IN-FLIGHT THRUST DETERMINATION BY LOAD MEASUREMENT ON THE ENGINE MOUNTING SYSTEM

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Abstract

In-flight thrust measurement is of much interest as it allows, in principle, to verify the specified engine and propeller performance as well as to quantify the drag of the aircraft.

Classical methods rely on well known techniques to determine propeller thrust in steady straight flight conditions, using data from the engine and propeller manufacturers. For the aircraft manufacturer the disadvantage of having to rely on data from the engine and propeller manufacturers is that any aircraft performance shortfall becomes identical to a larger than predicted airframe drag and consequently the sole responsibility of the airframe manufacturers.

This paper describes an alternative method of the in-flight thrust measurement, which does not require data from engine and propeller manufacturers and consequently would allow an independent assessment of thrust and drag. In principle, the thrust of the propeller is transferred to the airframe through the engine mounting system. By measuring the loads on this engine mounting system, the thrust of the propeller can be obtained.

A flight test program to determine the propeller thrust using small piston-prop PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft of the Department of Aeronautics and Astronautics, Institute of Technology Bandung, has been performed. Eight strain gauges were installed on the structure of engine mounting system of this aircraft. The propeller thrust obtained from the flight test program will be presented and discussed in this paper. Comparison with other test results using other methods to derive propeller thrust will be also given.

1. Introduction

Techniques for the precise measurement of aircraft propeller thrust are of great practical value, as they can be used to verify the specified engine performance and propeller efficiency as well as the quality of the airframe aerodynamics.

A variety of variables can be measured in flight which are related to the actual value of the thrust generated by the installed propulsion unit. However, it is difficult, if not impossible, to measure propeller thrust directly, so thrust is derived indirectly from these measurements by using different kinds of models. A problem is that most of these models contain parameters which are either not (precisely) known or must be provided by the propeller or engine manufacturer.

The approach pursued in this paper towards the measurement of propeller thrust is to measure the load transferred to the airframe through the engine mounting system. In principle, by measuring the loads on this engine mounting system, the thrust of the propeller can be obtained.

The paper starts with reviewing the existing techniques for deducing propeller thrust from flight test measurements. Next, an in-flight determination of propeller thrust through measurement of loads on the engine mounting system will be discussed. Prior to the flight test program, an analysis of the loads on the engine mounting system was carried out using finite element method. This analysis was aimed to determine the optimal numbers and position of the strain gauges to be installed on the engine mounting system.

Results of a flight test program to determine the propeller thrust with a small piston-prop PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft of the Department of Aeronautics and Astronautics, Institute of Technology Bandung, (ITB) are presented in this paper. Comparison with other test results using other methods, i.e. measurements of engine manifold pressure and engine rotational speed and measurement of the increase in total pressure behind the propeller will be also given.

2. In-Flight Determination of Propeller Thrust

Several techniques to deduce propeller thrust from in-flight measurements are discussed in [2]. Figure 1 gives an overview of the different methods to obtain the propeller thrust from flight tests.

In the order of increased reliance on direct measurements and the corresponding decreased use of data provided by engine and propeller manufacturers, the possible methods can briefly characterized as follows:

Engine and propeller models. This method uses engine and propeller models to obtain the propeller thrust. The engine model is expressed in terms of the major engine variables. In the simplest case, the engine model can be entered with one or more engine variables measured during flight tests at specific flight conditions. These variables are, for example, engine throttle position, fuel flow and engine speed. The engine shaft power, P_S, is the outputs of this model.

The functional relationship of the shaft power of the engine with the engine throttle position Γ_e, the engine speed n_e and the flight conditions, i.e. airspeed V and pressure altitude h_p in ISA can be written as follows [5]:

$$P_S = P_S(\Gamma_e, n_e, V, h_p) \quad (1)$$

If measurements of Γ_e, n_e , V, and h_p can be made available, then shaft power of the engine can be obtained. The shaft power can also be determined from measurements of fuel flow and engine speed using the following engine model:

$$P_S = P_S(\dot{m}_f, n_e, V, h_p) \quad (2)$$

For a piston-prop aircraft, the shaft power of the engine can be expressed as a function of the engine manifold pressure p_z, engine speed n_e, and the flight conditions as follows:

$$P_S = P_S(p_z, n_e, V, h_p) \quad (3)$$

The propeller thrust T_p can be obtained next from the estimated engine shaft power, either using equation (1), (2) or (3), using propeller model.

