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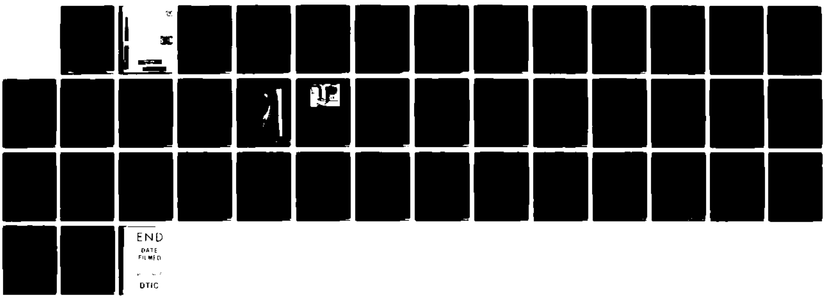

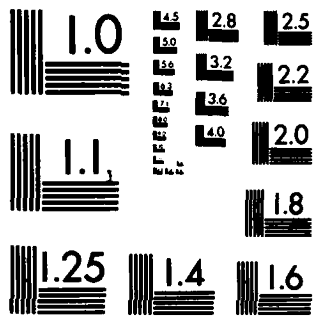

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Dans l'espoir que vous trouverez les notes intéressantes, je vous prie d'agréer, l'expression de mes sentiments les meilleurs.

G.M. Lindberg

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DEVELOPMENT OF THE MICROSAS LONGITUDINAL FLIGHT CONTROL SYSTEM FOR THE AUGMENTOR WING AIRCRAFT

MISE AU POINT DU SYSTÈME DE CONTRÔLE EN TANGAGE MICROSAS POUR L'AVION À AILE À VOLETS TROMPES

by/par

S. Kereliuk, K. Lum, W.E.B. Roderick

National Aeronautical Establishment

AERONAUTICAL NOTE
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FEBRUARY 1983 NRC NO. 21066

S.R.M. Sinclair, Head/Chef
Flight Research Laboratory/
Laboratoire des recherches en vol

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SUMMARY

A digital longitudinal stability augmentation system was designed and installed in the Augmentor Wing Research Aircraft by the Flight Research Laboratory of the National Aeronautical Establishment. This system partially replaced the computer-controlled control and display system called STOLAND owned by NASA Ames Research Center that was removed from the aircraft prior to its return to Canada. The computer system is described and the software flow charts are illustrated. Brief comments on the performance of the system during the flight test program are included.

RÉSUMÉ

Le Laboratoire de recherche en vol de l'Établissement aéronautique national a mis au point et installé sur l'avion à aile à volets trompes un système numérique d'augmentation de la stabilité longitudinale. Il remplace partiellement le système de contrôle et de visualisation informatisé STOLAND de l'Ames Research Center de la NASA qui avait été démonté avant que l'avion ne revienne au Canada. On décrit le système informatisé, illustrant cette description de figures représentant les organigrammes du logiciel. On fait également quelques brefs commentaires sur le comportement du système au cours du programme de vols d'essais.

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ILLUSTRATIONS (Cont'd)

APPENDIX

1.0 INTRODUCTION

The Augmentor Wing Research Aircraft (Fig. 1) is a product of Canadian technology and joint Canadian and American funding*. It successfully fulfilled a role as a proof of concept vehicle for the de Havilland Augmentor Wing STOL concept and has been a productive research tool for the U.S. and Canada during the last decade. It proved to be rugged, reliable and a relatively flexible tool for more general studies of the STOL operational environment and STOL certification requirements. These activities were carried out under the auspices of the NASA Ames Research Center, Moffet Field, California, with on site participation by a member of the NAE Scientific Staff during the major portion of this research period (Ref. 1).

With redundant longitudinal controls, and a control and display package called STOLAND, this vehicle was used in a series of advanced control/display programs addressing both the operational problems and operational benefits of lowspeed terminal area flight, varying dynamic characteristics, curved steep decelerating approaches, and autoland.

2.0 ADVANCED STOL TRANSPORT

Coincidental with the termination of this joint program in 1980 the Canadian Government committed funds to enable de Havilland of Canada to execute a "Definition Phase of an Advanced STOL Transport". As part of the Canadian Government program, funds were established to return the Augmentor Wing Research Aircraft to Canada for a final flight test phase. NAE took over operational control of the aircraft and it was ferried to Ottawa in September 1981.

3.0 NAE ROLE

The central, computer-controlled control and display system called STOLAND was owned by NASA Ames Research Center and

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* Canadian Department of Industry, Trade and Commerce and the American National Aeronautical and Space Administration.

committed to further research in that establishment. It was removed from the aircraft with only sufficient avionics retained to allow ferrying the aircraft. In order to undertake useful work related to the Canadian program, it was necessary to re-equip the aircraft with a replacement system preserving some of the capability to improve aircraft control characteristics and to allow experimental investigations involving minor configuration changes. The program agreement assigned the responsibilities for the design, implementation and testing of a longitudinal digital flight control system to the Flight Research Laboratory.

The aircraft was maintained and operated at Uplands by the FRL of NAE from September 1981 until it was handed over to de Havilland in September 1982. During that period of time qualified FRL maintenance engineers carried out an engine and airframe inspection. De Havilland personnel assisted in this work to obtain the experience necessary to assume full responsibility for maintenance on hand over. The control laws were selected and the mechanical installation of the computer system was carried out during the airframe inspection and the programs were written and run on the ground.

This was followed by a flight test program of twenty flights during which gains and coefficients were adjusted and tuned.

The following is a more detailed description of the system installed by NAE.

4.0 THE MICROSAS COMPUTER SYSTEM

4.1 System Hardware

The MICROSAS Computer System (Fig. 2) was designed at the Flight Research Laboratory to meet the following requirements:

- to be a digital flight controller system for the pitch and speed SAS;

- to be a data acquisition system for the real-time on-board calculations and post-flight data analysis;
- to be a convenient ground-based computer facility for transducer calibrations, diagnostics, and ground check-outs.

Shown schematically in Figure 3, the 16-bit micro-processor, with 16K of core memory and 4K of EPROM/RAM memory is driven by a 32-Hz system clock for each computational cycle. Concurrent with the main task, the computer, on interrupts generated by the synchronous 800-Hz timer, performs the high speed digital filtering.

Transducer signals which are conditioned and sampled by the A/D converter are stored in the rotating data buffers before being output to the magtape recorder. Updated command signals to the flight controller are fed to the D/A interface to drive the servos through the SIU (Servo Interlock Unit) which among other functions, supervises the servo engagement and disengagement logic. Both airspeed and nozzle references are selected by thumbwheel switches in the center console. Critical system operational status is monitored and displayed to the pilot.

Although the MICROSAS is not designed to be interactive, the operator can make changes to the flight program such as gain optimization during the initial phases of flight testing by means of a small hand-held terminal. Stored in EPROM, the flight program is automatically loaded into core memory for execution on start-up. With the addition of a floppy disk, the computer system is often used for ground calibrations and system check-outs.

The flight system controller is fail-passive, with several levels of error checking and failure monitoring of both the hardware and software. The servo is automatically disengaged should a critical fault occur in the SAS.

4.2 Software Implementation

The MICROSAS software design requirements are based on simplicity and reliability. An attempt is therefore made to develop a small, modular stand-alone software package for the implementation of the real-time digital flight controller.

Written in Macro Assembler Language, the system application program is divided into a series of major tasks, some of which are executed as calls to subroutines (Figs. 4 through 9). Software limiting and error checking are extensively utilized throughout the flight program to enhance software integrity.

5.0 AIRCRAFT SYSTEMS

5.1 Description of Aircraft

The Augmentor Jet STOL Research Aircraft (AWJSRA) is a de Havilland of Canada DHC-5/C-8A Buffalo airframe modified with an augmentor flap system. The integrated propulsive-lift system incorporates two Rolls Royce Spey 801 split-flow turbofan engines providing cold fan flow to internally blow the augmentor flap for powered lift.

With the augmentor flap (Fig. 10) a small mass of high energy air is directed over the leading ledge of the lower flap, the so called Coanda surface. This high energy air entrains a larger flow of ambient air between the upper and lower flap resulting in a larger mass flow of lower velocity. This means higher momentum or thrust from the flow and a lower velocity or a lower specific energy in the flow, resulting in higher efficiency and lower losses.

The addition of movable surfaces on the lower flap, the chokes, allows direct and immediate control of the augmented lift. This can be used for powered roll control or for direct lift control. The flow for the augmentor flaps is bled from the engine compressors.

The residual hot thrust (approximately 60%) can be independently vectored over a range of 98^{0} by means of two conical nozzles, thereby providing generous (and immediate) steep descent or go-around capability over a range of about 12^{0} of flight path angle. The cold thrust is cross-ducted in appropriate amounts so that minimum asymmetric lift results in the event of engine failure.

5.2 System Operation

The combination of the augmented lift due to the de Havilland designed blown flap system and the vectored thrust from the nozzles gives the Augmentor Wing Research Aircraft its limited five degrees of freedom variable stability capability. This ability to independently control vertical and longitudinal accelerations along with the conventional three degrees of freedom in pitch, roll and yaw, gives the aircraft its unique capability for the evaluation of STOL procedures, control techniques and instrument displays.

In order to appreciate another unique capability of the Augmentor Wing Research Aircraft the concept of front-side and back-side operation must be understood. As an aircraft is decelerated the power required for level flight decreases until the minimum power speed is reached. A further reduction in speed below minimum power speed will result in increased drag and increasing power requirements to maintain level flight. Operation below the minimum power speed is normally characterised by a requirement to control flight path with engine power and airspeed with pitch attitude, increased power with reduced speed called the "back-sided" control technique. Figure 11 is a plot of flight path angle vs airspeed at a fixed nozzle and flap configuration, with variations in pitch attitude and engine power. Deficiencies in handling qualities of power-lift STOL aircraft in the approach and landing phase have been exposed during flight tests and ground-based simulations, and have been well documented (Ref. 2, 3 and 4). Characteristics associated with "back-sided" low speed flight, high wing loading and substantial thrust turning have resulted in deficiencies in longitudinal stability and control in the form of sluggish control response and highly coupled response characteristics. Furthermore, the introduction of additional controllers into the cockpit, though allowing a much greater flexibility in path performance, tends to increase pilot work load substantially.

6.0 CONTROL LAWS

The control laws implemented by the Flight Research Laboratory have been selected from the wide range of systems used in the earlier Augmentor Wing research programs (Refs. 3, 4, 5 and 6). The criterion for this selection was the effectiveness of providing work load relief for the pilot.

6.1 Pitch SAS

A block program of the pitch SAS is shown in Figure 12. This system is a form of rate-command-attitude hold, with stick force providing the command signal. Use of pitch attitude feedback permits attitude stabilization, a function necessary to reduce the effects of the coupled response characteristics of the aircraft. Pitch-rate feedback provides good closed-loop stability. Gain-scheduling is applied to the resultant command signal as an inverse function of airspeed.

