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Research paper

METHODOLOGY FOR EFFICIENCY DETERMINATION OF TIP-JET HELICOPTER PROPULSION SYSTEM

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Abstract: *The paper presents the methodology for determination of efficiency of tip-jet helicopter propulsion system with use of the equivalent construction. The testing installation involves a structure with pipes that gives equivalent values of thrust force like real blades found in helicopter propulsion system. Paper further describes construction problems that lead to high losses and ideas for solutions.*
Experimental tests show how energy can be transformed to increase thrust force with reduction of nozzle area in order to maximise lift power useful for helicopter flying and control.

Key words: *Tip-jet helicopter, thrust measurement, force measurement, acquisition systems*

1. INTRODUCTION

Hot cycle system transmits power pneumatically by lightweight ducting and a nozzle that directs high-energy gas from a turbine engine to the rotor blade tips to drive the rotor for helicopter flight.
Reaction driven rotor acts as a power turbine which directly convert the energy of the gases from the engine into rotary power by using light weight ducting (Fig.1.).
With this hot gas powered transfer system, the complexity and excess weight of the gearboxes, shafting, and tail rotor are eliminated. This is due to the fact that the reaction drive concept does not import a torque on the fuselage, and therefore there is no need for a tail rotor [1]. The necessary torque that creates the rotor rotation is now being generated by the moment [Nm] (i.e. rotor radius) and by the force (F_j) created when mass flow is ejected through the tip jets located at the blade tips. The magnitude of this torque – generating force is based on the amount of mass flow ($\dot{m}_j$) ejected, and by the difference of velocity between the tip jet (v_j) and tip speed (v_T).

$$F_j = \dot{m}_j \cdot (v_j - v_T) \tag{1}$$

In order to calculate F_j, the mass flow and velocity of the tip jet, $\dot{m}_j$ and v_j, respectively, must be calculated first. Both of these parameters depend on the results of the engine cycle analysis. Based on these facts, it is obvious that the engine and rotor form a highly coupled system. The variable that couples the engine with the rotor in the sizing procedure of a reaction driven rotor is the tip jet velocity v_j. This parameter is calculated by assuming that the flow expands isentropic from the internal rotor duct pressure to the freestream pressure outside the tip jet nozzles. Equation below shows explicitly how the tip jet velocity is dependent on the temperature and pressure inside the rotor duct:

$$v_j = \sqrt{2RT_{od}\left(\frac{\gamma}{\gamma-1}\right)\left[1-\left(\frac{p_\infty}{p_{od}}\right)\right]^{\frac{\gamma-1}{\gamma}}} \tag{2}$$

Since it is usually impractical to include a divergent part into the thrusting nozzle, the exit velocity would be close to the sonic one corresponding to temperature of the exhaust gasses. The propulsive efficiency of the thruster in hover can be expressed as

$$\eta_p = 2v_T/(v_T + v_j) \tag{3}$$

where v_j is the jet exit velocity, and v_T is the rotor tip blade.

2. TESTING SYSTEM

the tip-jet helicopter, hot compressed air goes out on the nozzles of blade tips, it produces torque for rotation of the rotor system [2].
Power of the tip-jet system is calculated as:

$$P_S = Q_m \cdot \Omega \cdot \eta_p \; [W] \tag{4}$$

where Q_m is torque of the tip jet system:

$$Q_m = F_j \cdot D \; [Nm] \tag{5}$$

F_j is thrust force of the tip nozzle, and D is diameter of the rotor.
Ω [rad/s] is angular speed of the rotor.

$$\eta_p = \frac{2v_T}{v_T + v_j} \tag{6}$$

η_p is the efficiency of a jet propulsion system, v_T is tip speed and v_j is the speed of the hot air that is ejected through nozzles on the blade tips (Fig.1.).
From equations above, we can see that the power P_S is directly proportional to F_j (thrust force). That's why it is very important that thrust force is measured properly.