Propeller model. If direct measurement of either engine torque or the propeller blade angle is possible, this torque or propeller blade angle together with engine or propeller speed and air data, can be used to obtain the propeller thrust from the propeller model. This method avoids the inaccuracies involved in using an engine model.

The propeller thrust coefficient C_T, power coefficient C_P, and advance ratio J, are defined as follows:

$$C_T = \frac{T_p}{\rho n_p^2 D_p^4} \; ; \quad C_P = \frac{P_S}{\rho n_p^3 D_p^5} \; ; \quad J = \frac{V}{n_p D_p} \quad (4)$$

where n_p denotes the speed of the propeller in revolutions per second [rps], D_p denotes the diameter of the propeller and ρ is air density.

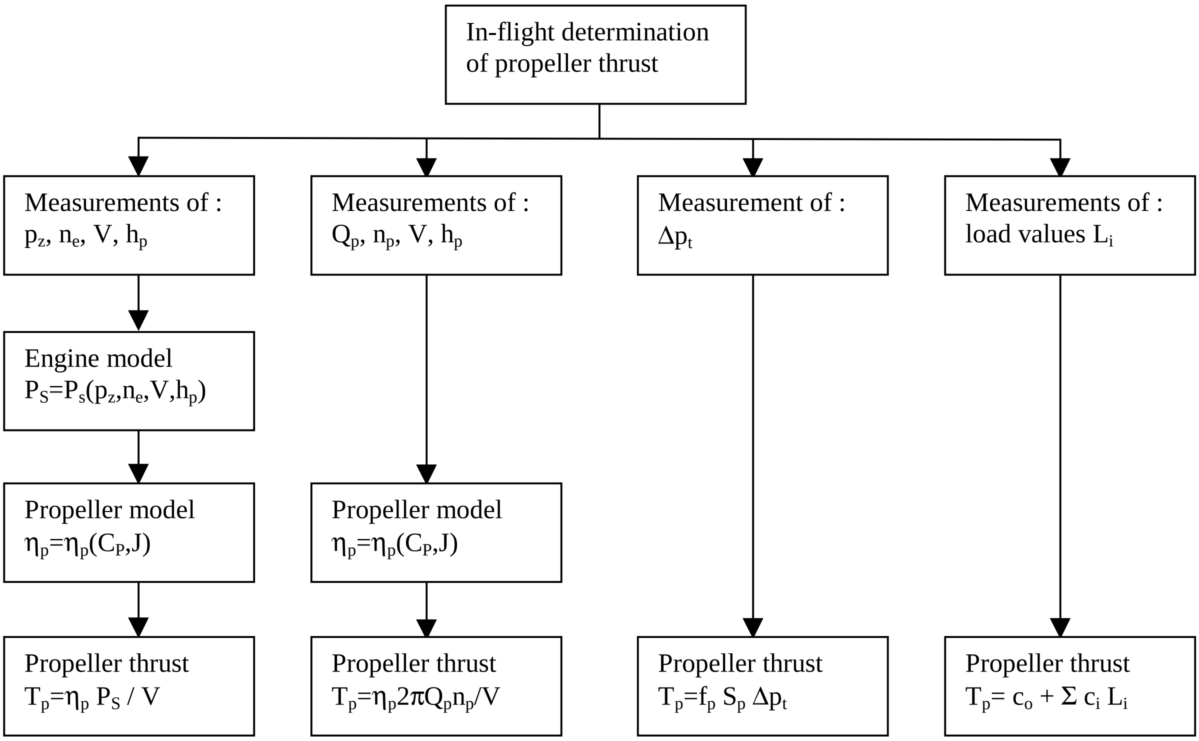

Figure 1 : In-flight determination of propeller thrust

In (quasi) stationary conditions, C_T and C_P depend only on the propeller advance ratio J and the propeller blade angle $\beta_{3/4}$. This leads to the following set of non-linear algebraic relations, expressing mathematical model of propeller [5]:

$$\begin{aligned} C_T &= C_T(J, \beta_{3/4}) \\ C_P &= C_P(J, \beta_{3/4}) \end{aligned} \qquad (5)$$