6.2 Airspeed Stabilization

The nozzle control system is presented as a block diagram in Figure 13. Airspeed stabilization is accomplished by driving the nozzles with a speed error signal. An airspeed complimentary filter arrangement combines calibrated airspeed and longitudinal acceleration through a second-order filter which maintains the high-frequency velocity component prevalent in aircraft manoeuvring but removes gust components above about 0.25 rad/sec. A V_{ref} selection on a thumbwheel on the SAS panel provides a reference for the speed error signal. Ramping the speed error signal gain over a 4 second time period limits nozzle excursions on initial engagement when large speed errors are present. Integral plus proportional paths of the speed error signal comprise a closed-loop system ensuring that the steady state value of the output signal washes out. A quickened response to speed errors is provided by a washed-out pitch attitude signal driving the nozzles. In the short term, this tends to decouple speed excursions due to pitch attitude changes. A nominal position of nozzle angle on approach is selected with the nozzle control levers before engagement. This allows a reference position for nozzle modulation, although the low frequency trim nozzle angle will subsequently vary to maintain the reference speed due to the integral path discussed above. Symmetrical nozzle motion is insured by comparing left and right nozzle positions. Nozzle angle differentials greater than 25° will cause the nozzle servo to disengage. A filtered nozzle position signal is provided by combining averaged position of left and right nozzle with integrated nozzle servo rate. This avoids non-linearities in the electrical servo control loop caused by hysterises in the pneumatic motor drive mechanism, and allows the pilot to manually over-ride the electrical nozzle servo through a clutch mechanism.

6.3 Choke Loop

A block diagram of the choke control system is presented in Figure 14. Washed-out pitch attitude to chokes provides augmented heave damping which serves to quicken flight path control with pitch attitude. Likewise, washed-out throttle deflection to chokes provides a quickening of the flight path control with throttle. Lift losses due to large nozzle aft rotations are partially offset by driving the chokes open, from a normal trim bias setting of 35% closed, with a nozzle position signal at a ratio of 0.75% choke per degree nozzle. First order smoothing of the raw nozzle position signal is used. A thumbwheel switch is provided on the SAS panel to enable a reference nozzle position to be selected. Nozzle angles less than that selected would drive the chokes open, with any remaining choke authority available for quickening flight path response to pitch attitude and throttle discussed above.

6.4 Throttle Loop

The software for the throttle loop, shown in block diagram form in Figure 15, was implemented but the system was not test flown by NAE. The intent in using the throttle servo was to further augment aircraft heave damping by providing a pitch attitude to throttle loop which would quicken flight path response to pitch attitude, similar to that obtained through the chokes. A further quickening of this control mode is supplied through pitch rate to throttle. An averaged throttle position provides loop closure around the throttle servo.

7.0 COMMENTS

A total of 20 flight hours were spent optimizing loop gains, troubleshooting faults and demonstrating the system. Out of a total of 57 landings, 18 were performed with some or all of the system loops engaged.

On approach, the combination of pitch attitude stabilization and speed stabilization were effective in reducing pilot work load. The coupled response characteristics of the augmented aircraft were considerably improved and less severe than the unaugmented aircraft. Speed control was automatic, and the pilot could devote most of his attention to flight path control with pitch attitude, with only occasional throttle movements required to maintain the required angle of attack trim point. The more precise, less "contaminated" coupling of pitch attitude to flight path provided a significant improvement in flight path performance and work load.

When flaring from a steep approach, the nozzles tracked aft in an attempt to maintain speed and the chokes opened on command of pitch rate and nozzle deflection. This resulted in a prolonged float before touchdown accompanied by an uncomfortable increase in angle of attack. Coordinating throttle reduction during the flare often resulted in "untidy" landings. Inhibiting the speed stabilization during the flare would allow more comfortable and accurate landings. There was no attempt to optimize the landing flare handling and performance during the NAE program.

The NAE digital SAS as implemented, satisfies the performance requirements of the final flight test phase. It successfully replaced STOLAND in pitch and airspeed stabilization, and heave damping, significantly reducing pilot work load and simplifying task performance during approach. Although in its present configuration the system is somewhat less flexible than STOLAND, minor modifications to the control laws for the flare would allow enhanced capability in future programs.

8.0 REFERENCES

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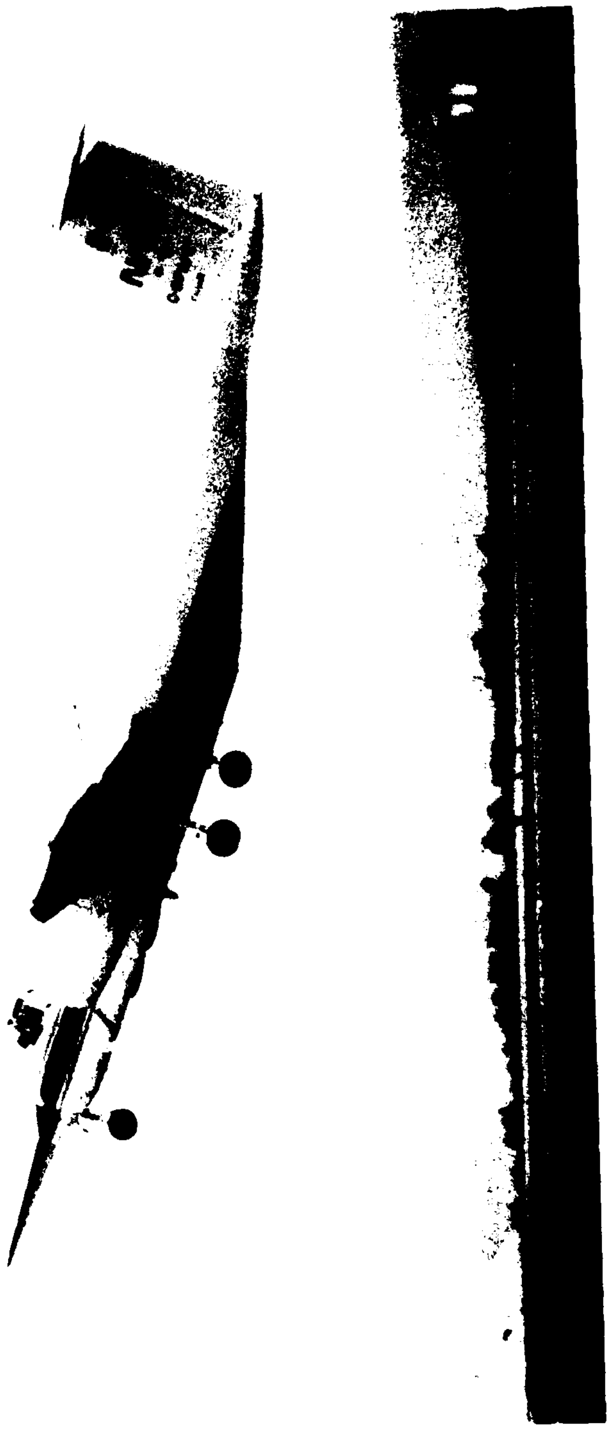