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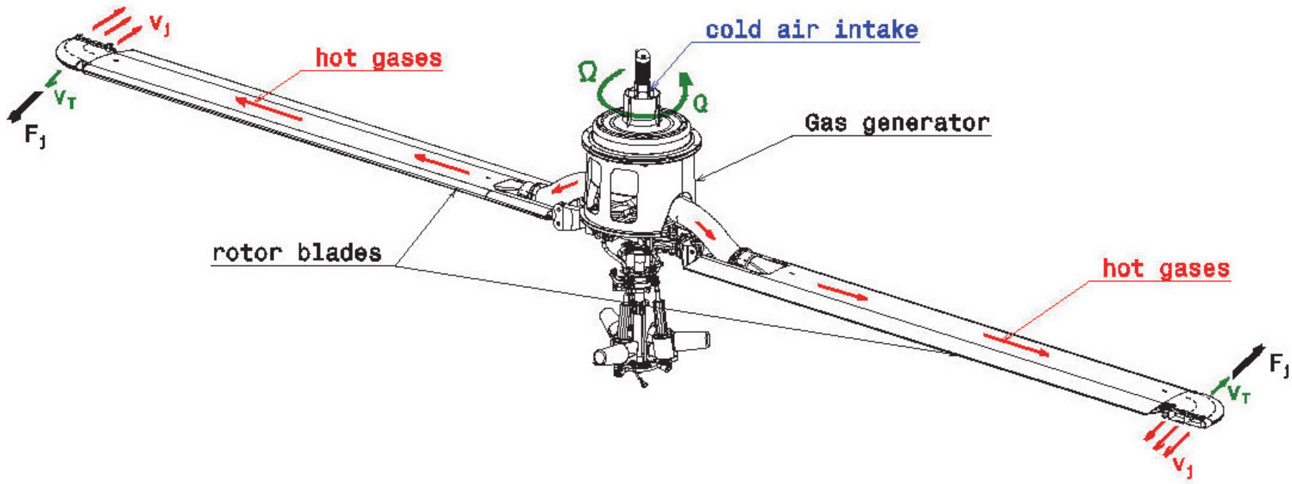

Fig.1. Tip-jet propulsion system

Purpose of the test was to measure thrust force on the blade tips - F_j. In order to realize what is the nature of hot air flow inside the blades and to see where the losses are, the test was performed on actual blades, on cylindrical tubes of different diameters, with and without flexible pipes. We also wanted to experimentally check, and define nozzle area on the blade tips so it can provide maximum thrust without exceeding critical temperature.