Another typical form of the propeller model can be derived directly from equation (5). The propeller efficiency η_p, for example, can be derived from the propeller thrust coefficient, power coefficient, and advance ratio as follows:

$$\eta_p = \frac{C_T}{C_P} J \qquad (6)$$

or, it can be written as:

$$\begin{aligned} \eta_p &= \eta_p(C_P, J) \\ \eta_p &= \eta_p(\beta_{3/4}, J) \end{aligned} \qquad (7)$$

A similar expression can be written for the propeller thrust coefficient:

$$\begin{aligned} C_T &= C_T(C_P, J) \\ C_T &= C_T(\beta_{3/4}, J) \end{aligned} \qquad (8)$$

If direct measurements of engine torque or propeller blade angle can be made then it is possible to obtain propeller thrust from the propeller model using equation (7) or (8) and measurements of propeller speed, airspeed and air density.

At constant engine speed, the shaft power of the propeller can be obtained from the following expression:

$$P_S = 2\pi n_p Q_p \qquad (9)$$

where Q_p is the shaft torque of the engine in [Newton-meter]. The propeller speed may be obtained from the measured engine speed, assuming that the gearing ratio of the engine to the propeller is known.

If a graph of the propeller thrust coefficient is available, then its value can be read directly from the graph using C_P and J as inputs. The thrust of the propeller can be obtained from equation (4).

Total pressure measurement behind the propeller. If neither engine model nor propeller data are available, measurements of the increase in total pressure with respect to undisturbed airflow behind the propeller with pitot rakes can be used to obtain propeller thrust [2].

Propeller thrust can be determined from the static pressure difference between two positions just behind and in front the propeller disk as follows:

$$\begin{aligned} T_p &= 2\pi \int (p_{s_2} - p_{s_1})\, r\, dr_p \\ &= 2\pi \int \Delta p_s\, r\, dr_p \end{aligned} \qquad (10)$$

As static pressure measurements are impractical, it makes sense to express equation (10) in terms of total pressure which is more accessible to measurement.

The total pressure jump Δp_t is defined as the difference between the total pressure just behind and the total pressure just in front of the propeller. Since the velocities in these points are the same, Δp_t can be written as:

$$\Delta p_t = p_{t_2} - p_{t_1} = \Delta p_s \qquad (11)$$

Substitution of equation (11) into (10) gives:

$$T_p = 2\pi \int \Delta p_t\, r\, dr_p \qquad (12)$$

An attractive alternative for the measurement of the total pressure distribution behind the propeller with pitot rakes is to measure total pressure at just one or two locations at approximately 75% of the propeller radius [4], [6]. In this case, the effective propeller thrust may be written as:

$$T_p = f_p\, S_p\, \Delta p_t \qquad (13)$$

where S_p is the propeller disk area. The factor f_p in equation (13) is a yet unknown factor depending on the selected location of the pitot tubes, and may be determined from the flight test measurements.

Measurement of loads on the engine mounting system. This direct measurement of propeller thrust requires neither engine nor propeller model. The thrust produced by the propeller is transferred to the airframe through the engine mounting system. In principle, if loads on the engine mounting system can be directly measured, i.e. using strain gauges, then the propeller thrust can be obtained from the following relation:

$$T_p = c_0 + \sum_{i=1}^{m} c_i\, L_i \qquad (14)$$

where m is the total number of strain gauges installed on the engine mounting system, L_i is value measured at each strain gauge, and c_0 and c_i are constant coefficients determined from ground calibration.

This paper will discuss in more detail about the measurement of loads on the engine mounting system to obtain the propeller thrust, in particular the engine mounting system of the PZL-104 Wilga-Nurtanio ‘Gelatik’ laboratory aircraft ITB.

