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**EXPERIMENTAL STUDIES OF A LUDWIG TUBE  
HIGH REYNOLDS NUMBER TRANSONIC TUNNEL**

R. F. Starr and C. J. Schueler

ARO, Inc.

December 1973

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**VON KÁRMÁN GAS DYNAMICS FACILITY  
ARNOLD ENGINEERING DEVELOPMENT CENTER  
AIR FORCE SYSTEMS COMMAND  
ARNOLD AIR FORCE STATION, TENNESSEE**

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## FOREWORD

The study reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65802F.

This work was done by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, Arnold Air Force Station, Tennessee. The research covered the period from July 1972 to February 1973, and the manuscript was submitted for publication on July 2, 1973. The ARO Project No. was VD209.

The authors wish to acknowledge the assistance of James C. Sivells, ARO, Inc., who modified Becker's theory to account for the high Reynolds number skin-friction coefficient, and Dr. Arloe Mayne, Jr., ARO, Inc., who provided the theoretical calculation of the turbulent boundary-layer growth on a flat plate with a starting profile similar to that at the charge tube exit. The series of experiments conducted in the NASA MSFC 14-in. transonic tunnel (Ref. 25) were carried out with the cooperation of Mr. A. R. Felix, Chief, Experimental Aerophysics Branch, NASA - Marshall Space Flight Center, Huntsville, Alabama.

This technical report has been reviewed and is approved.

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## ABSTRACT

A significant justification for a much higher Reynolds number ground test capability in the transonic regime has developed in the past few years. An extensive experimental investigation of a high Reynolds number transonic wind tunnel employing a Ludwieg tube air storage system has been undertaken at the Arnold Engineering Development Center to assess the utility of such a device. The transonic starting process and starting time of this impulse facility have been carefully evaluated, and the spatial and timewise quality of the test section flow has been analyzed. Results from studies of the aerodynamic flow response time at transonic speeds and measurement of the pressure distribution and forces on selected models are presented. Also included are the results from associated studies of the influence of plenum volume on test section flow quality and the acoustic environment of the tunnel exhaust.

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### NOMENCLATURE

. 48	A	Cross-sectional area
. 48	A*	Cross-sectional area at sonic point
	A <sub>M</sub>	Main starting device effective open area
. 49	A <sub>PE</sub>	Plenum exhaust effective open area
. 49	A <sub>W</sub>	Porous wall effective open area
	a	Speed of sound
. 50	a <sub>4a</sub>	Speed of sound behind unsteady wave in charge tube
. 51	b	Vehicle wing span
	C <sub>D</sub>	Total drag coefficient, drag/q <sub>∞</sub> S <sub>b</sub>
. 52	C <sub>DB</sub>	Base drag coefficient, (p <sub>∞</sub> - p <sub>B</sub> )/q <sub>∞</sub>
	C <sub>DF</sub>	Forebody drag coefficient, C <sub>D</sub> - C <sub>DB</sub>
. 52	C <sub>p</sub> *	Sonic pressure coefficient
	C <sub>p<sub>u</sub></sub>	Pressure coefficient on upper surface, (p <sub>L</sub> - p <sub>∞</sub> )/q <sub>∞</sub>
. 53	c	Chord length
	D	Characteristic dimension - hole diameter or model base diameter
. 55	d <sub>s</sub>	Sting diameter near the base of the model
	f	Frequency
. 56	h	Height above ground
	h <sub>HIRT</sub>	Characteristic dimension of full-scale tunnel - test section height
. 57	h <sub>Pilot</sub>	Characteristic dimension of HIRT Pilot tunnel - test section height

$l$	Characteristic dimension over which flow must respond
$M$	Mach number
$\bar{M}_p$	Average plenum chamber Mach number (from plenum pressures)
$\bar{M}_{TS}$	Average test section Mach number (from centerline static pipe)
$p$	Static pressure
$\bar{p}$	Root-mean-square fluctuating pressure
$p_B$	Model base pressure
$p_L$	Local pressure
$p_o$	Stagnation pressure
$p_p$	Plenum chamber static pressure
$q$	Dynamic pressure
$Re_c$	Length Reynolds number based on chord length, $Re/ft \times c$
$Re_D$	Length Reynolds number based on model base diameter, $Re/ft \times D$
$Re/ft$	Unit Reynolds number, $\rho_\infty U_\infty / \mu_\infty$
$Re_{\Delta x}$	Length Reynolds number based on distance to head of unsteady wave, $Re/ft \times \Delta x$
$r$	Radial distance from exhaust stack
$S_b$	Model base area
$T$	Nondimensional flow response time, Thompson number, $t_r U / l$
$t$	Time
$t_r$	Flow response time
$U$	Local flow velocity
$U_{4a}$	Local flow velocity behind unsteady wave
$U_e$	Local flow velocity at boundary-layer edge
$U_W$	Velocity through the porous wall
$V_p$	Plenum chamber volume
$V_T$	Test section volume

$\dot{W}_{1a}$	Flow rate through porous test section wall
$\dot{W}_{1b}$	Flow rate through plenum exhaust system
$\dot{W}_2$	Flow rate out of charge tube
$\dot{W}_T$	Flow rate through main starting device
$x$	Axial dimension on body or in test section
$Y$	Vertical height from wall
$Z$	Spanwise dimension
$\alpha$	Angle of attack
$\Delta C_D$	Difference between total drag coefficient at any Mach number and coefficient at some reference Mach number
$\Delta C_{DF}$	Difference between forebody drag coefficient at any Mach number and coefficient at some reference Mach number
$\Delta C_p$	Fluctuating pressure coefficient, $\bar{p}/q_m$
$\Delta t_p$	Time between opening of main starting device and opening of plenum exhaust diaphragm
$\Delta W$	Length between head and tail of unsteady wave
$\Delta x$	Length from measurement station to head of unsteady wave
$\delta$	Boundary-layer total thickness
$\delta^*$	Boundary-layer displacement thickness
$\eta$	Nondimensional semispan location, $Z/(b/2)$
$\theta$	Angular position relative to tunnel axis in the ground plane
$\mu$	Viscosity
$\rho$	Density
$\sigma \Delta M$	Standard deviation in test section axial Mach number distribution
$\tau$	Time during run, since passage of the head of the unsteady wave, at which thickness measured
$\tau_w$	Test section wall porosity

SUBSCRIPTS

- 4 Charge tube storage condition
- ° Free-stream conditions

