A METHOD FOR MEASUREING PROPULSIVE POWER AND EFFICIENCY FROM A VEHICLE WAKE

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A key indicator of the overall propulsive performance of a self-propelled vehicle is the propulsive efficiency, defined as the ratio of the rate of useful work done propelling the vehicle ($\dot{W}_u$) to the total mechanical propulsive power expended propelling the vehicle (P_{mech}) [1]. For unsteady cases, propulsive efficiency can be taken as the ratio of time averages ($\overline{\dot{W}_u} / \overline{P}_{mech}$). In traditional engineering applications such as airplanes and submarines, $\dot{W}_u$ and P_{mech} can be measured directly by placing sensors between the propulsor and the vehicle body. As the propulsion mechanism increases in complexity, this approach becomes impractical (e.g., pulsed jets and/or flapping appendages). In biological cases, direct measure of $\dot{W}_u$ and P_{mech} is often impossible because the propulsion mechanism is integrated into the animal body.

An alternative method for determining propulsive efficiency is to probe the vehicle wake. Typically wake velocities are measured [2] and propulsive efficiency is inferred using idealized formulae. This approach is, however, problematic for most biological or biomimetic propulsion systems because they generate wake flow that varies in space and time, but the formulae used to infer propulsive efficiency assume steady, uniform flow.

A more general approach is to determine $\overline{P}_{mech}$ directly from wake measurements. This paper presents a method for measuring $\overline{P}_{mech}$ using a porous obstruction towed behind a self-propelled vehicle. The time-averaged power required to tow the obstruction is related to the mechanical power shed into the wake by the vehicle because the obstruction is designed to dissipate the kinetic energy in the wake. The difference in towing power with and without the vehicle present, therefore, is directly related to $\overline{P}_{mech}$ and can be used to measure $\overline{P}_{mech}$ with appropriate calibration. For a properly designed obstruction, the measurement of $\overline{P}_{mech}$ is, in principle, independent of spatial and temporal variations in the vehicle wake.

With $\overline{P}_{mech}$ known, the propulsive performance of equivalent vehicles that use different propulsive schemes can be compared. Moreover, if $\overline{\dot{W}_u}$ is known by other means, propulsive efficiency can be determined. Finally, if the time-averaged mass flow rate ($\overline{\dot{m}}$) through the propulsion system is known (e.g, $\overline{\dot{m}}$ from a pulsed jet), then equating the measured $\overline{P}_{mech} / \overline{\dot{m}}$ with that for a steady jet at the same vehicle speed (U) gives an equivalent jet velocity ($U_{j,eq}$) which can be used to find an equivalent Froude propulsive efficiency, namely, $\eta_{F,eq} = 2U / \left(U + U_{j,eq}\right)$.

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References

[1] M.J. Lighthill, "Note on the swimming of slender fish," *J. Fluid Mech.* **9**, 305 – 317, 1960.
[2] W. W. Schultz and P. W. Webb, "Power requirements of swimming: do new methods resolve old questions?" *Integr. Comp. Biol.* **42**, 1018 – 1025, 2002.

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