3. In-Flight Measurement of Loads on the Engine Mounting System

As already mentioned above, thrust of propeller can be determined by measuring loads on the engine mounting system. In principle, the loads on the engine mounting system can be measured with strain gauge [1]. To obtain the optimal numbers and position of the strain gauges to be installed on the engine mounting system, a preliminary analysis of the load path on the engine mounting structure were carried out using finite element method. In this way, the magnitude and load gradient at each structural members of the engine mounting can be predicted.

Figure 2 shows the structure of the engine mounting system of the PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft of ITB. This mounting structure is connected to the bulkhead-frame of the airframe through six joints. The engine (Continental O-470-I/R) is placed on this mounting system.

The connection system between the mounting structure and the airframe is shown in Figure 3. Based on the structural characteristics of the engine mounting system, a finite element model was built. This finite element model is also shown in Figure 3.

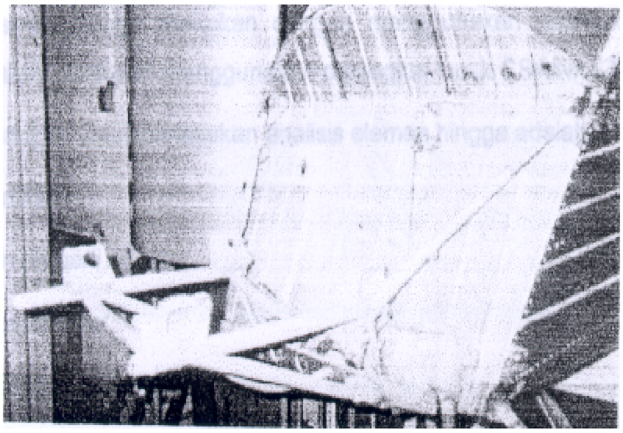

Figure 2: The structure of the engine mounting system of the PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft.

The structural members were modelled as BAR elements. The engine itself was modelled as a rigid body element.

