Discrepancies in the Measurement of Aircraft and Rotor Power

Summary

The engine output power was measured on both engines during the UH–60A Airloads Program, as well as power to the main rotor and the tail rotor. The difference between the engine output power and the combined main and tail rotor power should reflect the requirements for aircraft systems power and instrumentation power, plus small gearbox losses. This small difference should be largely independent of flight condition. However, contrary to expectation, power balance comparisons made for six airspeed sweeps at constant weight coefficients have determined that the power difference is different for each airspeed sweep. Moreover, for the most highly loaded conditions, the power difference is negative which is not physically possible. Thus, there is an uncorrected measurement error in one or more of the power measurements. The power difference was correlated with a number of flight parameters and it was observed that most of the variation is explained by outside air temperature (OAT). No causal explanation is available for the dependency of the measurement error on temperature at this time.

Discussion

Torque measurements were obtained at five points in the UH–60A aircraft drive train during the UH–60A Airloads Program. Together, these measurements are used to determine the aircraft power required. The five measurements are the output shaft torque on each of the two engines (Item Codes EQ01 and EQ02), the main rotor torque (Item Code RQ10), and duplicate measurements of the tail rotor intermediate drive shaft torque (RQ20 and RQ21).

The torque measurement device on the engine output shaft was installed and calibrated by the engine manufacturer. A table was provided with this calibration to enable the calculation of torque corrections that were functions of the output shaft speed and torque level. For the vast majority of flight conditions, this torque correction was slight and represented less than 1% of measured engine output shaft torque. These corrections were applied for all of the data in the TRENDS data base. The main rotor torque was measured with a standard strain-gauge bridge installed on the rotor drive shaft. The calibration was performed by Sikorsky Aircraft in a special test rig. Tail rotor torque was not measured at the tail rotor but instead was measured on the tail rotor drive shaft just prior to the intermediate gearbox. Thus, tail rotor torque was based on the gear box ratios and efficiencies for the intermediate and 90 deg. gearboxes

$$Q_{TR} = Q_{DS}\, R_{IN}\, \eta_{IN}$$

where Q_{TR} is the calculated tail rotor torque, Q_{DS} is the measured intermediate drive shaft torque, R_{IN} is the gear ratio between the intermediate drive shaft and the tail rotor (4.6136), and η_{IN} is the combined efficiencies of the intermediate and 90 deg. gearboxes (0.988). Two measurements of the intermediate drive shaft torque were obtained, both from conventional strain-gauge bridges. The values used for the gear ratios and efficiencies are from Nagata et al. (1981).

Airspeed sweeps were flown for six weight coefficients on Flights 84–90 with C_W/σ values ranging from 0.08 to 0.13. Based on the torque measurements obtained for these sweeps it is possible to calculate a power balance for the aircraft, that is,

$$SHP_c = \eta_1\, SHP_{MR} + \eta_2\, SHP_{TR} + \eta_3\, SHP_{acc} + \eta_3\, SHP_{R/A}$$

where SHP_c is the combined output power from the two engines, SHP_{MR} is the main rotor power, SHP_{TR} is the tail rotor power, SHP_{acc} is the accessory power required for the normal aircraft electrical systems, and $SHP_{R/A}$ is the power required for the NASA-installed RDAS and ADAS data acquisition systems. Nagata et al. (1981) reported that the accessory power for normal daytime operation was 13 HP. Measurement of the RDAS and ADAS system power during the Airloads Program indicated that approximately 2.67 HP was required (Dan Loney, pers. comm.). The values of the various gearbox efficiencies, η_i , are not currently included in the aircraft documentation, but probably exceed 0.98 or 0.99. Ignoring the gearbox efficiencies and the accessory and instrumentation powers, this power balance can be constructed graphically, as shown in Figure 1 for the case of $C_W/\sigma = 0.08$. As is seen, most of the power required is for the main rotor with only a small portion required for the tail rotor.