FIG. 1: AUGMENTOR WING RESEARCH AIRCRAFT

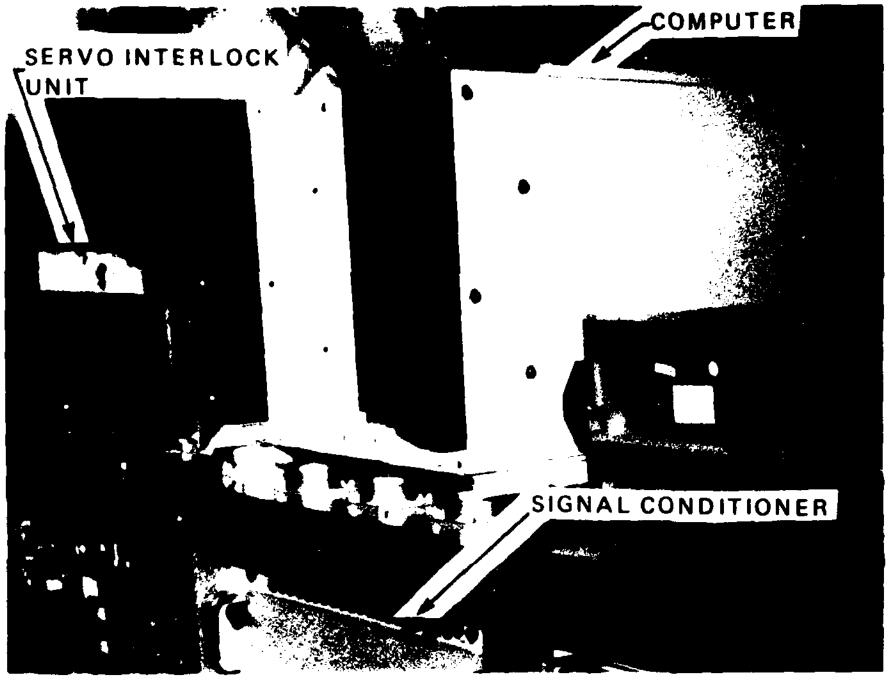


FIG. 2: MICROSAS COMPUTER SYSTEM

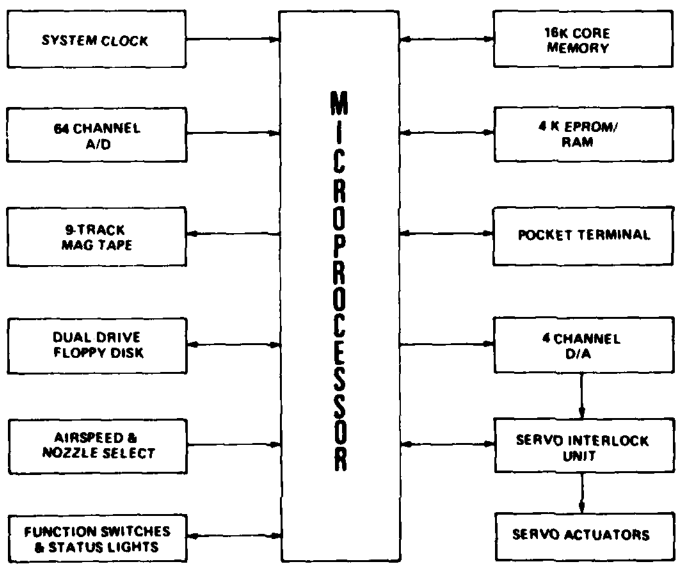


FIG. 3: MICROSAS BLOCK DIAGRAM

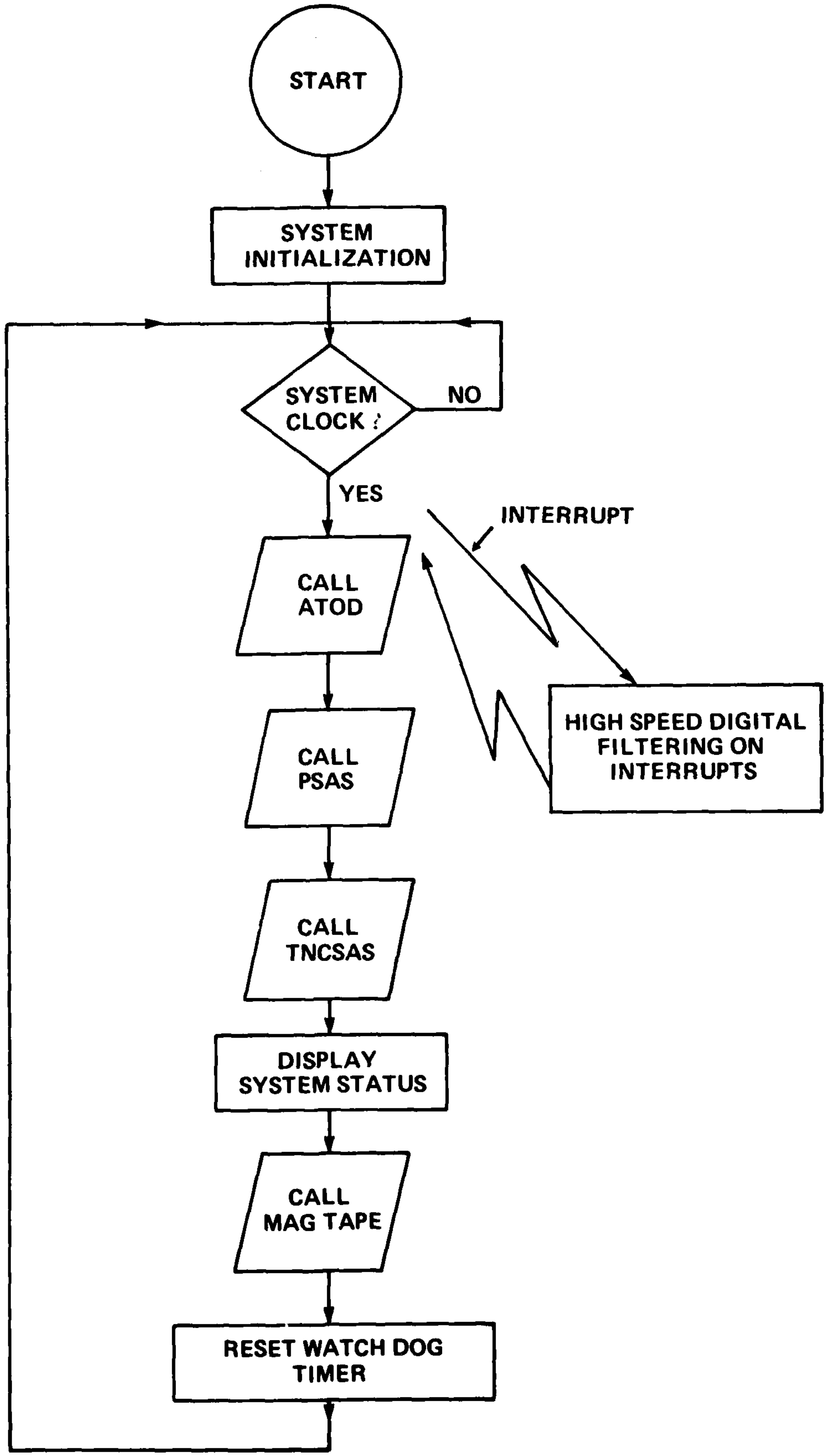


FIG. 4: SYSTEM PROGRAM FLOW CHART

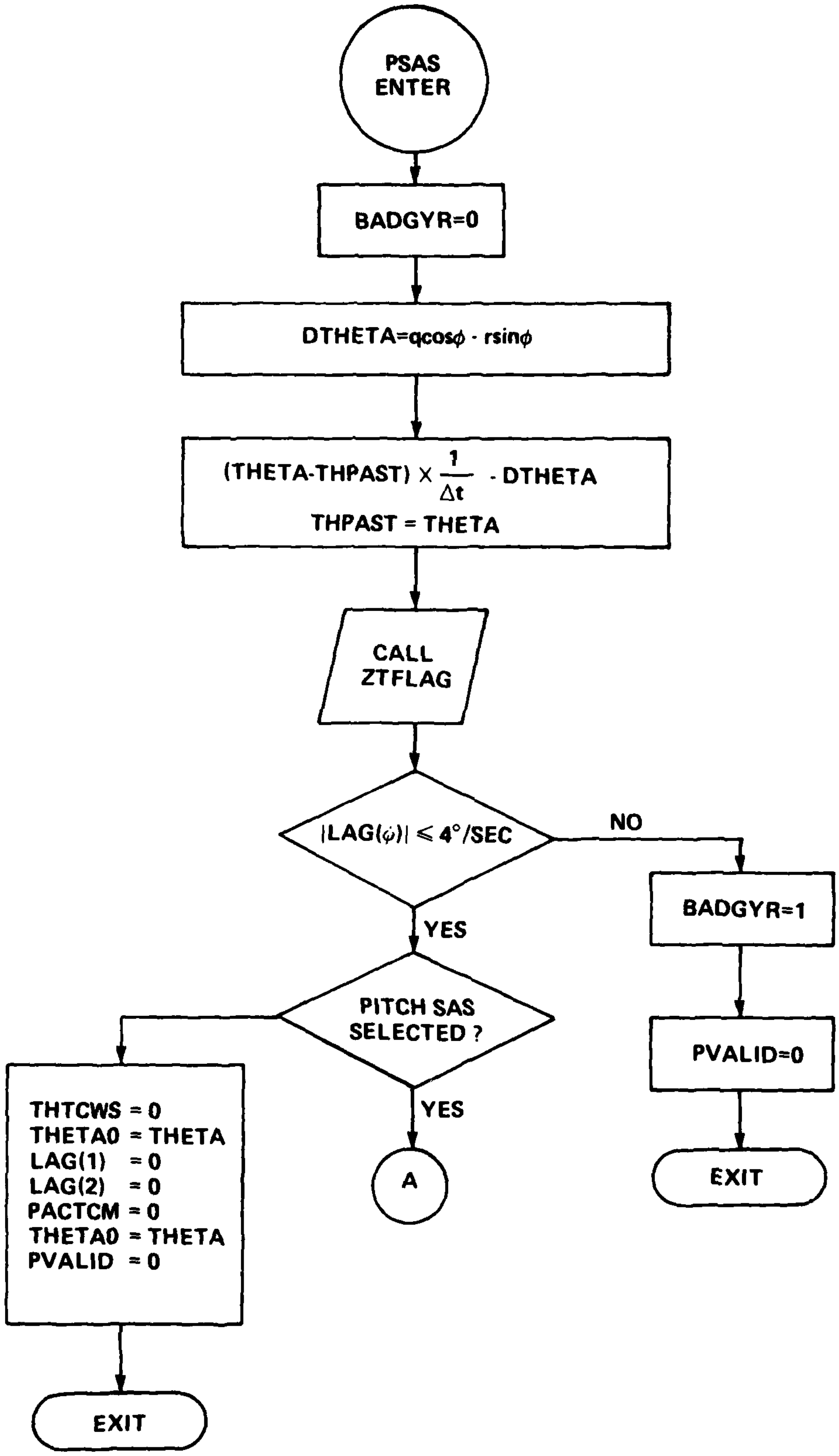