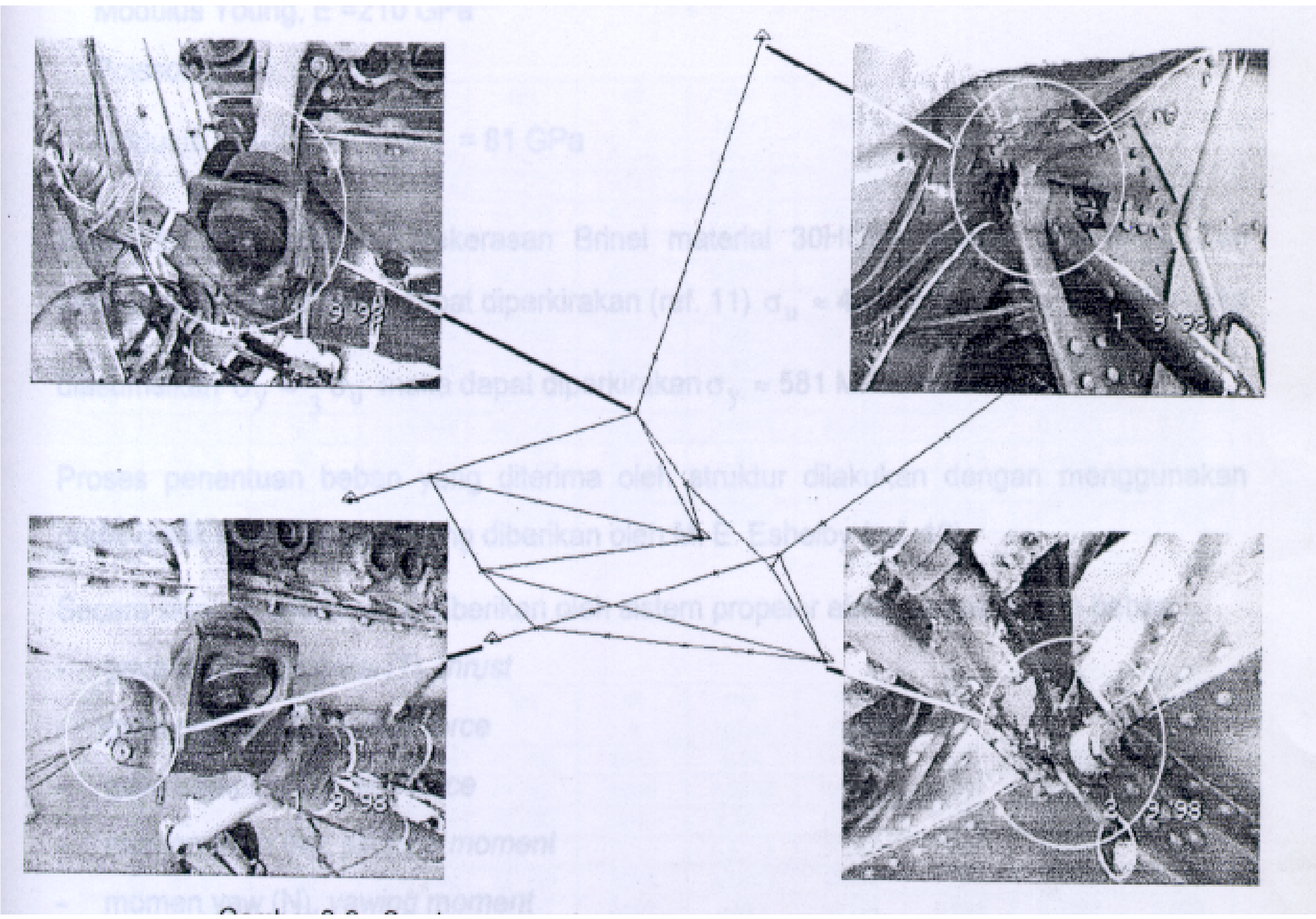

Figure 3: The connection system between the engine mounting system and the airframe of the PZL-104 Wilga-Nurtanio 'Gelatik' and the associated finite element model.

Finite element analysis was performed using CSA/NASTRAN software. Based on the load path analysis of the engine mounting system, it was decided to install eight strain gauges at certain locations as shown in Figure 4.

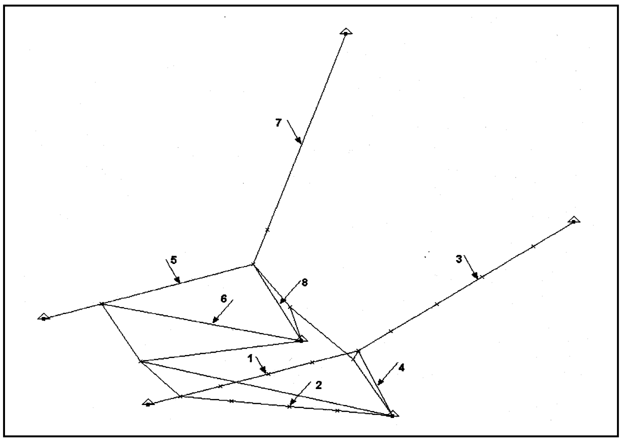

Figure 4: Position of eight strain gauges on the structure of the engine mounting system of the PZL-104 Wilga-Nurtanio 'Gelatik'.

A flight test program with the PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft of ITB was carried out. In addition to eight strain gauges installed on the structure of the engine mounting system as already mentioned above, this laboratory aircraft is also equipped with a flight instrumentation system to measure the airspeed, pressure altitude, Outside Air Temperature, engine rotational speed, and engine manifold pressure. Two pitot tubes were also mounted on the engine nacelle behind the propeller to measure the increase of total pressure behind the propeller.

Prior to the flight test program, a ground calibration to obtain the relation between strain gauge outputs with the thrust load was carried out. Figure 5 gives an example of the ground calibration result of the strain gauge #8.