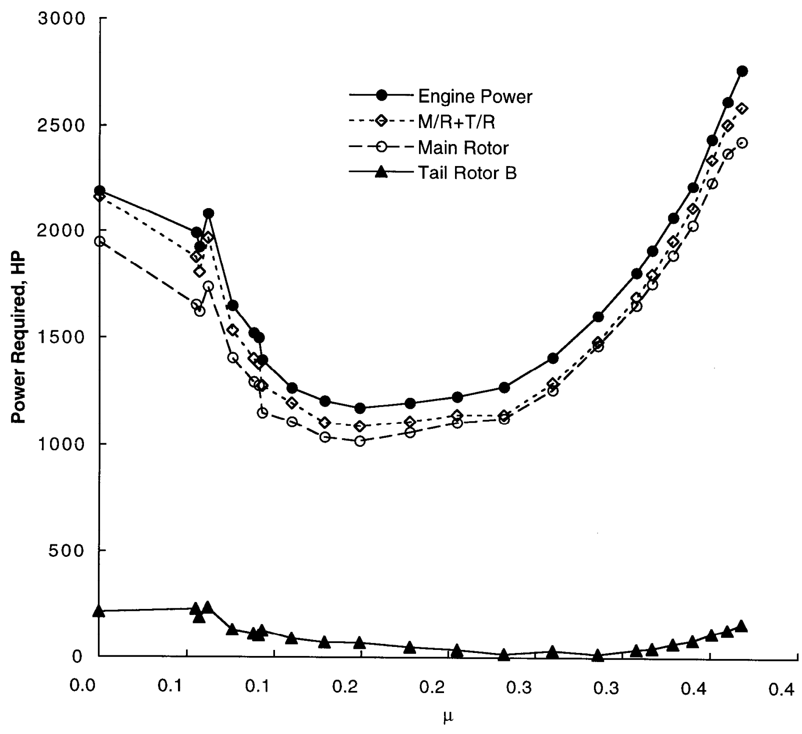

Figure 1. UH–60A power balance, $C_W/\sigma = 0.08$.

From Figure 1 it can be seen that the engine power is greater than the combined main and tail rotor powers, as is expected. However, because of the variation of power over the range of advance ratios it is difficult to determine how consistent the power difference is. A better way of comparing these two powers is to plot the main and tail rotor powers as a function

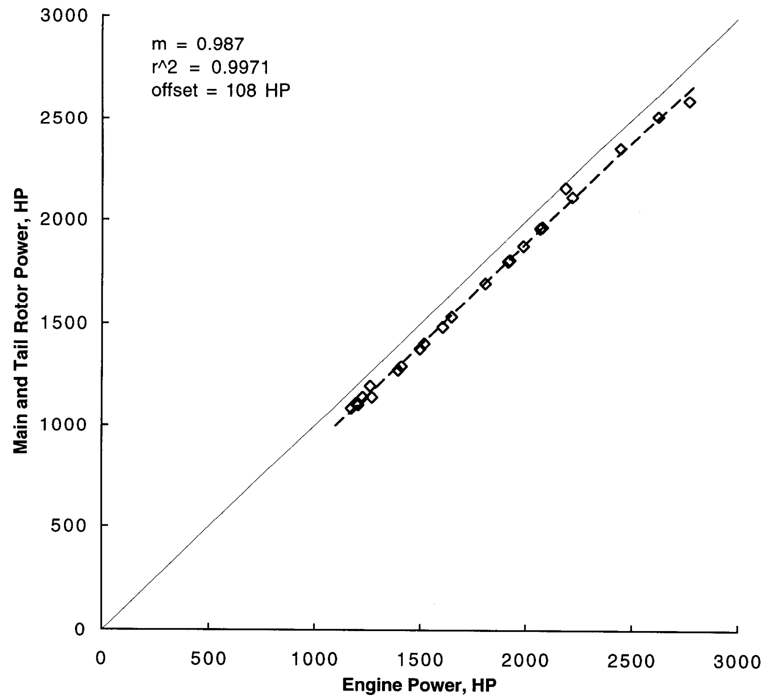

Figure 2. UH–60A power correlation, $C_W/\sigma = 0.08$.