FIG. 5a: PITCH SAS FLOW CHART 1

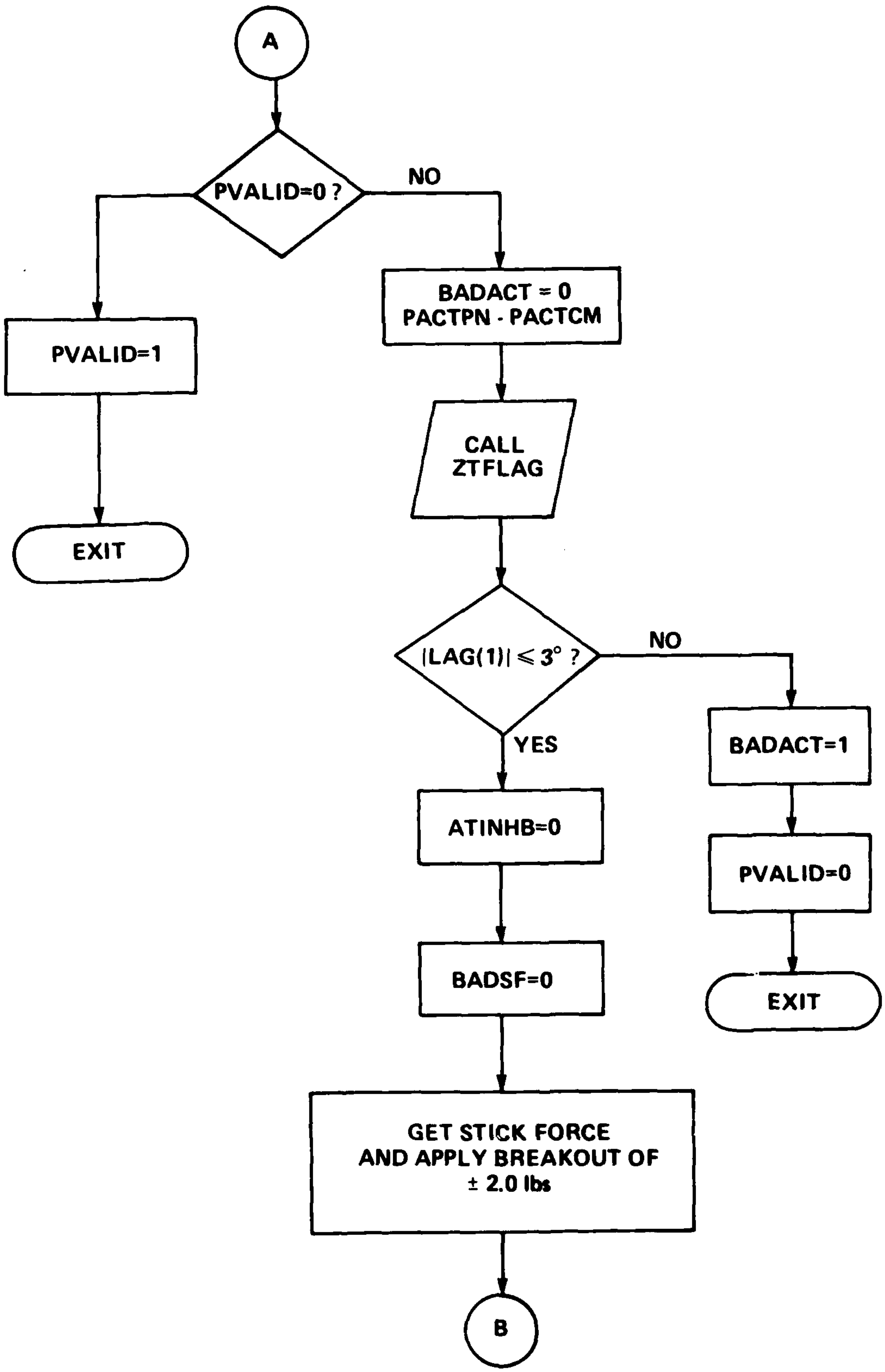


FIG. 5b: PITCH SAS FLOW CHART 2

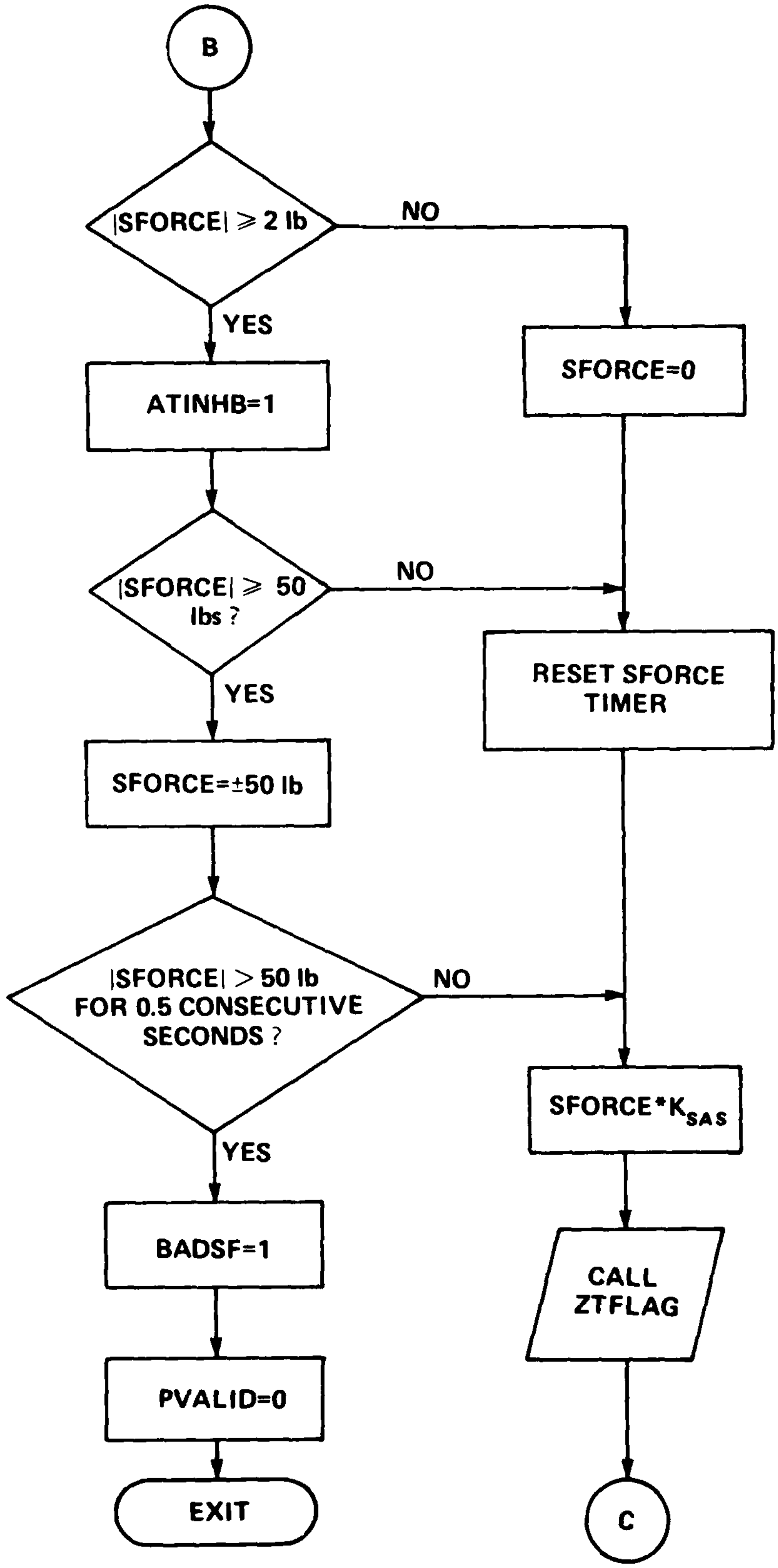


FIG. 5c: PITCH SAS FLOW CHART 3

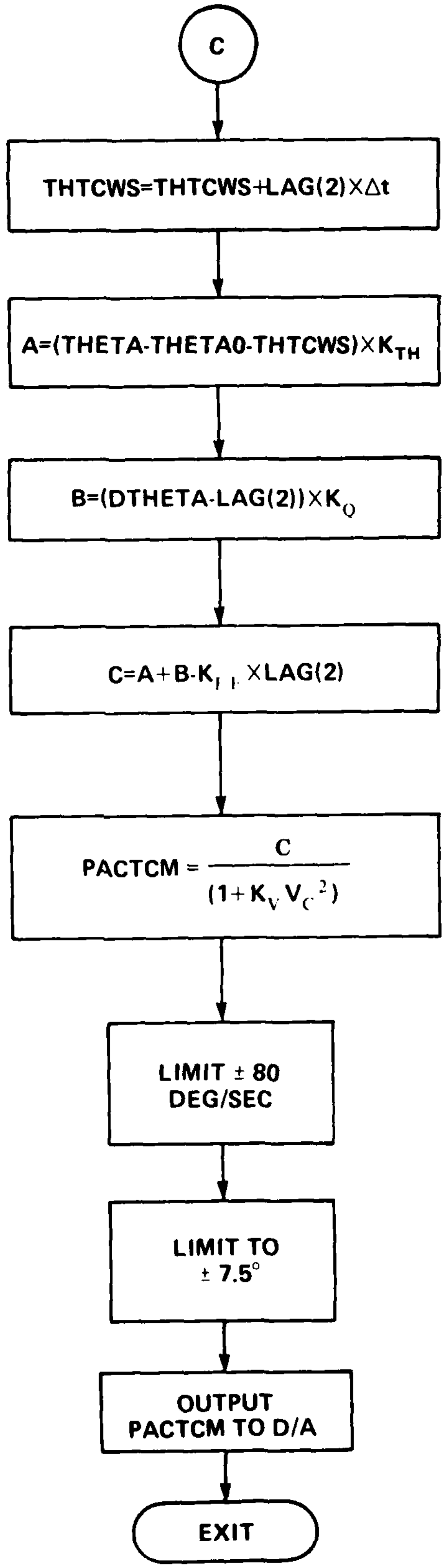


FIG. 5d: PITCH SAS FLOW CHART 4

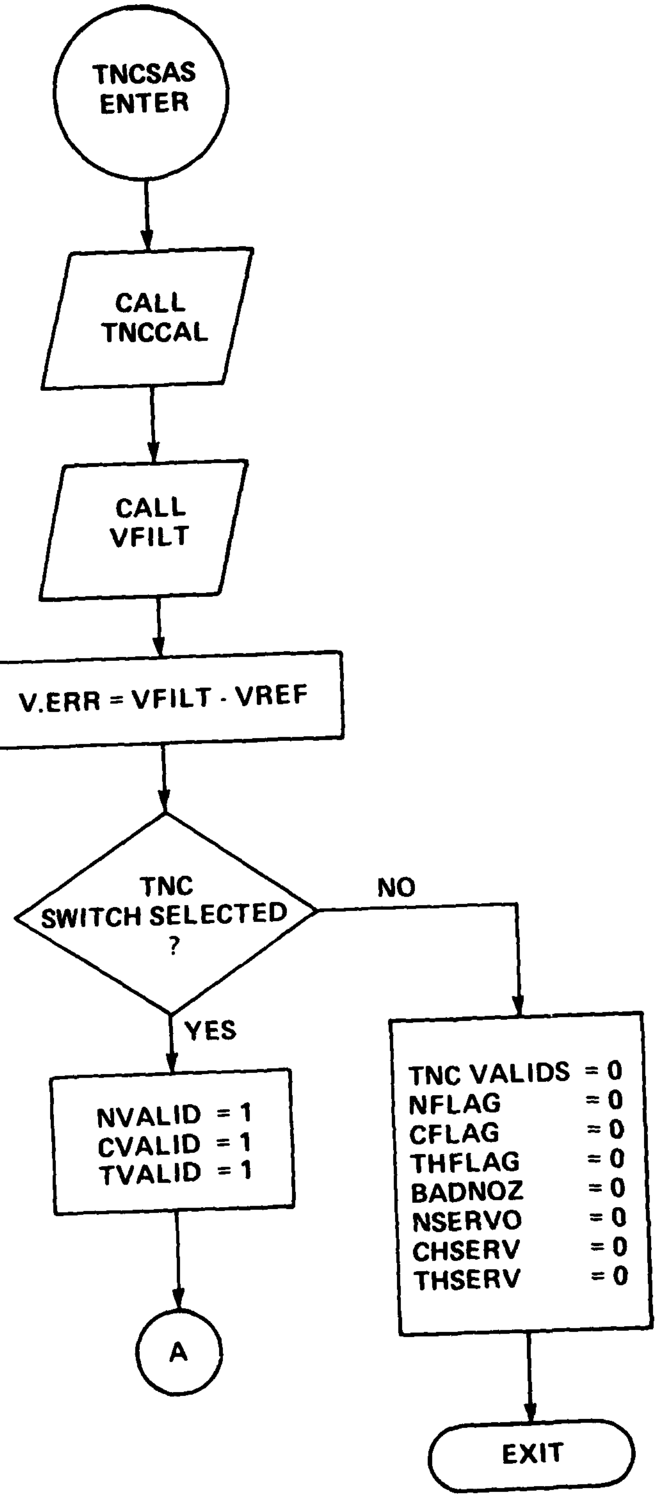


FIG. 6a: TNCSAS FLOW CHART 1

