Engineering Notes

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Duct Effects on the Dynamic Fan Characteristics of Air Cushion Systems

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Introduction

EXPERIMENTAL results have recently been reported[1] which show that the dynamic characteristics of an air cushion fan can deviate appreciably from its static characteristic, where, by definition, the characteristic of a fan is its pressure-volume flow relationship. These results are qualitatively in agreement with earlier results obtained by Durkin and Langhi.[2] Typically, the results show that for low disturbance frequencies the deviations from the static characteristic are small, whereas for intermediate frequencies the deviations can be very large. Deviations from the static characteristic associated with the dynamics of a vehicle supported by the cushion (ACV) can arise from at least three sources: unsteady aerodynamics of the flow through the fan blades, one-dimensional unsteady flow in the fan volute-duct system and, ultimately at high enough frequencies, wave propagation phenomena in the ducting.

It is the purpose of this Note to observe that, for the frequencies and duct lengths typically involved in the dynamic operation of air cushion vehicles over land and water, the inertia of the air flow in the fan volute-duct or annulus-duct system appears to be the dominant factor in generating the effective unsteady characteristics. This conclusion was drawn from results obtained by analysis based on well-established models and numerical procedures for treating one-dimensional unsteady flows[3] together with an application of a criterion available for determining the importance of unsteady aerodynamic effects in fan blades.[4] The analysis is reported in greater detail in Ref. 5. In Ref. 6 the present authors show, by using the same analytical models, that the inertia of the air in the duct can have a major destabilizing influence on the heave dynamics of fan-duct-plenum systems for even relatively short ducts.

Analytical Model

The system examined[5] consisted of one cell of a Canadian multicell amphibious ACV raft known as the HJ-15 together with its duct-volute work. The cell, which was 1.83 m in diameter and 0.915 m deep, was modeled as a lumped capacitance.[7] The duct flow was modeled in two ways, first as a one-dimensional unsteady flow with friction, and second as a lumped inertance. It should be noted that the first model included the possibility of wave propagation effects. For this analysis, following the methods outlined for hydraulic transients,[3] the partial differential equations describing unsteady duct flow, namely, continuity and momentum, were reduced to ordinary differential equations by the method of characteristics.[3] For the lumped inertance analysis, Newton's second law for the motion of the slug of air in the duct was used. The nonlinear quasisteady inviscid incompressible orifice flow law was used to describe the flow from the duct into the cell and from the cell to atmosphere. The cell inlet orifice diameter was 0.305 m. The ordinary differential equations for each model were integrated numerically.

Results

Typical computed dynamic characteristics are shown in Fig. 1, where the standard fan pressure and volume flow coefficients[8] are used to present the results nondimensionally. That is $C_p = p/\rho N^2 D^2$, where p is the pressure at the end of the supply duct adjacent to the cushion, ρ is the atmospheric air density, N is the fan rotational speed, and D is the wheel diameter. Also $C_Q = Q/ND^3$ where Q is the instantaneous volume flow rate at the entrance to the cushion. The results show the dynamic pressure-flow characteristics which occur at the downstream end of the duct when the hover-gap is oscillating sinusiodally, and thus the effect of ducting on the fan characteristic as seen at the cushion. For these results, the duct, which has the proportions typically occurring on a practical vehicle, is 3.04 m in length and 0.457 m in diam. A typical static fan characteristic is imposed at the upstream end of the duct, and the effective static characteristic as seen at the cushion is given for reference in Fig. 1. The mean hover-gap is 0.64 cm while the amplitude of the sinusoidal variation is 50% of this gap. The cell volume variation associated with the hover-gap variation has not been included.The arrowhead on the loops shows the direction in which the operating point is moving in time. The results are qualitatively in agreement with those presented in Refs. 1 and 2. For the three frequencies f given, which span the range typically occurring in the dynamics of the vehicle modeled, and which are 1, 5, and 10 cps, respectively, the lumped inertance and the full one-dimensional unsteady results are in very close agreement. In fact, the difference is too small to be plotted. This implies that wave propagation effects are not significant. When one considers the duct length and frequencies involved, this is not

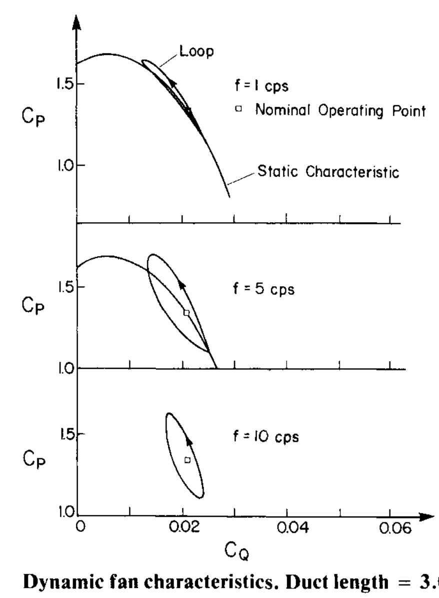

Fig. 1 Dynamic fan characteristics. Duct length = 3.03 m.