of the combined engine power as shown in Figure 2. The two power terms are well correlated and the coefficient of determination is 0.9971. The slope between the two sets of power is slightly less than 1.0. There is an offset between the two powers and, in this case, it is about 108 HP. This offset is largely independent of power level or airspeed and is quite a bit higher than the estimated values of accessory and instrumentation power that were discussed above.

The power balance data from the five other airspeed sweeps are similar to what is shown in Figures 1 and 2, with the exception that the power difference between the engine power and the combined main and tail rotor powers is different for each case. These differences in power or power losses are shown in Figure 3 as a function of advance ratio. Considerable scatter is seen in the data which may be related to small errors in the measured engine power, measured main rotor power, or both. What is surprising, however, is that the mean difference for each airspeed sweep is different and, for $C_W/\sigma = 0.12$ and 0.13, the mean difference is negative, which is physically impossible. Thus, this comparison indicates that there are significant errors in the measurement of the engine output torques, the main rotor torque, or both.

The engine output torque measurements obtained on the two engines show excellent agreement for all of the airspeed sweeps. The correlation between the two measurements is 0.9984 and the slope of the correlation curve is 0.993, where perfect agreement would give a slope of 1.000. There is a slight offset in power with Engine 1 providing about 18 HP more than Engine 2. The good agreement that is observed suggests that the power discrepancy is not caused by a single erroneous measurement on one of the engines. Rather, if the source of the power discrepancy is the engine output power calibration, than the problem occurs on both engines.

Duplicate torque measurements were obtained for the tail rotor power and these also show good agreement for the six airspeed sweeps. The two measured torques show a

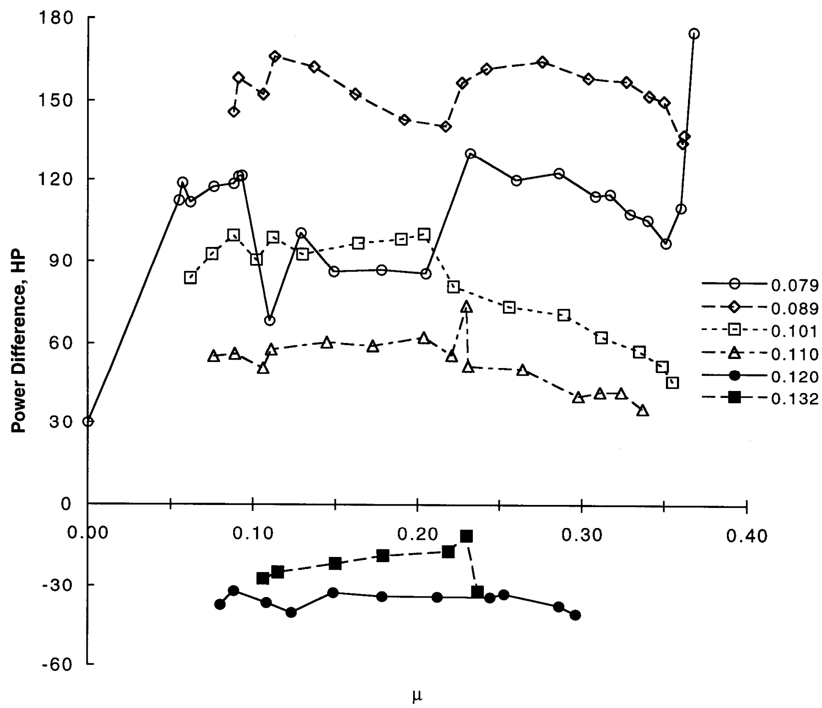

Figure 3. Difference between engine output shaft power and combined main and tail rotor powers.

correlation coefficient of 0.9955, and the slope of the correlation curve is 0.965. The B measurement is used in the power balance calculations shown here, but it is clear that potential errors in this measurement are not the cause of the difference in power that is observed in Figure 3. The tail rotor power changes significantly from low advance ratios where it is in excess of 200 HP to moderate advance ratios such as 0.25 and 0.30, where it is less than 50 HP, and this kind of variation is not seen in the data in Figure 3.