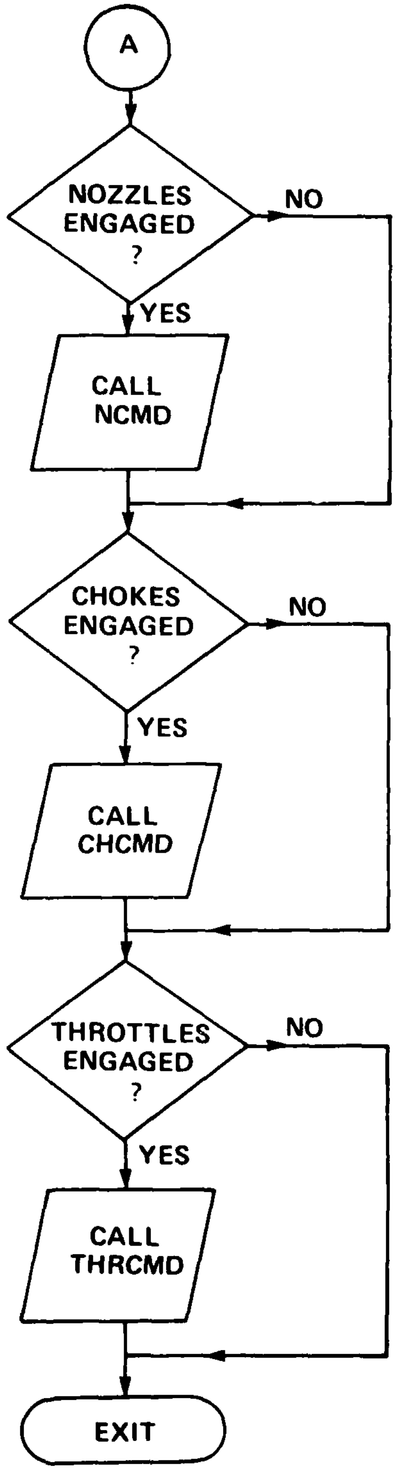


FIG. 6b: TNCSAS FLOW CHART 2

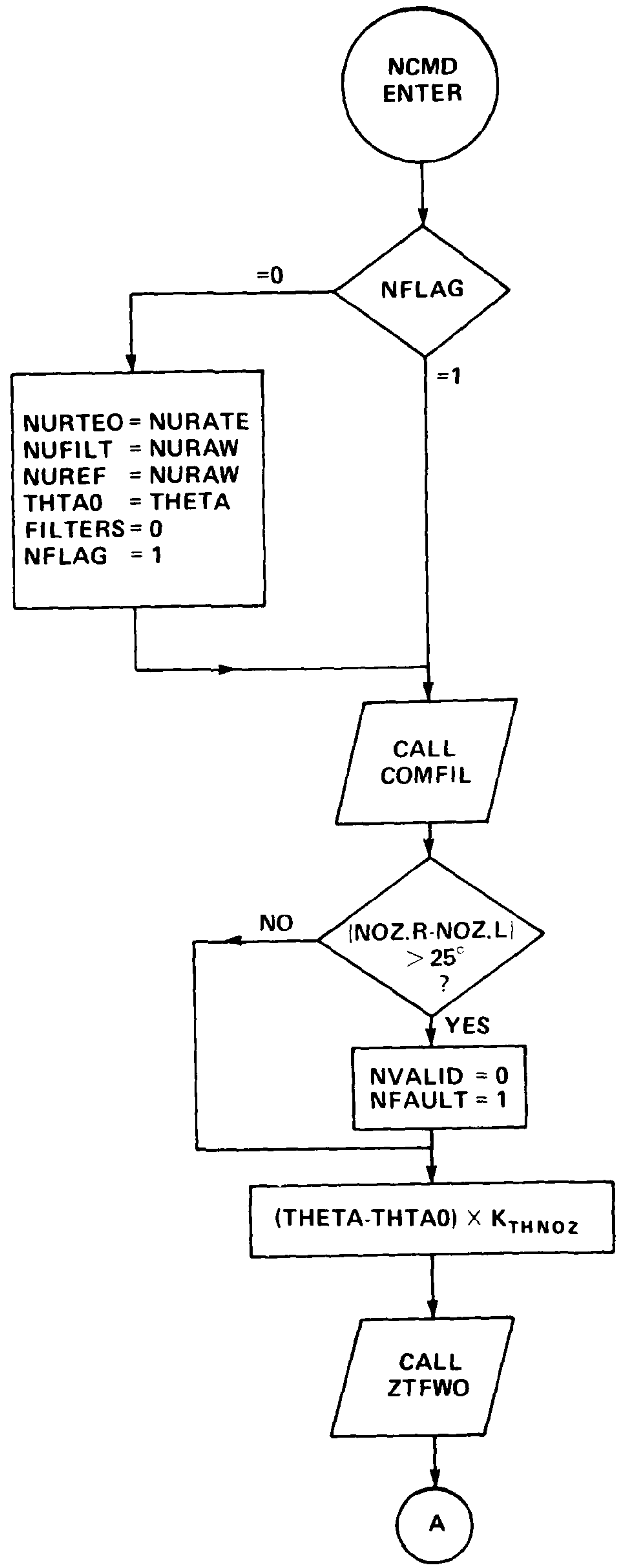


FIG. 7a: NOZZLE CONTROL FLOW CHART 1

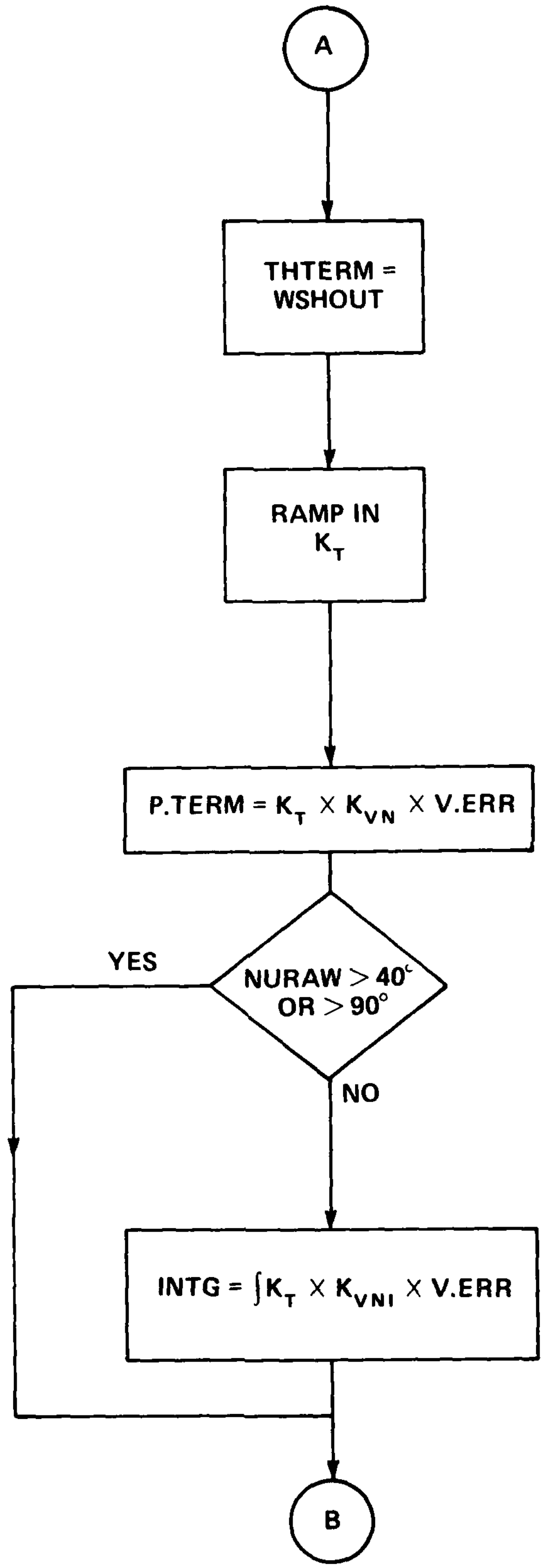


FIG. 7b: NOZZLE CONTROL FLOW CHART 2

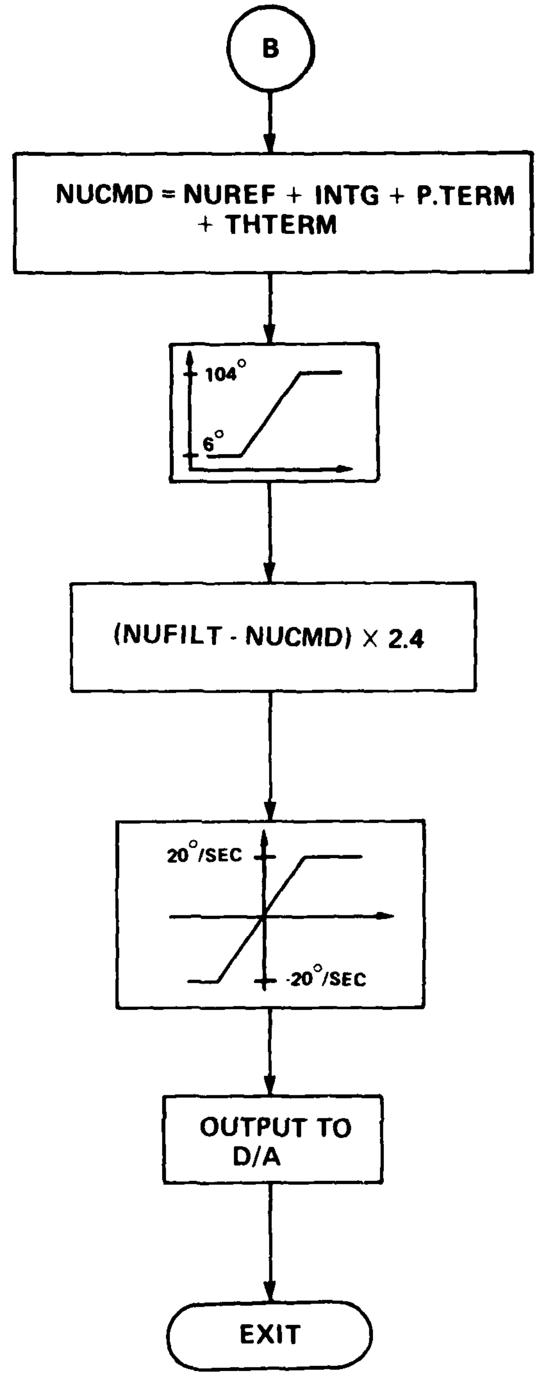


FIG. 7c: NOZZLE CONTROL FLOW CHART 3

