Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Dynamics of a Multiple-Skirt Air Cushion Vehicle

L. L. Bickford* and G. K. Olson†
Aerojet-General Corporation, Sacramento, Calif.

Nomenclature

A = cross-sectional lift area, plenum
A_J = cross-sectional lift area, inner circular skirts
A_L = cross-sectional lift area, outer peripheral skirt
A_0 = flow area, inlet orifices
C = discharge coefficient
g = gravitational constant
h = initial steady-state hovergap
I_y = moment of inertia in pitch
k = adiabatic coefficient of air
P = internal gage pressure
P_P = internal gage pressure, fan discharge plenums
P_J = internal gage pressure, outer peripheral skirt
$\bar{P}$ = absolute steady-state pressure
ΔP = internal gage pressure loss
Q = volumetric flow
Q_L = volumetric flow, leakage
S = circumference
$T(t)$ = load, transient excitation
V = internal volume
W = vehicle weight
X = moment arms from c.g. to centers of pressure
X_T = moment arm from c.g. to transient excitation load
Z = transient and trim hovergap
ρ = density of air
θ = transient and trim pitch angle

Introduction

SEVERAL advanced air cushion vehicle (ACV) designs use a multiple-skirt air cushion system as shown in Fig. 1. The design of this type of vehicle requires the prediction of vehicle dynamic behavior where this behavior is determined by the complex interaction of vehicle and cushion mechanics. Past studies have indicated the necessity of utilizing a computer model of this nonlinear interaction to obtain the vehicle dynamic behavior as a function of vehicle design parameters.

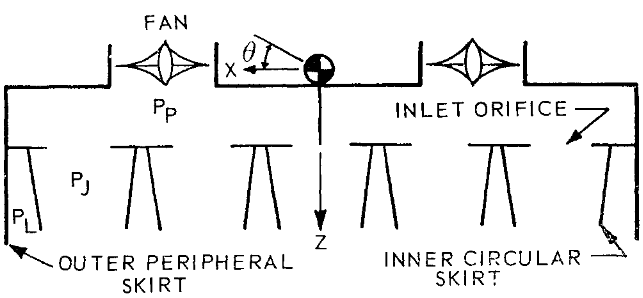

Fig. 1 Multiple-skirt air cushion system.

Received June 16, 1969. This work was supported by the Aerojet-General Corporation.

* Supervisor, Control Dynamics Group, Liquid Rocket Operations Engineering Department.

† Senior Dynamics Engineer, Systems Analysis Group, Liquid Rocket Operations Engineering Department.

This Note describes the mathematical modeling and the results of a corresponding analog computer simulation that is used to investigate multiple-skirt ACV dynamic characteristics in the pitch and heave degrees of freedom. In addition, a description of pitch dynamic testing of a multiple-skirt ACV is presented and the results are compared with the analytical predictions.

Mathematical Model

The internal flow dynamics of a multiple-skirt ACV have not been defined and verified previously. Therefore, emphasis is placed on the detailed mathematical modeling of the air cushion system shown in Fig. 1. The components of the air cushion system are the lift fan system, ducts, plenums, and flow restrictions associated with orifices and flexible skirt leakage gaps.

The air cushion system elements are mathematically modeled using a lumped parameter approach. The lift fans operate with a head-capacity curve corresponding to a constant speed. This head-capacity curve is approximated by the parabolic equation

$$P = a + bQ - cQ^2 \tag{1}$$

Since only small pressure and temperature changes occur in the system, incompressible flow equations are used to describe the flow through the restrictions. The air cushion circuit leakage from beneath the inner circular skirts and the peripheral skirt, which extends completely around the base of the vehicle cushion, is effected by vehicle motions in pitch

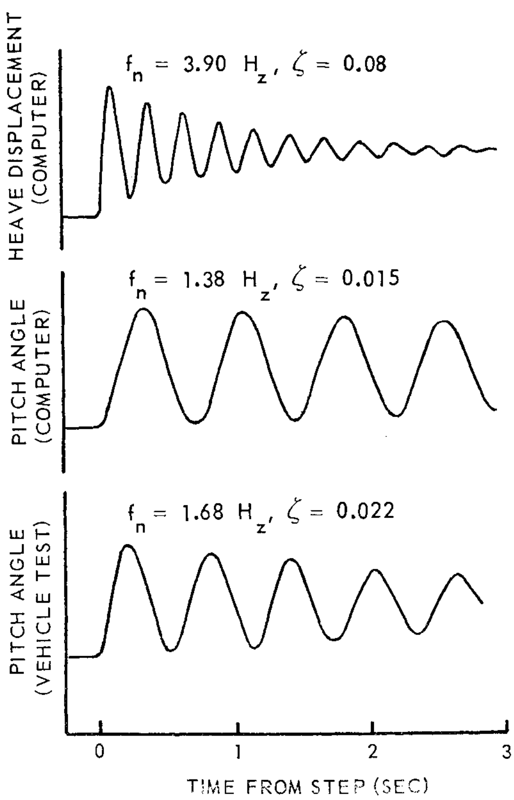

Fig. 2 Transient response to step excitation.

