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Static thrust recovery of PAR craft on solid surfaces

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Abstract

Power-Augmented-Ram Vehicles belong to a new class of ground-effect machines with hybrid support. Recovered static thrust and static lift on solid surfaces are important amphibious characteristics of this craft. Experimental data for the static thrust recovery and the transition to a hovering mode are obtained in the tests with a vehicle model on two types of ground surface and with variable engine thrust and flap trailing-edge gap. The uphill surface and increased mass of the model demonstrate reductions in thrust recovery. A comparison with a two-dimensional potential-flow theory is presented. The static thrust accumulation, identified in the pre-hovering regime of a model on solid surface, does not significantly benefit the low-speed forward motion.

Keywords: Power-Augmented-Ram; Thrust recovery; Hovering

1. Introduction

Power-Augmented-Ram Vehicle (PARV) is a new promising means for fast and amphibious cargo transportation. The essential PARV elements include a platform with a stern flap, side hulls, and front engines. A two-dimensional schematic of a PAR system with one possible airflow pattern in the static regime is shown in Fig. 1 with important parameters depicted. A high-velocity jet from a front engine is directed under the platform, where a pressurized air cushion is generated that supports the platform. The stern flap controls the amount of airflow exiting downstream and a proportion between the platform lift and drag. The vehicle can be partly supported by hulls on the sides of the platform. A radio-controlled PARV model is illustrated in Fig. 2 (Matveev and Malhiot, 2007).

At high speeds the passive aerodynamic lift of the platform due to forward motion in the ground effect can become significant. Although PAR systems were developed mainly as auxiliary take-off means for wing-in-ground (WIG) craft [e.g., Maskalik et al. (1998)], the ideas for PARV with combined support were also presented (Gallington, 1987; Kirillovykh and Privalov, 1996). Because of higher relative weight (or lower speeds) of PARV in comparison with WIG, the contact with a surface and low-speed capabilities are more vital for PARV performance.

Important design specifications of these crafts are the static thrust and lift, characterizing amphibious capabilities. The exhaust jets from the front engines generate a backward force (drag) on the PAR platform. Another backward force is the static friction at the contact between the vehicle hulls and the solid surface. The difference between the horizontal component of the front-engine thrust and the sum of backward forces is defined here as the recovered thrust.

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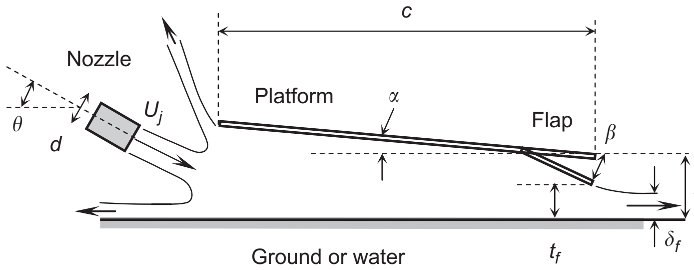

Fig. 1. Two-dimensional scheme of PAR airflow in the overfilled regime. Arrows indicate jet directions.

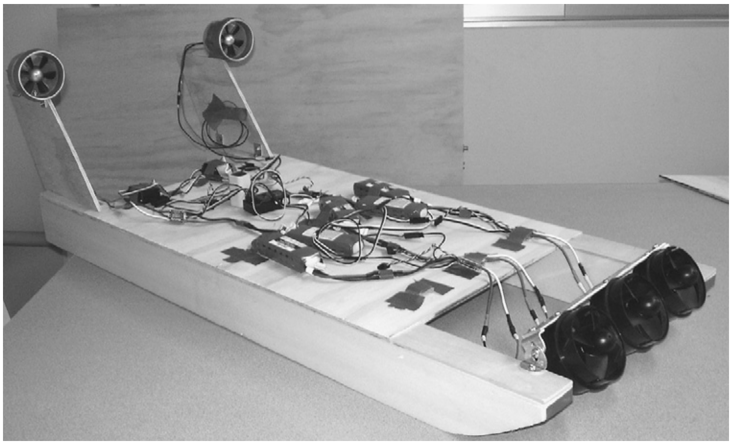

Fig. 2. Radio-controlled PARV model under assembly.

Some test data for similar forces on WIG craft configurations were reported previously [e.g., Gallington et al. (1976), Maskalik et al. (1998)]. In this paper we present the measurements of the recovered static thrust and the transition to the static hovering regime of a PARV model on two solid surfaces. The test results are compared with a two-dimensional potential-flow theory.