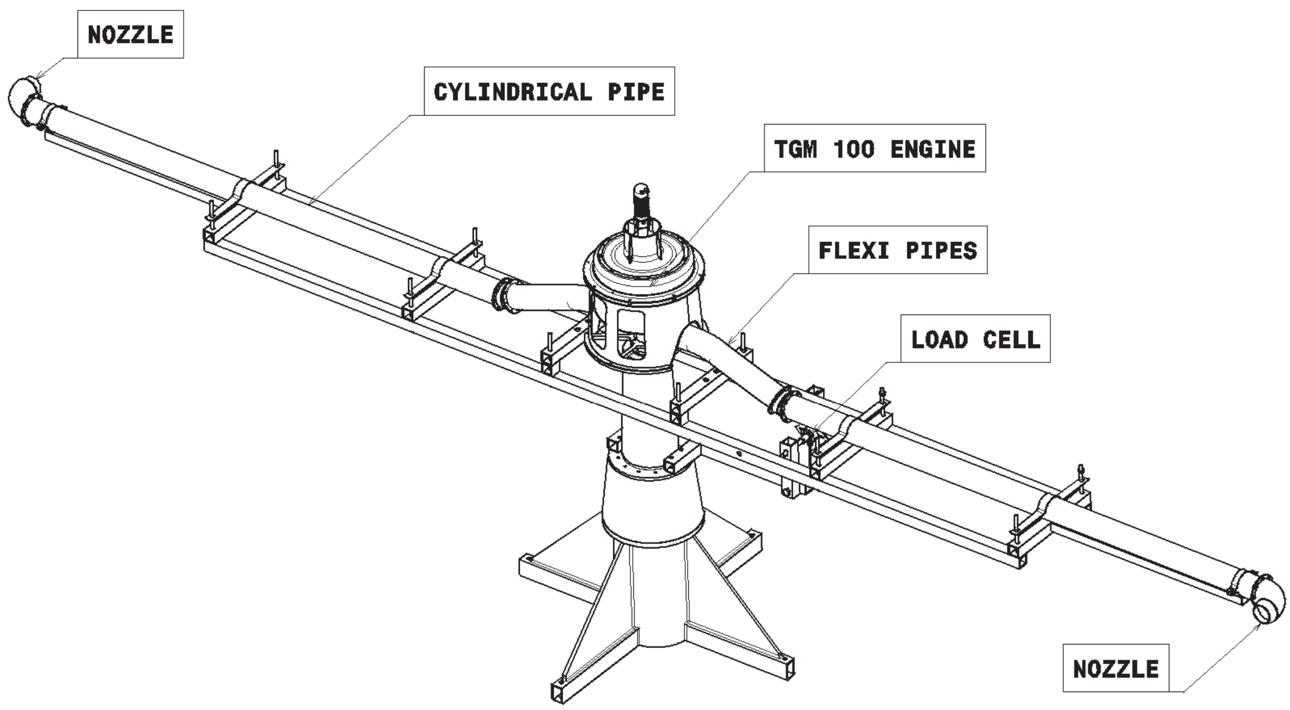

Fig.2. Test stand for measuring of the thrust force on blade tips

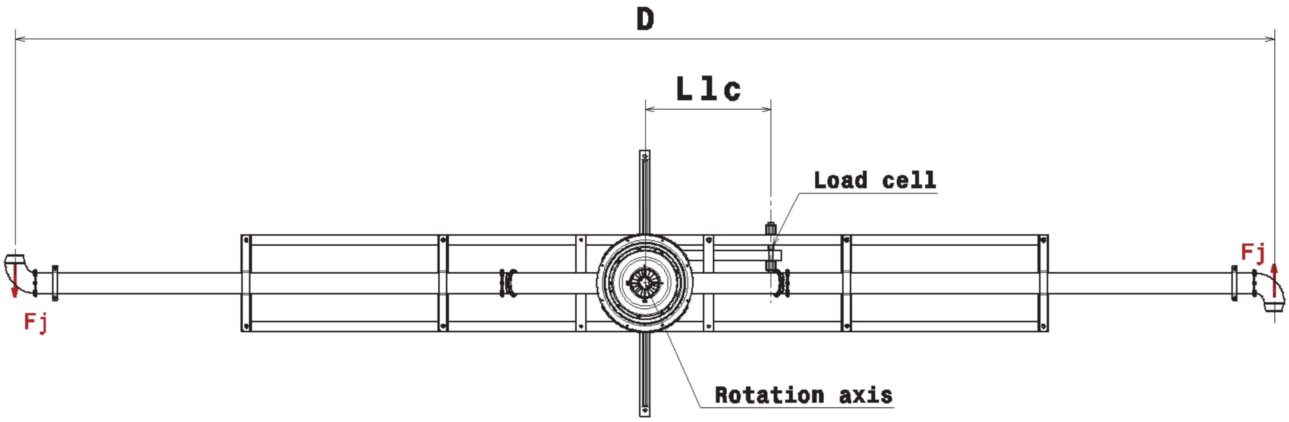

Fig.3. Test stand – load cell position

Test stand is designed to measure thrust force on the blade tips with load cell. Load cell [3] was positioned on L_{lc} distance from rotation axis so it prevents rotation of the system and in the same way indirectly measure the force on the blade tip nozzle (Fig.3.). F_j (thrust force) is calculated:

$$F_j = F_{lc} \cdot \frac{L_{lc}}{D} \tag{7}$$

Where F_{lc} is force measured on load cell, L_{lc} is distance from load cell to rotation axis and D is distance between nozzles on two blades.
We used OMEGA LCHD-2K load cell [4] with capacity of 2Klb (909kg).
For the pressure measurement [5], a pressure transducer PX602-150GV, produced by OMEGA, is used. Since the working temperatures of these sensors are low for measuring the total pressure in the nozzle, where the gas has considerably higher temperature, a special installation was introduced. It consists of a probe for total pressure with a corresponding extension for lowering the gas temperature.
The temperature was measured on one spot inside the nozzle with a K-type thermo couple CH+ AL-, produced by OMEGA

3. EXPERIMENTAL RESULTS

Tables test was conducted on actual blades that had nozzle area of 2300mm^2. Blades with same nozzle area were used on previous hovering test. On that hovering test we managed to lift 210[kg]. Engine rpm, bearing temperature and pump PWM were also measured, with acquisition system that was designed for static test of the engine.