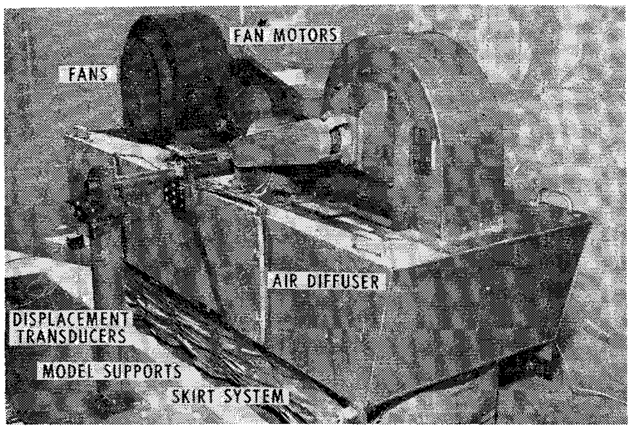

Fig. 3 ACV pitch test assembly.

and heave. As a result, the skirt leakage pressure-flow relation is represented by

$$Q_L = CS(h \pm X\theta - Z)(2\Delta P/\rho)^{1/2} \qquad (2)$$

The plenum pneumatic capacitances are based on isentropic compressibility. The pressure rates associated with the inner circular skirt plenums and the inskirt plenum, which lies between the inner circular skirts and the outer peripheral skirt, vary with vehicle motion in pitch and heave where

$$dP/dt = (k\bar{P}/V)[\Sigma Q + A(dZ/dt \pm xd\theta/dt)] \qquad (3)$$

The equations of vehicle motion in pitch and heave represent a rigid craft operating over a nondeforming surface with zero forward speed and are simplified by limiting the motion to small perturbations. A body-fixed coordinate system is used with the origin fixed at the vehicle center of gravity. A further simplification is realized due to symmetry about the x-z and y-z planes of the vehicle. The equation of motion in heave for the multiple-skirt ACV is

$$d^2z/dt^2 = g - (g/w)T(t) - (g/w)(\Sigma A_0P_P + \Sigma A_JP_J + A_LP_L) \qquad (4)$$

The equation of motion in pitch is given by

$$d^2\theta/dt^2 = [\Sigma A_JP_JX + X_TT(t)]/I_y \qquad (5)$$

The air cushion pressures contained in the vehicle motion equations are obtained from the nonlinear air cushion supply system model. The resulting forces and moments are coupled to vehicle motion in a feedback manner since the air flow in the skirted regions beneath the vehicle is modulated by vehicle motions in pitch and heave.

Analog Computer Simulation

The equations for the behavior of the multiple-skirt ACV are programed on a PACE 231R analog computer. The use of the computer simulation results in predictions of the steady-state trim and the transient variation in the pressures, flow rates, and motions of the air cushion vehicle for transient excitations. The transient excitations are in the form of step changes in applied force for heave and applied moment for pitch. Computer results were obtained for transient motion of an ACV with a weight of 375 lb, a pitch moment of inertia of 40 ft-lb-sec², a length to beam ratio of 2.7, and a cushion density of 7.2 lb/ft³. The results are shown in Fig. 2 and indicate lightly damped dynamic behavior in pitch and heave. In particular, the predicted damping ratios are 0.08 for heave and 0.015 for pitch.

Experimental Check of the Model and Conclusions

To verify the analytical predictions, the multiple-skirt ACV is mounted in a pitch test fixture with hovergap adjustability as shown in Fig. 3 and subjected to step changes in an externally applied moment during cushion operation. The vehicle pitch motion is sensed by a pull wire displacement transducer connected between the vehicle and the level concrete pad beneath the vehicle. The oscillatory pitch motion output from this sensor is recorded using a galvanometer recorder and is shown in Fig. 2.

An additional pitch transient test is run with a calibrated spring at each corner of the ACV with the air cushion circuit inactive. From this test, the rotational supporting structure damping ratio is found to be 0.004 and the vehicle pitch moment of inertia is found to be 31.0 ft-lb-sec².

At a 0.6-in. hovergap corresponding to the vehicle trim conditions in the computer study and correcting for supporting structure damping and the moment of inertia difference, the pitch damping and natural frequency obtained from the vehicle test data agree very closely with those obtained from the analog computer predictions. As a result, the analytical technique described in this Note is a valid design tool for predicting the overland dynamics of a multiple-skirt ACV.

Gross Thrust Coefficient—Turbofan Engines

Joseph F. Boytos*
Naval Air Propulsion Test Center, Trenton, N. J.

Nomenclature

A = exhaust nozzle area, ft²
Cg = exhaust nozzle gross thrust coefficient
Fg = gross thrust, lb
Mn = flight Mach number
NPR = nozzle pressure ratio, P_t/P_a
P_a = ambient pressure, in. HgA
P_t = nozzle exit total pressure, in. HgA
SLS = sea level static
γ = ratio of specific heats

Introduction

CURRENT and future military aircraft will utilize turbojet and turbofan engines as their basic powerplants. In developing a new-model engine, the engine manufacturer issues an engine model specification that contains performance estimates for the range of altitudes and Mach numbers over which the engine can be used. These estimates enable the airframe manufacturer to determine installed engine performance and the Government to determine if the proposed engine will be adequate for specific mission requirements.

The estimation of gross thrust at a given flight condition is of primary importance. This can be done by calculating an ideal engine gross thrust and multiplying by an appropriate nozzle gross thrust coefficient (Cg). This Note concerns the gross thrust coefficient to be used for thrust estimates on turbofan engines.

Current Method of Estimating Thrust

The current method used for both turbojet and turbofan engines is to calculate an ideal gross thrust and then multiply by the proper value of Cg ($Fg = Cg \cdot Fg_{\text{ideal}}$). Figure 1 illustrates schematically the exhaust nozzle of a turbofan engine. The gross thrust coefficient Cg is defined as the ratio of actual to ideal gross thrust, with the ideal gross thrust based on an isentropic expansion of the pressure ratio P_t/P_a across the nozzle. Since the engine manufacturers do not have the

Received June 2, 1969.
* Project Engineer. Associate Member AIAA.