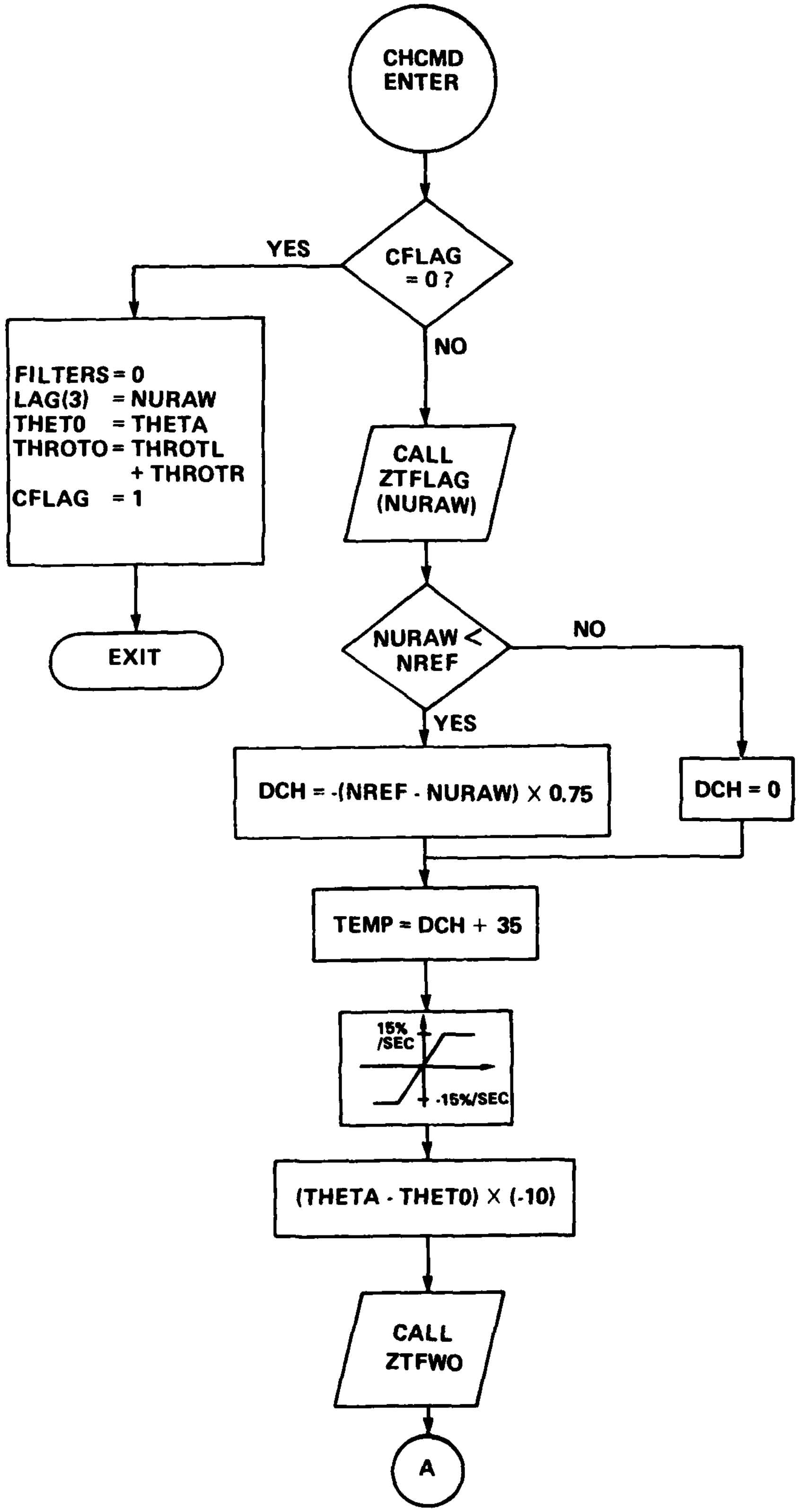


FIG. 8a: CHOKE CONTROL FLOW CHART 1

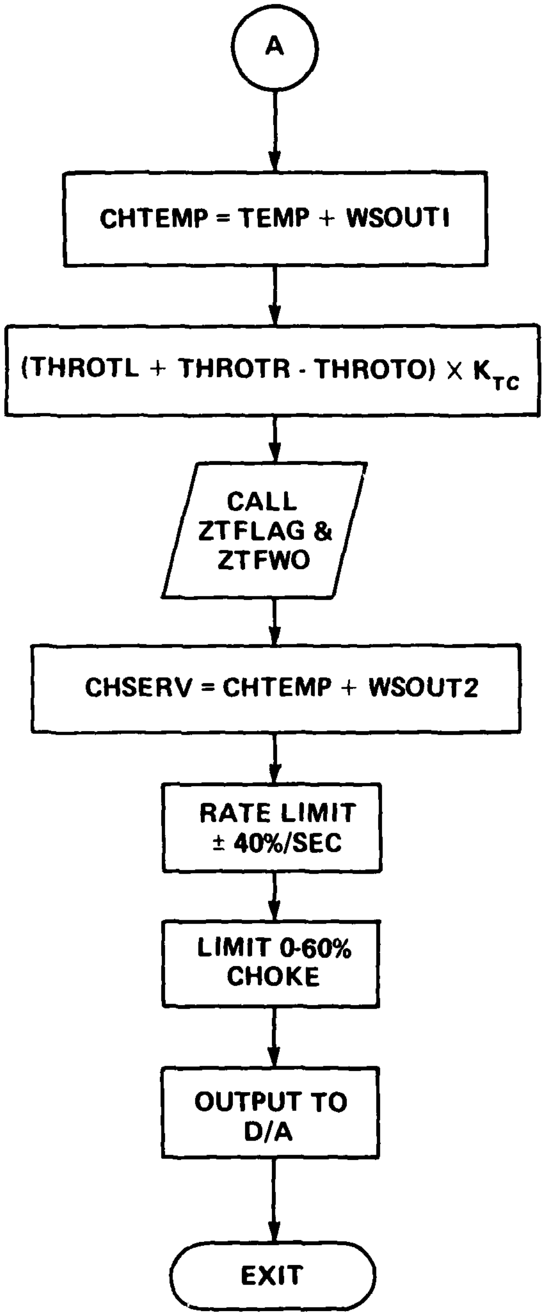


FIG. 8b: CHOKE CONTROL FLOW CHART 2

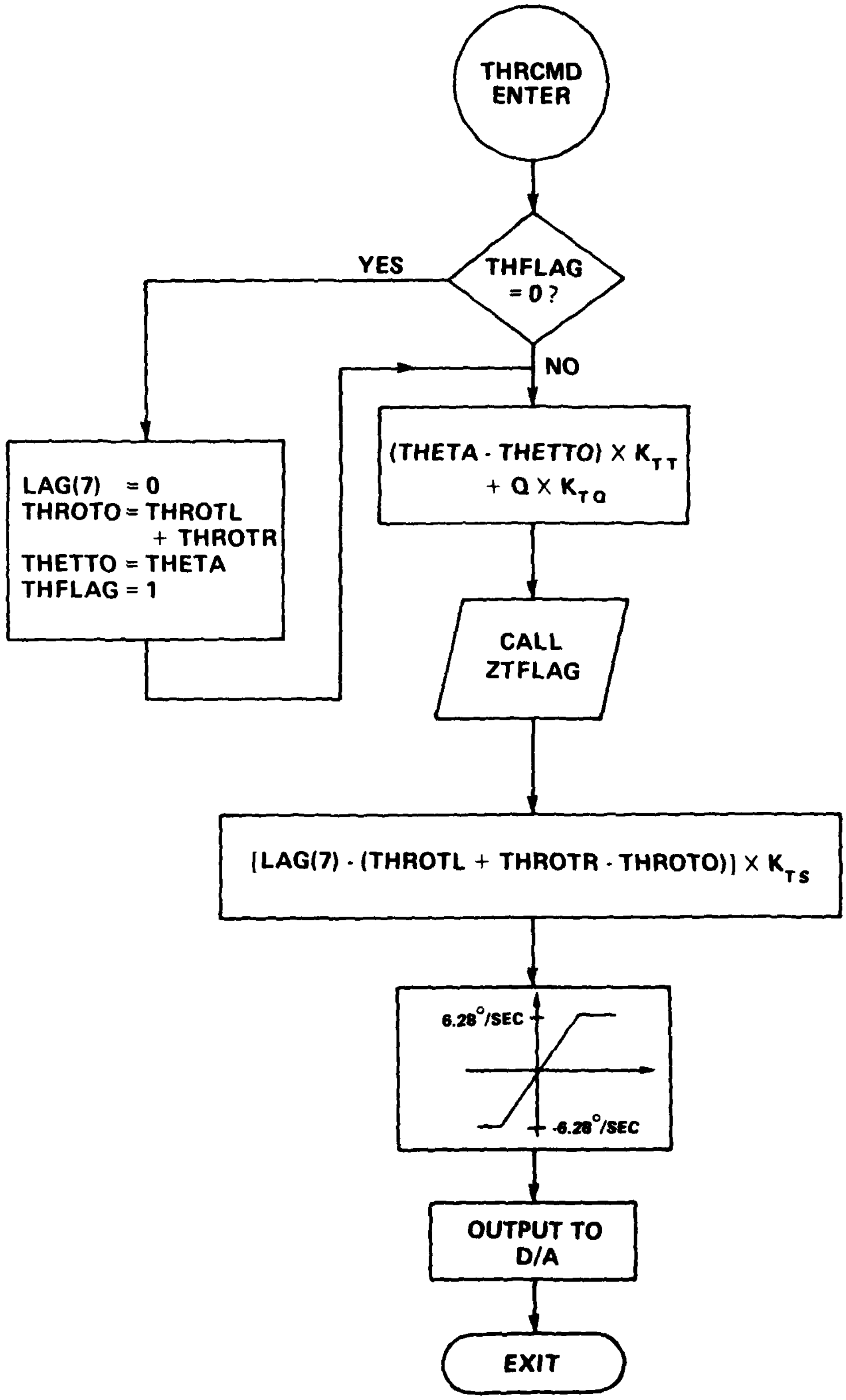


FIG. 9: THROTTLE CONTROL FLOW CHART

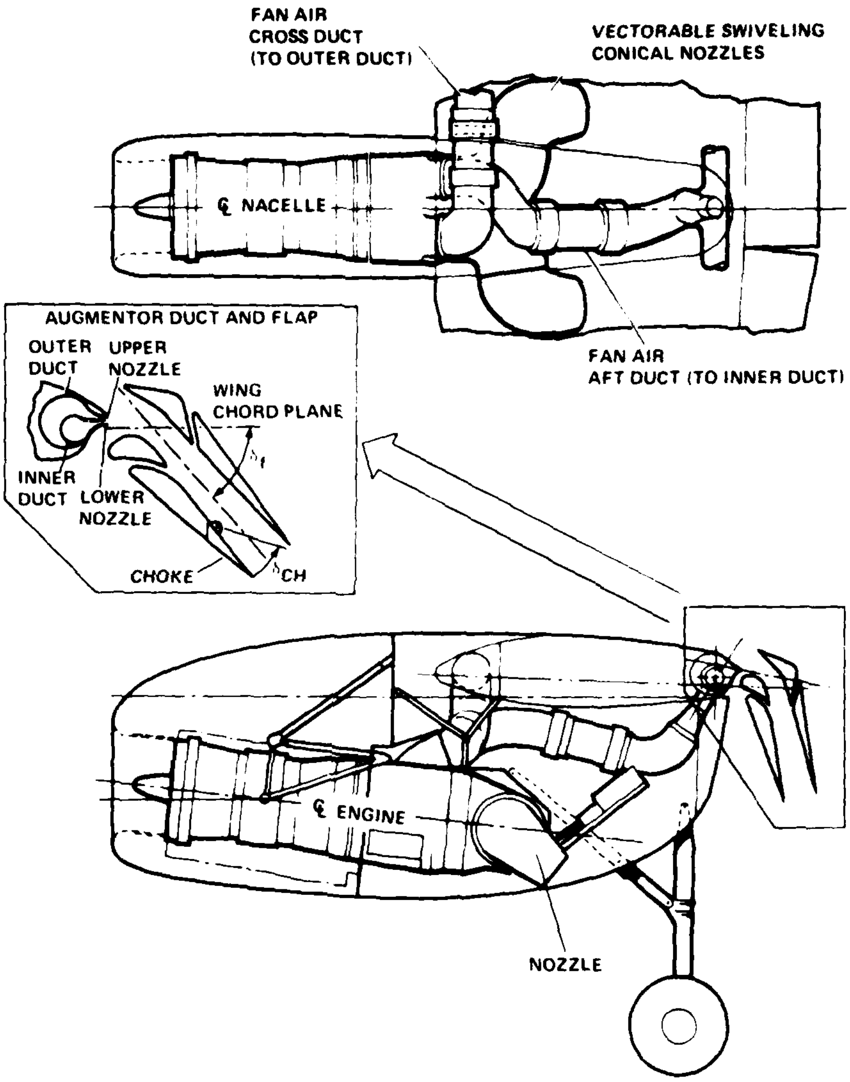
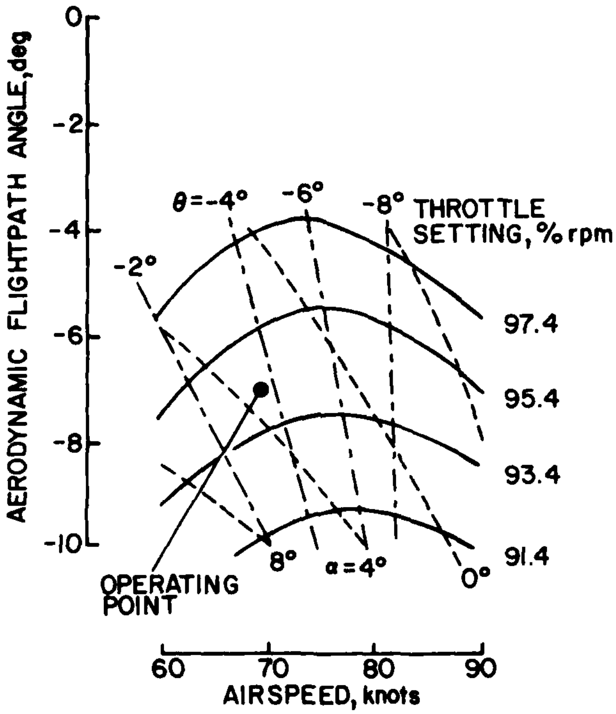