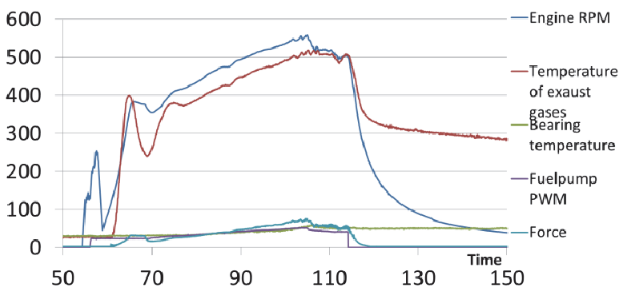

Fig.4. Acquisition system data of one of the tests (nozzle area 2300mm2)

Second test was conducted on cylindrical pipes with inner diameter D_{in}=76mm. Nozzle area was little smaller than on the actual blades – 2200mm^2. We used same acquisition system as on the first test.
Third test was conducted on cylindrical pipes with inner diameter D_{in}=70mm. Nozzle area was also 2200mm^2. The purpose of the test was to see how the reduction of inner flow area affect tip-jet ejection performances.
Fourth test was conducted on cylindrical pipes with inner diameter D_{in}=70mm but without flexible pies. The purpose of this test was to verify loses caused by flexible pipes.

Overpressure on the distributor and on the nozzle was also measured and the results can be seen on Fig.5.

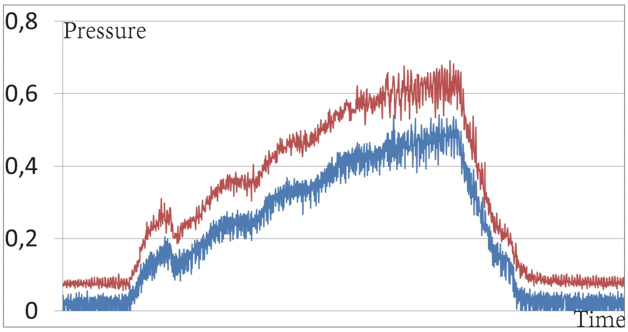

Fig.5. Overpressure on the distributor (red) and on the nozzle (blue)

The last test was with actual blades but with nozzle area of 2000mm^2. All test data could be seen in table 1.

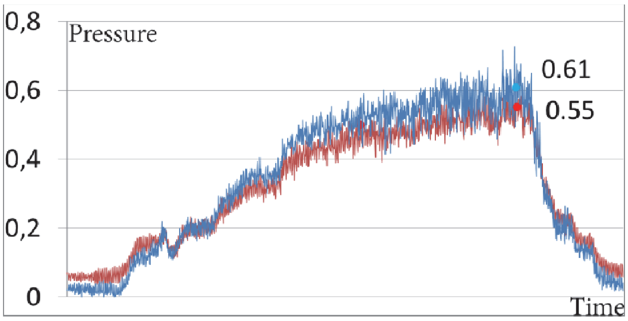

Fig.6. Overpressure on the distributor (red) and on the nozzle (blue) on actual blades

Table 1. Test results data

Test No.	Load cell force F_{lc} [daN]	Load cell position L_{lc} [mm]	Nozzle distance D [mm]	Thrust force F_j [daN]
1.	80	500	4800	8.33
2.	145	500	5000	14.5
3.	155	500	5000	15.5
4.	90	500	2400	18.75
5.	140	500	4800	14.58

4. CONCLUSION

With nozzle area reduction from 2,300 mm2 to 2,000 mm2, the lift force that we managed to increase was more than 25%. If the losses in flow through the flexible pipes stay the same, it is possible to reduce nozzle area a little bit more because exhaust gas temperature is 100[^{0}C] smaller than the critical value. By doing that, the lift power could be increased by additional 5-10%.
Tests with cylindrical pipes both with and without flexi pipes showed that losses in the flexi pipes proved to be 17% (nozzle thrust force with the flexi pipe is 15.5[daN] and without it 18.75 [daN]). This causes a direct reduction of the rotor system power and it can be somewhat mitigated with use of flexi pipes that have better sealing. In that case, the system will be a little bit heavier but it could reduce these losses to less than 10%. This way, an increase of the power of the system by as much as 7% can be achieved.
Tests with cylindrical pipes with different inner diameter proved that it is possible to reduce the area of the channel inside the blades. This allows the use of extruded aluminum blades that have inner Inconel channel for the flow of the hot air. Another possibility is to continue using current all Inconel blades design with reduced chord of the blades.

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