2. Model parameters and test set-up

A PAR model with a remote control capability was constructed for both test and demonstration purposes (Fig. 2). The side hulls with a flat bottom are made of Styrofoam. The horizontal platform and vertical stern struts are made of $\frac{1}{4}$ inch (1 inch = 2.54 cm) plywood. The model and platform widths are 40 and 30 cm, respectively. The model length is 100 cm, and the platform length (c in Fig. 1) is 80 cm. The distance from the platform bottom to the baseline (i.e., hull bottom) h is 8 cm. The platform pitch α with respect to the baseline is zero for this model. The length of the flap is 15 cm. The distance from the flap trailing edge to the baseline t_f is a variable parameter in the tests. The chosen standard mass of the model is 3.3 kg. The longitudinal position of the center of gravity is 42.5 cm forward from the stern. The standard inclination of the front engines (electric-motor driven fans) to the horizontal plane is 25°. The center of the exit area of the fans is 7 cm above the baseline and 13.5 cm forward from the platform leading edge.

The combined thrust of three 8-cm-diameter fans (GWS Ducted Fan EDF-3045 × 4) is an another variable parameter. The fan thrust was previously quantified in terms of applied voltage (Matveev and Malhiot, 2007). The stern fans and all radio-controlling equipment shown in Fig. 2 were not used in this study. In the tests presented in this paper the front engines received electric power from an external power supply and the flap angle was mechanically fixed.

For the measurement of the recovered static thrust, a digital force gauge, Omega DFG60-11 (with accuracy 10 g), was utilized. The force gauge was located sufficiently far downstream from the model in order not to affect the stern jet exiting under the flap. The gauge was connected to the model via a horizontally oriented narrow aluminum plate.

The model was free to heave and pitch. This gauge-model connection allowed us to measure the static thrust with minimal effect on small heave and pitch displacements of the model and to prevent the model from the lateral motion in the hovering regime. This connection is estimated to produce the maximum downward force on a hovering model that constitutes 2% of the model weight.

Two ground surfaces were used in the static tests, i.e., a rigid table cover and a small-cell elastic foam rubber sheet. Friction force between these surfaces and the hull material was measured in separate tests with low forward velocities. The rigid and elastic surfaces were found to have friction coefficients 0.23 and 0.87, respectively. These surfaces imitate different operational conditions that a full-scale vehicle may encounter.

3. Simplified theory

Results of the two-dimensional potential-flow PAR theory developed by Gallington et al. (1976), and extended by Rozhdestvensky (2000), can be applied for the estimation of our model performance. Small variations in heave and pitch of the model and the side-wise air leakage are ignored. The total lift provided by the PAR system can be presented as a sum of the vertical component of the front-fan thrust and the air cushion lift:

$$L = T\sin\theta + \min\left\{\frac{1-(t_f/h)^2}{2t_j/h};\,2\frac{1-t_f/h}{1+t_f/h}\right\}\frac{c}{h}T\cos\theta, \tag{1}$$

where t_f is the distance between the flap trailing-edge gap and the baseline (hull bottom), t_j the effective thickness of the incident jet (evaluated from the vertical projection of the fan exit area and the platform width), h the distance between the platform bottom and the baseline, c the platform length (including flap), θ the fan inclination angle to the horizontal plane (reasonably small in our tests), and T is the combined thrust of the front fans. The difference between the flap gap and the thickness of the jet exiting under the flap is neglected. If the second term within the brackets in Eq. (1) is smaller than the first term, this equation provides the upper bound estimation for the lift that can be achieved with an increased jet thickness.

Under the same assumptions, the recovered thrust T_r can be expressed as follows:

$$T_r = \max\left\{\left[1-\frac{(1-t_f/h)^2}{2t_j/h}\right]T\cos\theta - \mu\max(W-L;0);0\right\}, \tag{2}$$

where W is the model weight and μ is the friction coefficient. According to Eq. (2) the recovered thrust is always directed forward and the friction force is directed backward.

4. Results and discussion

The measured recovered static thrust is shown in Fig. 3 for three variable parameters, i.e., the total front-fan thrust, the gap between the flap trailing edge and the baseline t_f, and the ground surface type. A non-zero recovered thrust appears only when the total fan thrust exceeds a certain threshold value, since the model must overcome the static friction between side hulls and the ground surface. The friction force depends on the model weight fraction supported by the hulls in contact with ground. The operating fans build a pressurized zone under the platform, so that the model weight can be partially or completely supported by the air cushion.

For conditions corresponding to those as shown in Fig. 3, larger flap gap results in higher recovered thrust, but only at sufficiently high values of the fan thrust. To initiate the model motion, especially on high-friction surfaces, the flap gap should be decreased in order to lift the model by means of the air cushion and to minimize the static friction. The established thrust values showed variations around 10%, which included measurement differences in repeated tests and fluctuations in each run. This variation can be higher near the threshold point.

