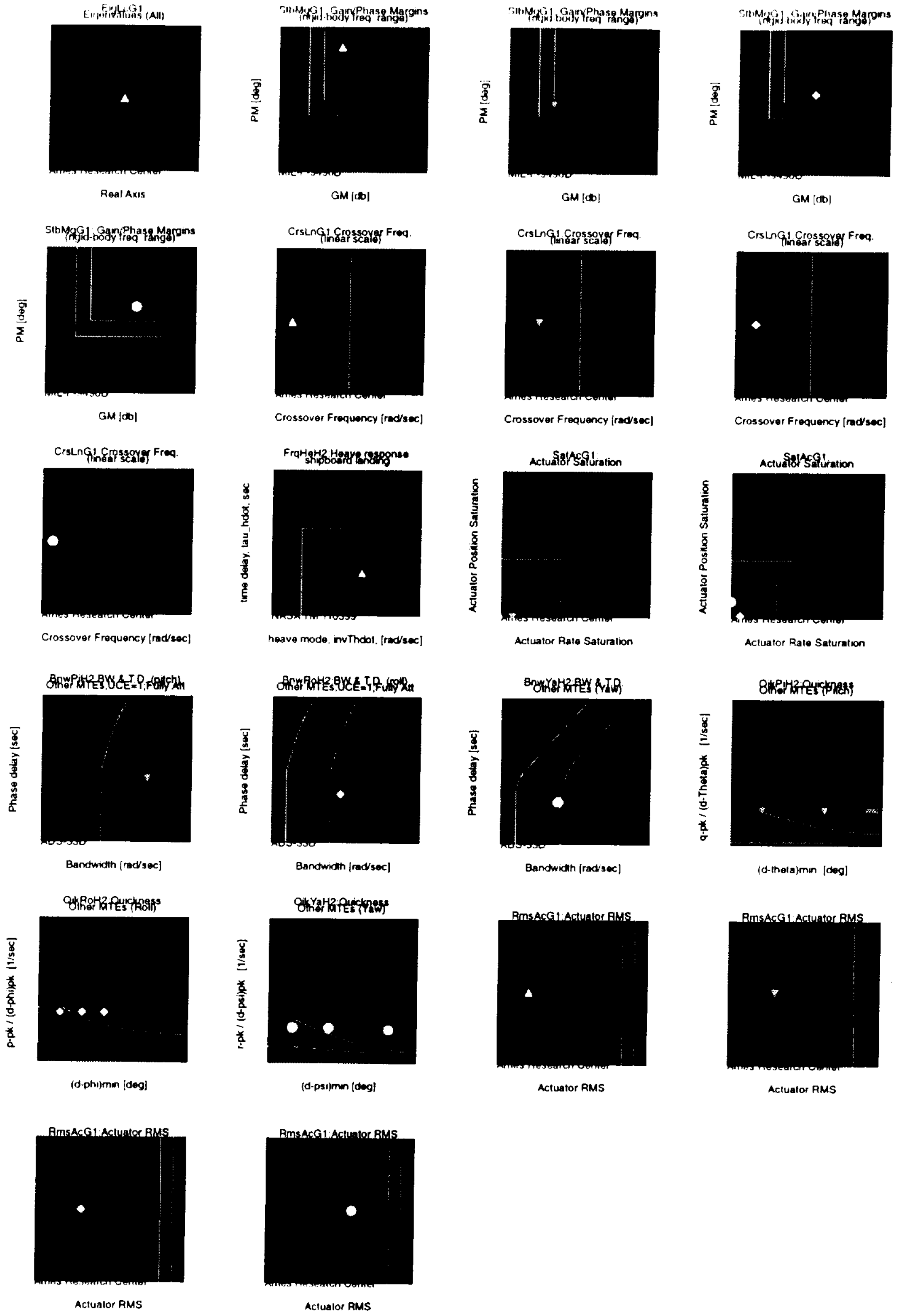

Figure 8. Tuned CONDUIT specifications