4. Flight Test Results

The flight tests were carried out with the following configurations: take off weight 1219 kg, center of gravity position at 39% of mean aerodynamic chord, and flaps for cruising and

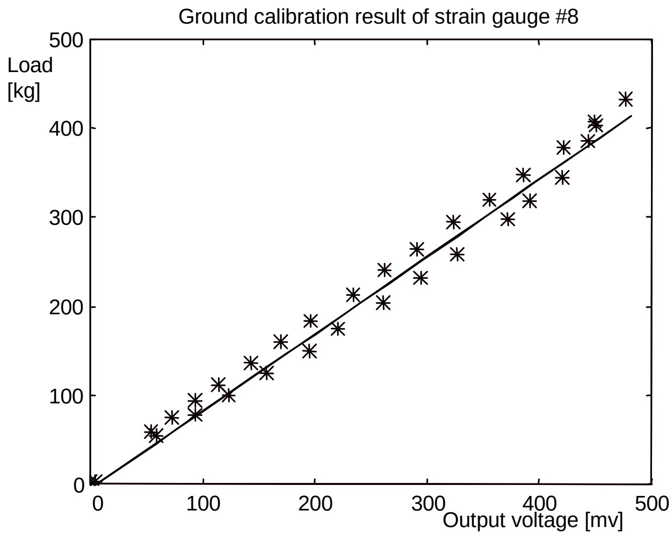

Figure 5: Example of ground calibration result of strain gauge # 8.

landing. The flight conditions during the tests were: altitude at 5000 ft and 7000 ft, speed range for cruise configuration: 50 to 90 KIAS, and speed range for landing configuration: 45 to 75 KIAS. The engine rotational speed during the tests was set constant at 2400 rpm.

The propeller thrust were determined using three different approaches to the measurement of propeller thrust as described in the previous section. Figure 6 shows the test results for cruise configuration at an altitude of 5000 ft. In that figure, the propeller thrust obtained from the measurements of engine manifold pressure and engine rotational speed (denoted by T_{p_chart}) is used as the 'reference', absisca in the figure. The propeller thrust obtained from measurements of loads on the engine mounting system (denoted by o) is compared to this reference [3]. The similar comparison is also made for the propeller thrust determined from measurement of the increase in total pressure behind the propeller at position 75% of the propeller radius (marked by +) [6]. It can be seen that the thrust estimation through engine mounting load measurement and the increase in total pressure behind the propeller are in closed agreement with the propeller thrust derived from measurements of engine manifold pressure and engine rotational speed.

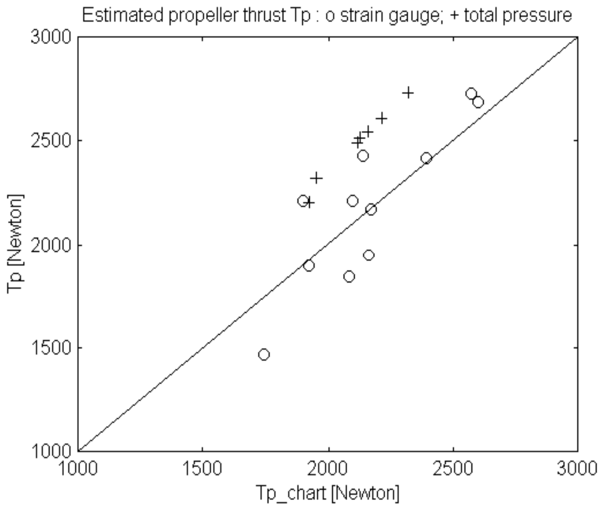

Figure 6: Comparison of the propeller thrust obtained from three different methods.

5. Concluding Remarks

In-flight determination of propeller thrust by measuring the loads on the engine mounting system has been discussed in this paper. Finite element analysis of engine mounting system had been performed and was proved to be important in obtaining the optimal numbers and positions of strain gauges to be installed in the engine mounting. A flight test program with the PZL-104 Wilga-Nurtanio 'Gelatik' laboratory aircraft of ITB had been performed.

The results of the in-flight determination of propeller thrust has been presented and discussed in this paper. From the flight test results, it can be concluded that the propeller thrust obtained from measurement of loads on the engine mounting system was in closed agreement with other test results of propeller thrust derived from measurements of engine manifold pressure and engine rotational speed and measurement of the increase in total pressure behind the propeller using pitot tubes.

6. References

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