It was observed that in cases with large flap gaps and near the threshold, it might take a few minutes for the model to achieve the maximum recovered static thrust. At sufficiently high fan thrust with smaller flap gaps, a stable value for the recovered thrust was quickly established.

The PAR lift calculated in Eq. (1) and the model mass are shown in Fig. 4(a) for variable total fan thrust and flap gap. The intersections between the mass and lift curves indicate the transitions to the hovering regime. In Fig. 4(b) they are compared with the transitions approximately determined during the tests on both low- and high-friction surfaces, estimated as the states with the minimum fan thrust at which the model provided little resistance to the side

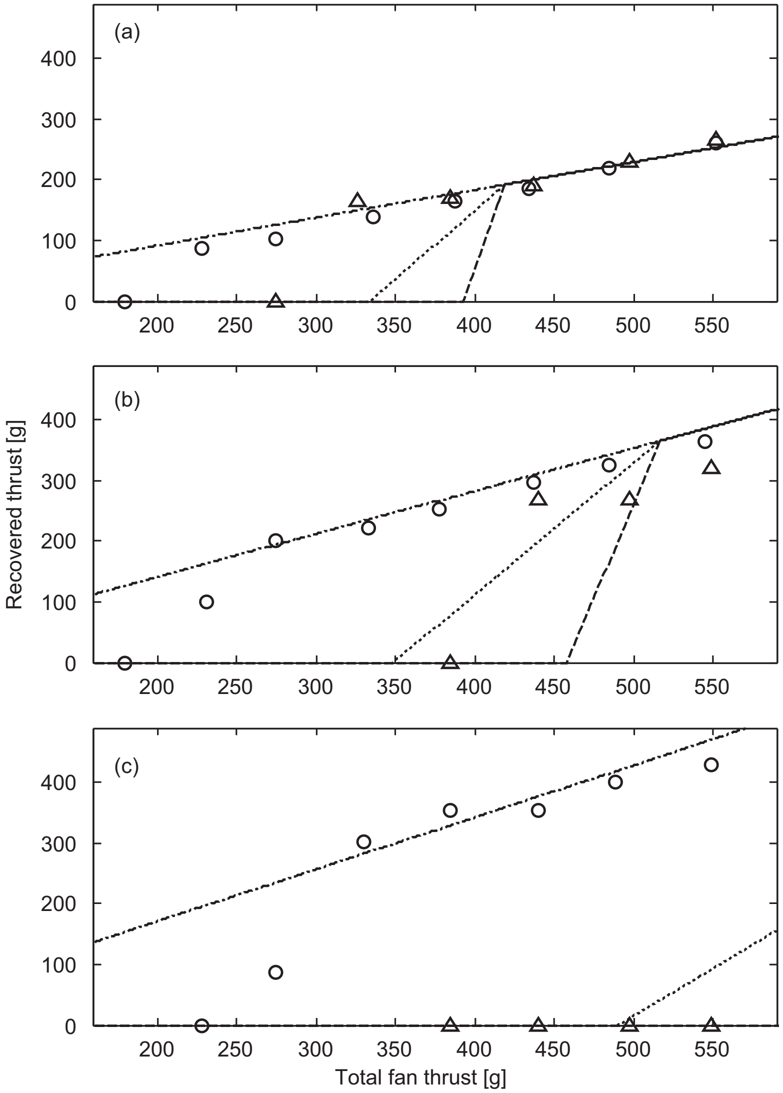

Fig. 3. Recovered static thrust. Flap gap: (a) 2 cm, (b) 4 cm, (c) 6 cm. ○, Rigid low-friction surface; △, elastic high-friction surface. Theoretical calculations: solid line, in hovering regime; dotted line, in pre-hovering regime on low-friction surface; dashed line, in pre-hovering regime on high-friction surface; dash-dotted line, assuming zero hull friction.

force. The agreement between the theory and experimental observations is satisfactory. Since the actual lift of the model was not measured in this study, experiments specifically addressing the PAR lift are recommended for future studies.

With indications that the PAR lift calculated in Eq. (1) correlates with the obtained test data, Eq. (2) that involves the PAR lift can now be applied for the estimation of the recovered static thrust. The thrust is calculated in Eq. (2) for three cases, i.e., with low- and high-friction coefficients and with zero friction. Theoretical results are shown by the lines in Fig. 3. In the hovering regime (solid lines in Fig. 3(a, b)), the agreement between test data and theory is good. Lower values for experimentally obtained thrust at 4 cm gap on high-friction surface can be due to occasional contacts of the hulls with the surface. In the pre-hovering regime the measurements show significantly higher thrust than that the theory predicts for surfaces with friction. For the zero-friction theory the agreement with test data exists over a large fan thrust range in the pre-hovering regime, especially on rigid surfaces with larger flap gaps. However, under these conditions it takes several minutes in experiments for the static thrust to develop, opposite to quick thrust establishing in the hovering mode.