The measured differences shown in Figure 3 were compared to a number of independent variables including advance ratio, density ratio, outside air temperature, pitch attitude, main rotor power, and engine power. The differences are largely uncorrelated with the exception of the density ratio ($r^2 = 0.48$) and outside air temperature ($r^2 = 0.79$). The correlation between the power difference and the outside air temperature is shown in Figure 4. This correlation indicates that most of the variation in the power difference can be largely explained by the change in outside air temperature. However, there is no causal explanation for the effect of temperature.

The engine output shaft torque calibration was obtained from the engine manufacturer (Nagata et al. 1981) and has been used previously for power measurements on this aircraft. However, no documentation is currently available that describes in detail how the output torque is measured or how the calibration was obtained. In this sense, this calibration is not traceable.

The main rotor torque measurements were obtained from a conventional strain-gauge bridge mounted on the main rotor shaft. For calibration, the rotor shaft was removed from the aircraft and shipped to Sikorsky Aircraft who performed the calibration on special-purpose test rig. No attempt was made during the calibration to control temperature as it is well established that strain-gauge bridges are not sensitive to temperature changes if the individual gauges in the

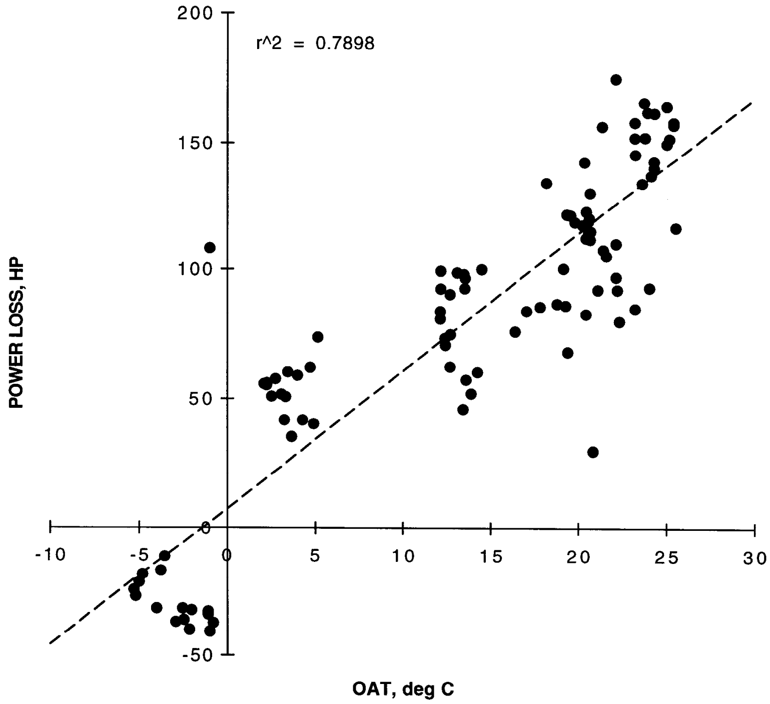

Figure 4. Correlation of power difference with outside air temperature for all airspeed sweeps

bridge are all at the same temperature. Calibration records are retained in the UH–60A Airloads Program files.

Reference

John I. Nagata, Robert D. Robbins, Gary L. Skinner, Robert A. Williams, and Robert M. Buckanin, "Airworthiness and Flight Characteristics Evaluation UH-60A (Black Hawk) Helicopter," USAAEFA Project No. 77-17, September 1981.

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