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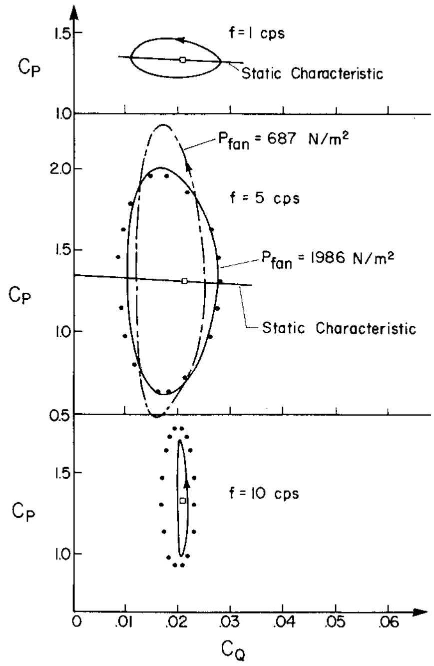

Fig. 2 Dynamic fan characteristics. Duct length = 7.62 m.

surprising. As is discussed at some length in Ref. 6 the system is behaving something like a Helmholtz resonator,[9] with the slug of air in the volute and duct oscillating back and forth on the spring associated with the plenum air capacitance.

Some results for a case in which the duct length has been increased to 7.62 m and the static fan characteristic is replaced by a constant pressure source are given in Fig. 2. The use of a constant pressure source facilitates the demonstration of a scale effect to be discussed later. All results in Fig. 2, except for the chain-dotted line marked "$P_{fan} = 687$ N/m^2," correspond to a nominal equilibrium operating fan pressure of 1986 N/m^2. The latter fan pressure is representative of that obtained on the prototype vehicle at full load. For the latter fan pressure, the continuous lines give the results of the one-dimensional unsteady analysis, and the dots are the result given by the lumped inertance model. The slight negative slope of the static characteristic is caused by friction losses in the duct. The peak in pressure fluctuations at about $f = 5$ cps is believed to be a Helmholtz resonator effect because for this geometry the Helmholtz resonator frequency is $f_h = 5.2$ cps.[9] A minimum in flow fluctuations, which occurs at about $f = 10$ cps, is believed to be a wave propagation effect because the natural frequency of the ducting f_d based on its wave propagation time is $f_d = 11.3$ cps.[3] Thus, it appears that for this case both Helmholtz resonator and wave effects are important. For frequencies greater than 10 cps, the direction of the loop often reverses, but the amplitude of both pressure and flow fluctuations remain small. As expected, the agreement between lumped inertance and full unsteady results becomes increasingly poorer as f increases.

The chain-dotted line for the results at 5 cps in Fig. 2 illustrates that, as might be expected, these effects do not scale according to the basic steady fan laws. It corresponds to a reduction of vehicle weight by a factor of about 2.90, but with the vehicle geometry unchanged and the equilibrium volume flow adjusted so that the same mean hover-gap, namely 0.64 cm is obtained. In the analysis the effective fan speed N was reduced to keep C_p the same as for the earlier results. It follows from the definitions of C_Q and the one-dimensional Bernoulli law for the air escaping from the cushion that, if the hover-gap is the same for both cases, then C_Q is also the same.

Using unsteady airfoil and cascade theory, Ohashi[4] has analysed the unsteady aerodynamic problem for the flow past the fan blades. He defines a critical frequency which characterized the frequencies required for significant unsteady blade aerodynamics to occur. It was found that for the present system this critical frequency is well above the typical frequencies expected to be encountered, so that unsteady blade aerodynamic effects are not significant.

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A Correlation of Spray Height Data for Jets Impinging on Water

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EXPERIMENTS done with small-scale jet nozzles at NASA Langley and observations of the X-13† suggest that operation of a vertical attitude takeoff and landing (VATOL) vehicle over water may produce considerable spray. The effects of this spray on visibility, corrosion, and thrust loss (due to water ingestion) could be considerable. Although a few experiments have been conducted with scale-model jets to determine spray height as a function of various flow parameters, none has resulted in a parametric formula for spray height that satisfactorily predicts full-scale results.[1,2] This Note presents the results of an analysis to find a parameter which correlates the available jet nozzle data, so that the spray height for VATOL aircraft may be estimated.

Considering the physics of this problem, spray height H_S is assumed to be a function of the nozzle exit dynamic pressure Q_N, the height of the nozzle above the water's surface H_N, the nozzle diameter D, the density of the water ρ_w, and the acceleration due to gravity g.

Thus,

$$H_S = F(Q_N, H_N, D, \rho_w, g) \tag{1}$$

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Hydrodynamics; Flight Operations.

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†The X-13 is an Air Force research VATOL aircraft powered by a Rolls Royce Avon turbojet engine. It first flew in 1955 and was demonstrated at the Pentagon in 1957. It has flown successfully in all flight regimes including: takeoff, hover, transition, and cruise.