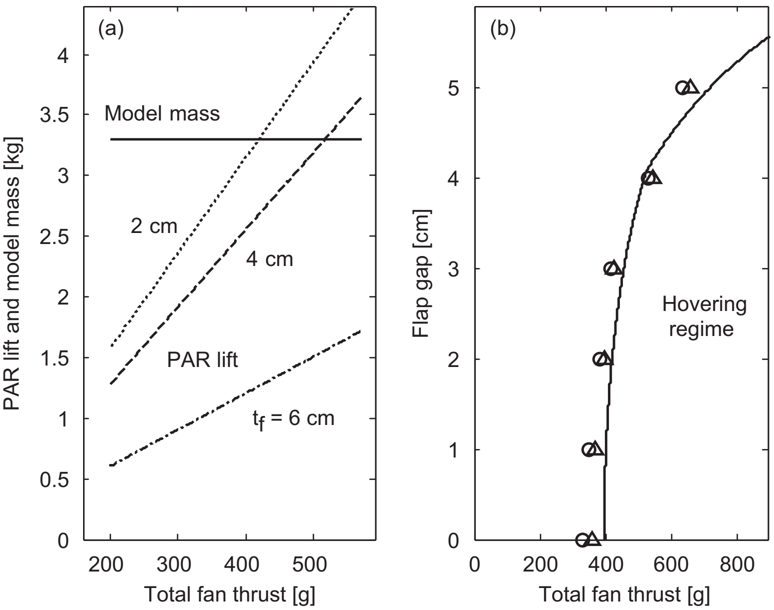

Fig. 4. (a) Model mass and theoretical estimations for PAR lift at different flap gaps. (b) Transition to hovering regime on the gap-thrust diagram. Test data: ○, low-friction surface; △, high-friction surface. Solid curve, theoretical calculation.

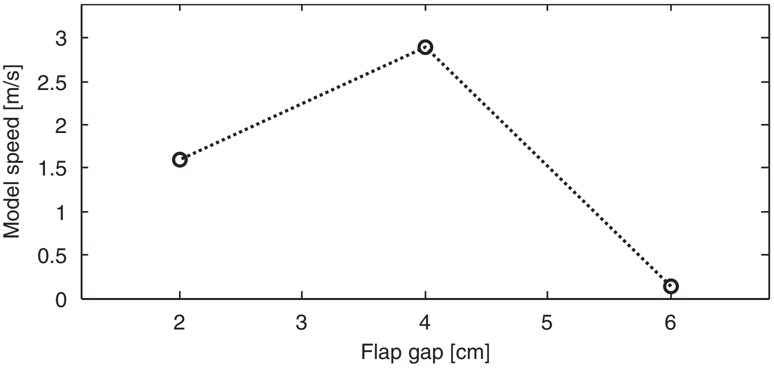

Fig. 5. Speed of self-propelled model with front-fan thrust of 570 g.

These observations can be explained as follows. The recovered thrust measured in the pre-hovering regime does not represent the average thrust values, but rather the peak thrust generated over short time periods. The flow from fans is highly turbulent, and the flow under the platform has a significant unsteady component. Flow fluctuations may partially unload the model over short time periods and push it forward. When flow fluctuations are accompanied by reductions in thrust and pressure (under the platform), the model does not return back due to high friction of hulls standing on the ground, and the measured thrust does not recede. Over time (several minutes in our tests), this thrust accumulates and may reach the predicted thrust level at zero hull friction. Therefore, the measured thrust recovery in the pre-hovering regime represents the accumulated thrust, which cannot be steadily sustained on a moving model even at low speeds.

This explanation is also supported by low-speed tests with a self-propelled PAR model on a low-friction surface, as shown in Fig. 5 (Matveev and Malhiot, 2007). At the same level of applied front-fan thrust (570 g), the largest flap gap results in the minimum average speed despite the highest accumulated static thrust (Fig. 3), since the model was in the pre-hovering static mode (Fig. 4). For the other gaps tested, the model was hovering at the given thrust level. Therefore, the intermediate flap gap resulted in the highest time-averaged thrust and speed.

