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Shroud and Ejector Augmenters for Subsonic Propulsion and Power Systems

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A new, simple, and handy control-volume formulation is put forward for propellers in ejector–augmenter systems where power is either added (e.g., for propulsion) or extracted (e.g., wind/water turbines.) The formulation is first principles based, free of empiricisms, overcomes past formulation limitations, and uncovers heretofore unknown high performance potential for such systems. For shrouded props, these new control-volume based predictions are shown to agree well with both independent experimental and computational data, as well as other analytical and empirical models. Solutions generally involve simple polynomials with a single input parameter that is easily determined from the aerodynamic performance of the empty shroud. This formulation provides new correlation parameters, plus greatly simplifies design optimization studies by decoupling the shroud and ejector design effort from that of the prop design.

Nomenclature

A = flow cross-sectional area
a = coefficient
b = coefficient
C_D = disk-loss coefficient
C_P = power coefficient
C_{pP} = pressure coefficient based on velocity V_P
C_S = duct/shroud force coefficient
C_{TP} = thrust coefficient based on velocity V_P
D = diameter
F_S = duct/shroud force
F_{S1}, F_{S2} = duct/shroud forces
g = coefficient
K_t = thrust coefficient $= T/\rho n^2 D_p^4$
n = propeller rotational speed in revolutions per minute
P = power
P_{iH} = shaft horsepower
p = pressure
r = power ratio
r_S = ejector inlet area ratio $= A_S/A_D$
T = thrust
u = V/V_a
V = velocity
V_c = characteristic velocity
V_n = velocity normal to shroud
V_P = "power" velocity
v = V/V_c
z = coefficient
η = propeller efficiency
ρ = fluid density

Subscripts

a = ambient freestream conditions
D = properties at duct exit plane
d = properties in ejector duct
E = properties at ejector duct exit plane
m = maximum power state
o = properties at downstream outlet area
p = conditions at the propeller plane,
S = properties at ejector inlet
T = flow conditions for finite tunnel cross-sectional area
0 = properties when $V_a = 0$
1, 2 = properties fore and aft of the prop, respectively

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I. Introduction

THERE has been considerable effort and discussion in the literature (see, for example, [1–8]) concerning the potential for shrouded power generators (wind and/or water turbines) such as depicted in Fig. 1 to outperform their unshrouded counterparts, most based on limited experimental and/or incomplete analytical formulations. Additionally, although ejector-based propulsion augmentation has been studied extensively for over 60 years (see [9–16] for examples), only limited attention has been given its application to subsonic/incompressible propulsors and power generators. This paper addresses both these shortfalls and extends the work of [17] to provide a new, corrected, unified and handy formulation applicable to ejector-augmented prop systems such as applicable to propulsors and/or power generators.

For ejector-based augmentation, literally hundreds, if not thousands, of papers, articles, reports, and books have discussed this problem at length (see [9–16] for a representative sampling) for configurations, such as depicted in Fig. 2, involving interactions between primary and secondary streams that are fluid dynamically independent. Two key papers on the subject are those of von Kármán ([10] and as discussed in [9], for example) and Heiser ([11]). Von Kármán introduced the simple one-dimensional momentum balance model of Fig. 2 to predict the amplification of a primary jet's thrust due to ingestion of freestream fluid into a constant area duct that exhausts to the freestream's static pressure level. All efforts since that time have employed this same basic model with its two critical assumptions/constraints: 1) independent primary and secondary streams plus 2) all the mixed flow exiting the ejector at the freestream pressure level. These both are inappropriate for low-speed/incompressible flow through prop-based systems. For these, the primary stream is but a portion of the freestream modified due to power injection or extraction. Also, the imposition of the freestream pressure at the ejector exit is a specialized case and is inappropriate