FIGURE 10: AUGMENTOR JET FLAP AND PROPULSION SYSTEM



WEIGHT 191 kN
FLAP 65°
NOZZLE ANGLE 78°
AUGMENTOR CHOKES 0% CLOSED

FIG. 11: DESCENT TRIM CONDITIONS, NOZZLES FIXED

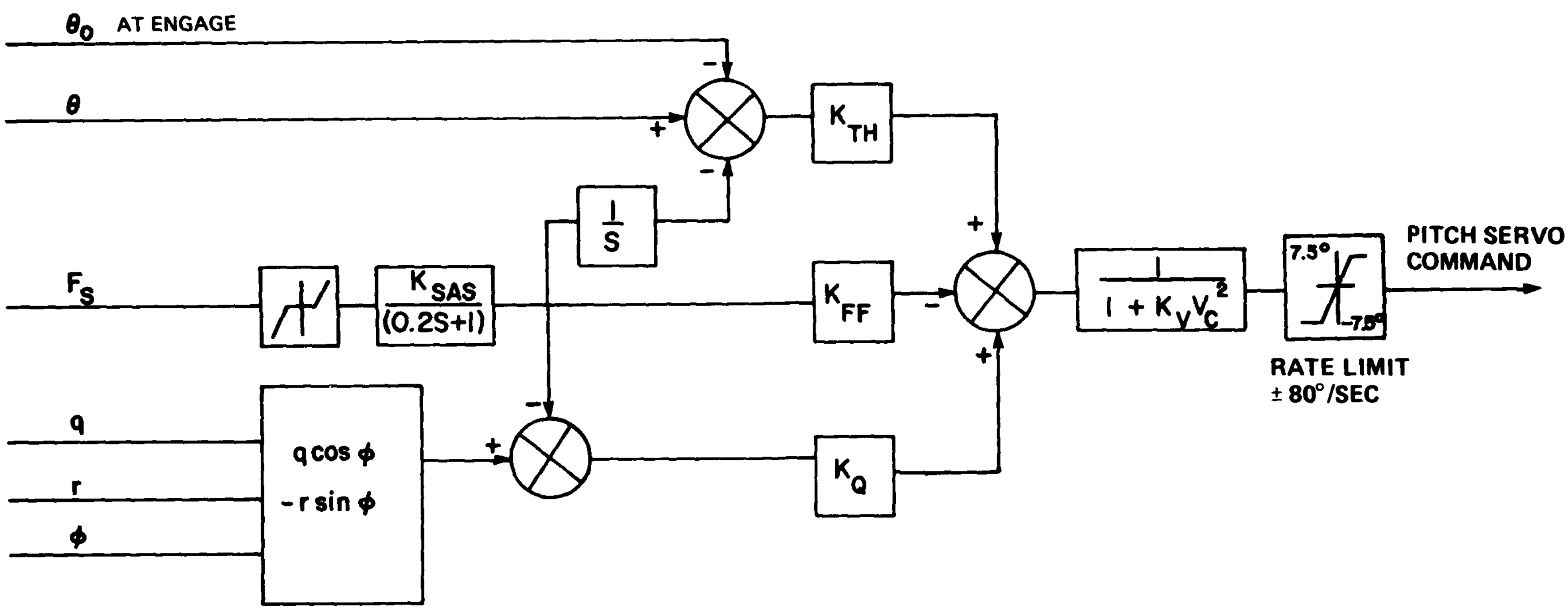


FIG. 12: PITCH SAS

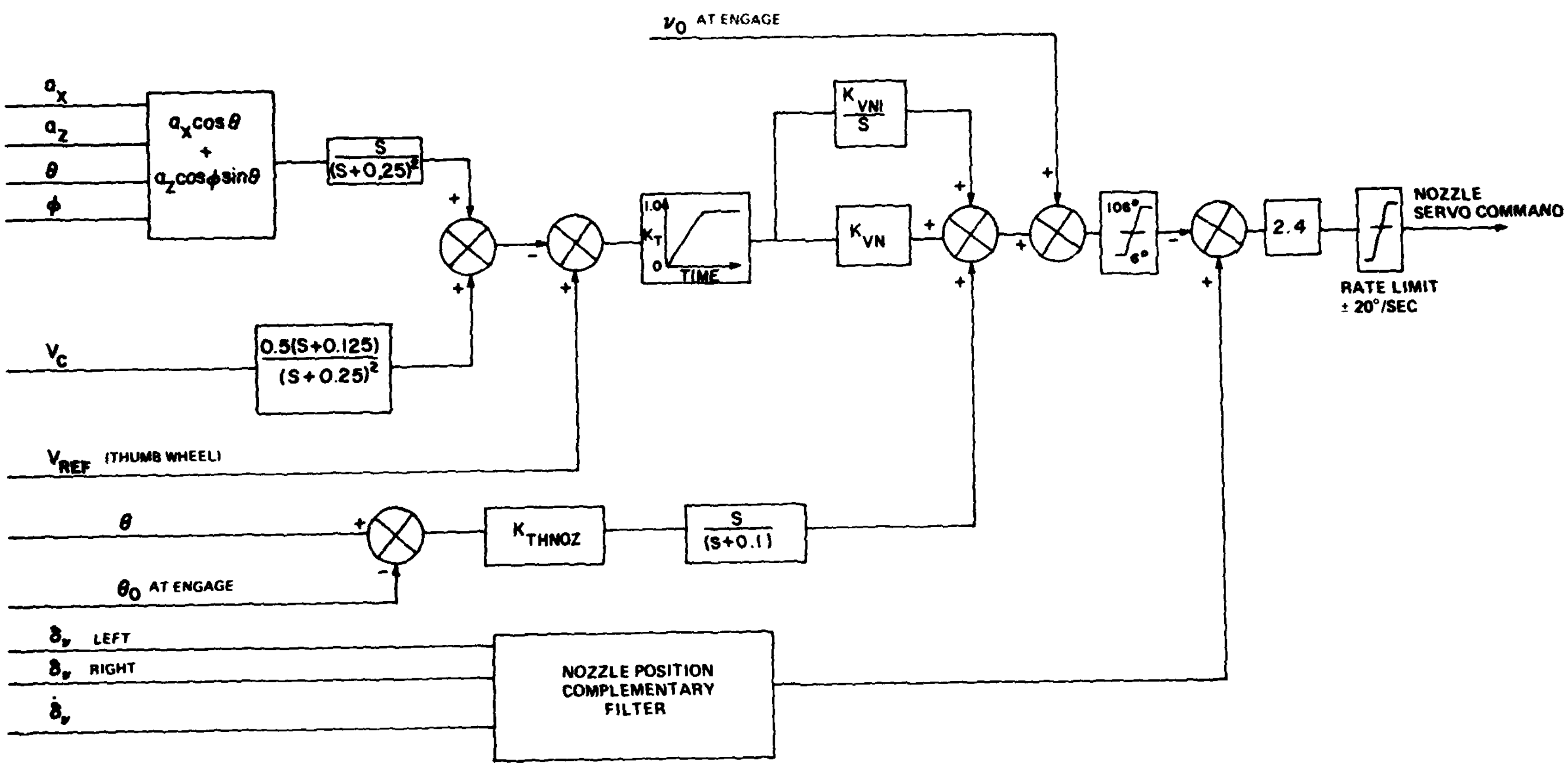


FIG. 13: NOZZLE CONTROL

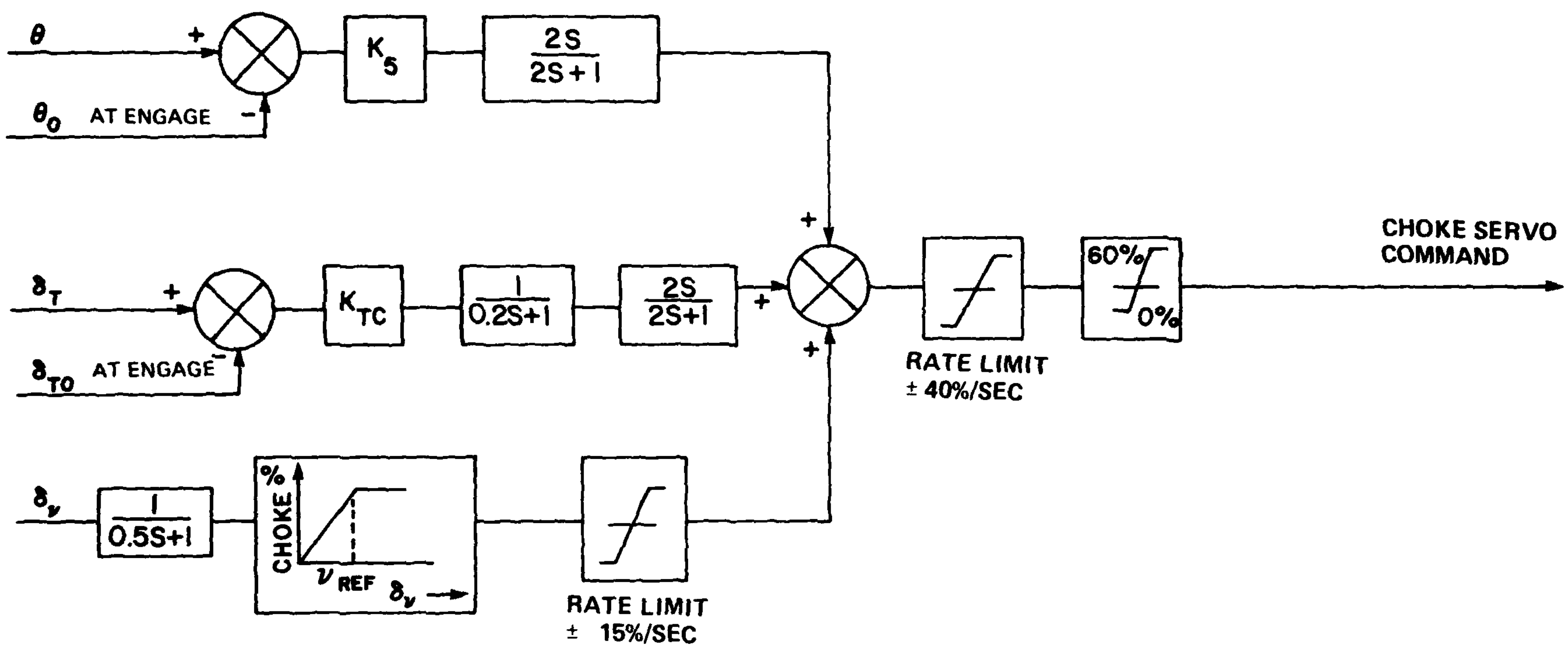


FIG. 14: CHOKE CONTROL

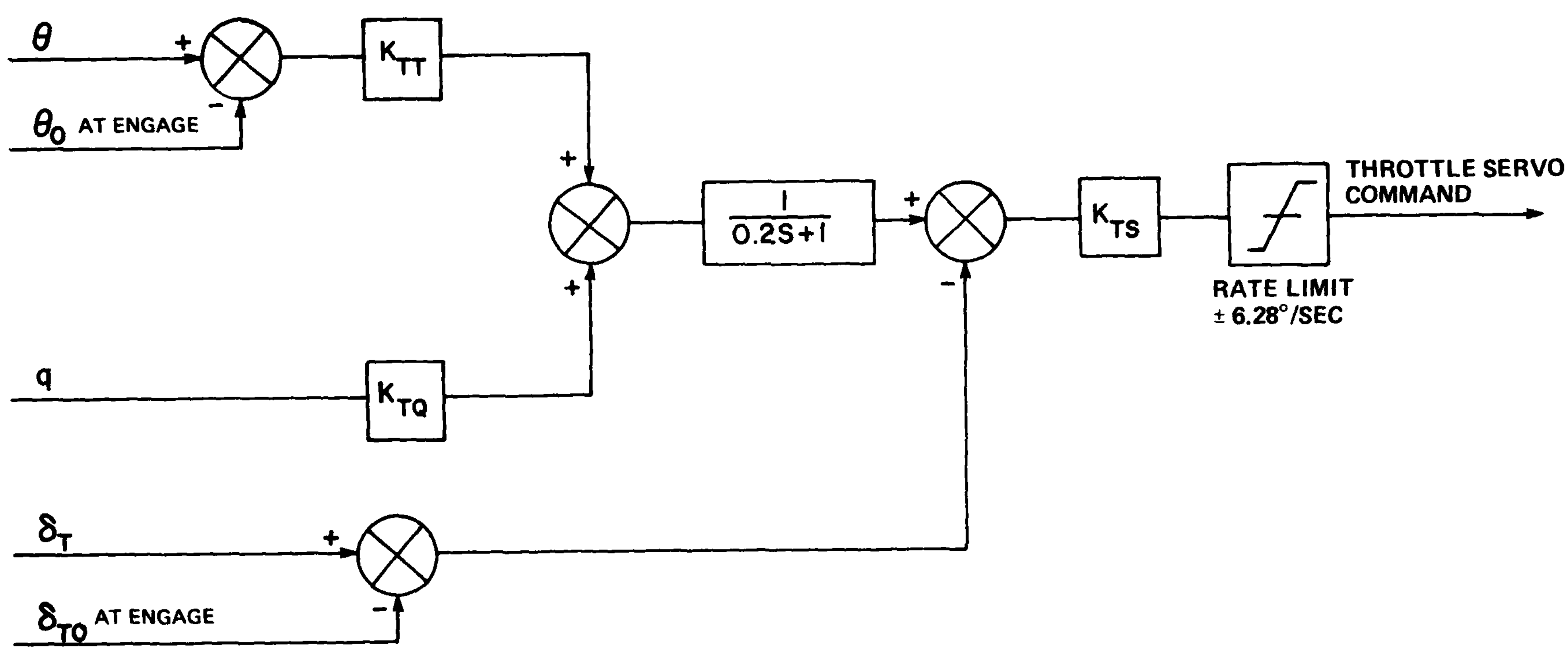


FIG. 15: THROTTLE CONTROL

APPENDIX A

MNEMONICS	DESCRIPTION
ATINHB	auto-trim follow-up inhibit
ATOD	A/D input subroutine
a_x	longitudinal acceleration
a_z	normal acceleration
BADACT	'bad actuator' software flag
BADGYR	'bad gyro' software flag
BADNOZ	'bad nozzle' software flag
BADSF	'bad stick force' software flag
CFLAG	initialization flag for choke control law
CHCMD	choke control law subroutine
CHSERV	choke command to servo loop
CHTEMP	temporary location for CHSERVO
COMFIL	nozzle position filter subroutine
CVALID	nozzle servo enable
DCH	per cent choke closed
DTHETA	pitch angle rate
FILTERS	low pass and high pass filters
F_s	stick force input
INTG	program label for speed error integration
K_{FF}	pitch feed forward gain
K_Q	gain on pitch rate error
K_{SAS}	stock force to pitch rate command gain
K_{TC}	cross feed gain on throttle to choke
K_{TH}	gain on pitch angle error
K_{THNOZ}	cross feed gain on pitch angle to nozzle
K_{TQ}	cross feed gain on pitch rate to throttle

MNEMONICS	DESCRIPTION
K_{TS}	throttle servo loop gain
K_{TT}	cross feed gain on pitch angle to throttle
K_V	gain on speed squared scheduling
K_{VN}	speed error gain
K_{VNI}	integral speed error gain
K_5	cross feed gain on pitch angle to choke
LAG	output of low pass filter
NCMD	nozzle control law subroutine
NFAULT	flag indicating nozzle asymmetry
NFLAG	initialization flag for the nozzle control law
NOZ.L	left nozzle position
NOZ.R	right nozzle position
NREF	nozzle reference position selected on thumbwheel switches
NSERVO	nozzle command to servo loop
NUCMD	calculated nozzle command
NUFILT	calculated filtered nozzle angle
NURATE	nozzle rate
NURAW	raw nozzle angle
NUREF	nozzle angle at engagement
NURTEO	nozzle rate at engagement
NVALID	nozzle servo enable
PACTCM	pitch SAS actuator command
PACTPN	pitch actuator position