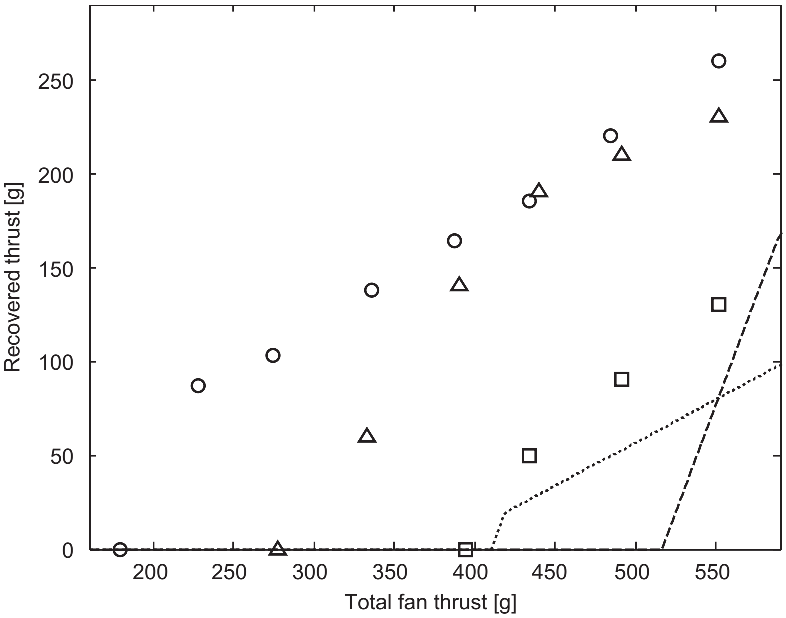

Fig. 6. Recovered static thrust with flap gap of 2 cm on low-friction surface. ○, Model mass 3.3 kg, slope 0°; △, model mass 5.1 kg, slope 0°; □, model mass 3.3 kg, uphill slope 3°. Dashed and dotted lines are theoretical estimations of recovered thrust at increased mass and uphill slope, respectively.

For practical PARV operations in low-speed regimes (maneuvering, transition between different surfaces, etc.) at given front-engine thrust, it is recommended to achieve the hovering regime and then to maximize the thrust by controlling the flap gap. The pre-hovering operations not only are inefficient but also wear the hull structure much more intensively due to high friction forces.

Additional experiments in this study were carried out with an increased mass of the model and on the uphill-slope surface. This information is useful for understanding the PARV capabilities in broader range of operational conditions. Results of two tests are shown in Fig. 6 and compared with one condition shown previously in Fig. 3(a) (low-friction surface, 2 cm flap gap). The increased mass delays the threshold of positive recovered thrust and the transition to the hovering regime (which is beyond the available thrust range for heavier model). The thrust in the pre-hovering regime is generally lower when the model mass is increased, because of higher friction force.

When an uphill slope is encountered, an additional backward force appears (weight projection on the baseline plane) reducing the thrust recovery. In the pre-hovering regime, practically no thrust accumulation occurs under the studied conditions because of the additional backward force. In the hovering regime on the uphill slope (above about 420 g of the total fan thrust in Fig. 6), the experimentally measured recovered thrust exceeded the theoretical values. More significant flow fluctuations noticed in the uphill-slope tests may increase the uncertainty of measurements in this state.

5. Conclusions

The recovered static thrust of power-augmented-ram vehicles on solid surfaces depends on the system structure, propulsor thrust, and friction between the vehicle's hulls and the ground. Once a craft achieves a hovering regime, the friction with the solid surface nearly disappears. A simple potential-flow PAR theory agrees well with the experimental data for the hover onset and for the recovered thrust in the hovering regime. Small pitch of the tested model and insignificant lateral air leakage under the hulls are in accordance with the theoretical assumptions.

A surprising finding is a significant accumulated static thrust measured in the pre-hovering regime. Despite a contact between the model's hulls and the ground, the accumulated thrust correlates better with the theory neglecting the ground friction rather than with the theory accounting for such friction. A possible reason for this phenomenon is fluctuations in the turbulent flow under the platform that may result in the static thrust accumulation over time. However, the accumulated thrust in the pre-hovering regime is unlikely to be practically useful for finite-speed forward motion. Preliminary tests with a moving model demonstrate higher speeds achieved at flap positions corresponding to the hovering regime rather than at the flap gap corresponding to the largest accumulated static thrust.

Time-resolved measurements of the lift and recovered thrust of PAR systems and fluctuations in the under-platform flow can provide further insight into the pre-hovering regime. Forward-speed tests over various terrains and modeling of air leakage under the side hulls are needed for the better understanding of PAR craft motion over land.

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