PHI	roll angle
PSAS	pitch SAS subroutine
PTERM	program label for speed error calculation
PVALID	pitch servo enable

MNEMONICS	DESCRIPTION
Q or q	pitch rate
r	yaw rate
SFORCE	pilot's stick force
TEMP	temporary storage location
THETA	pitch angle
THETAO	pitch angle at pitch servo engagement
THETO	pitch angle at choke servo engagement
THETTO	pitch angle at throttle servo engagement
THFLAG	throttle loop initialization flag
THPAST	value of pitch angle on previous cycle
THRCMD	throttle control law subroutine
THROTL	left throttle position
THROTR	right throttle position
THROTO	throttle position at engagement
THSERV	throttle command to servo loop
THTERM	theta to nozzle crossfeed term
THTAO	pitch angle at nozzle servo engagement
THTCWS	pilot's conditioned pitch rate command
TNC	throttle, nozzle and choke
TNCCAL	subroutine to scale inputs for throttle, nozzle and choke loops
TNCSAS	throttle, nozzle and choke executive subroutine
TVALID	throttle servo enable
V_C	calibrated airspeed
VFILT	output of the airspeed complementary filter
VREF	airspeed set by pilot on thumbwheel
VERR	error signal between filtered and selected airspeed
WSHOUT	output of high pass filter

MNEMONICS	DESCRIPTION
WSOUT1	output of first high pass filter
WSOUT2	output of second high pass filter
ZTFLAG	low pass filter
ZTFWO	high pass filter
θ	pitch angle
ϕ	bank angle
δ_V	nozzle position
δ_T	throttle position

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Development of the MICROSAS Longitudinal Flight Control System for the Augmentor Wing Aircraft

4

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SUMMARY/SOMMAIRE

A digital longitudinal stability augmentation system was designed and installed in the Augmentor Wing Research Aircraft by the Flight Research Laboratory of the National Aeronautical Establishment. This system partially replaced the computer-controlled control and display system called STOLAND owned by NASA Ames Research Center that was removed from the aircraft prior to its return to Canada. The computer system is described and the software flow charts are illustrated. Brief comments on the performance of the system during the flight test program are included.

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