Correlating rotor RPM on the Rotorway 162F helicopter

Introduction

Procedure for correlating main rotor and tail rotor RPM on the Rotorway 162F helicopter with the ATOM micro-controller, implementation of a low rotor RPM warning horn, and consideration of a digitally controlled throttle governor.

Explanation

The Rotorway Executive 162F is an experimental class 2-seat helicopter available in kit form (www.rotorway.com). One design decision made by the developers years ago was to use V-belts for the tail rotor drive system as opposed to the more common drive shaft and gearbox combination. The advantage of belts over shafts and gearboxes is mainly weight and complexity.

A system of three V-belts, each with a 33-degree twist, with intermediary pulleys, couples the vertical drive shaft to the horizontal tail rotor shaft. A pair of bolts at the aft end of the tail-boom serve to tension all the belts in unison.

Early models of the Rotorway Exec helicopter suffered from frequent belt stretching requiring vigilance on the part of the pilot to frequently check and adjust the belt tension.

If the tail rotor belts were to slip in flight, the pilot may be unable to apply adequate anti-torque, which can render the aircraft uncontrollable.

The factory now specifies Kevlar tail rotor drive belts that all but obviate the belt stretch issue. The pilot must still be vigilant, but the Kevlar belts stretch at a much slower rate, and it is highly unlikely that they will stretch enough between pre-flight checks to cause a hazard, and can go many flight hours without requiring any belt tensioning.

Objective:

A system utilizing an on-board micro-controller, to measure both the main rotor and tail rotor RPM, correlate the two measurements and hopefully provide an early warning of belt slippage.

When the main rotor is at 520 RPM, the tail rotor RPM should be at 2600 RPM. The main rotor RPM is variable but it is presumed that the tail rotor RPM will track closely and always remain at 5 times the main rotor RPM. Any divergence from direct correlation (within a tolerance band to be determined) indicates tail rotor drive belt slip. This condition is hazardous and should be avoided.

Once both the RPM measurements are captured with the micro-controller, some binary math is performed to determine if the tail rotor RPM is 5 times that of the main rotor RPM, within acceptable tolerance.

To sense the rotation of the main rotor shaft there is a “magnet bracelet”, which is attached to the main rotor shaft and a Hall effect magnetic sensor, mounted in close proximity to the magnet bracelet. The magnet bracelet is basically a stainless steel hose-clamp with 4 magnets attached at equi-distant intervals. The Hall effect sensor provides the signal to the stock analog tachometer. A second Hall Effect sensor will sense the same magnet bracelet and provide a separate and redundant signal for this application.

As the main rotor shaft turns, the Hall effect switch provides a brief low pulse while each of the magnets are adjacent to the Hall Effect switch. The signal then returns high and goes low again when the next magnet is adjacent to the sensor.

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Main rotor RPM measurement:

Main rotor RPM at 100% is 520RPM. This is equal to 8.67 revs per second (520 divided by 60), or 115.3 milliseconds (mS) per rev (1 divided by 8.67), or 115,340 microseconds (uS) per rev. Time-between-magnets (TBM) is then defined as 115,340uS divided by the number of magnets. In this case, 115,340uS divided by four = 28,835uS.

This TBM signal from the Hall Effect sensor is comprised of a low pulse while the magnet is adjacent to the sensor, and a high pulse for the remainder of the TBM interval. This cycle is repeated four times for each revolution of the main rotor shaft.

In order for the ATOM to accurately count the duration of a single TBM event with the PULSIN command, it would have to measure this low portion of the interval, and then quickly switch context and count the duration of the high remainder of the interval.

A 74HCT74 flip-flop circuit is implemented on the embedded computer main board to provide a single positive pulse spanning the leading edges of two consecutive magnets. In other words, it combines both the high and low portions of the TBM interval into a single high pulse, making the measurement faster, easier and more accurate.

The ATOM micro-controller **PULSIN** measures the duration of a pulse in 1uS increments, with a maximum of 65,535 counts. The TBM event lasting 28,835uS will accrue 28,835 counts.

Tail rotor RPM measurement:

Tail rotor RPM at 100% is 2600RPM. This is equal to 43.33 revs per second, or 23.07mS per rev, or 23,077uS per rev. With two magnets on the tail rotor shaft, 2 pulses occur every revolution. This means that time between magnets (TBM) at 2600 RPM is **11,538uS**. The TBM event lasting 11,538uS will accrue 11,538 counts.

Main rotor RPM calculation:

Taking into account the inverse relationship between RPM and time, a single constant can be found with which to convert the measured TBM to the corresponding RPM.

With 4 magnets on the main rotor shaft, the RPM is determined by the following means:

MR_RPM = 14,994,200 / TBM — where TBM = time between magnets in uS, given directly from ATOM measurement. The constant n, 14,994,200 was derived by the following formula:

$$520 = \frac{n}{28{,}835}$$

where 520 is main rotor RPM at 100%, 28,835 is the time between each of magnets at 520RPM.

Therefore n = 14,994,200

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Code Example.

```
TBM = 0                          'initialize variable
PULSIN P10,1,TBM                 'count duration of positive pulse on P10
MR_RPM = 14,994,200 / TBM        'entire measurement & calc takes 340uS
```

Result:
MR_RPM = 14,944,200 / 28835 = 520 (32-bit integer math is used for rapidity.

This value is an accurate RPM count and can be displayed as-is.

Tail rotor RPM calculation:
With 2 magnets the tail rotor shaft, RPM is determined by the following means:

TR_RPM = 29,998,800 / TBM — where TBM = time between magnets in uS, is given directly from ATOM measurement. The constant 29,998,800 was derived by the following formula:

$$2600 = \frac{n}{11{,}538}$$

where 2600 is tail rotor RPM at 100%,
11,538 is time between each of 2 tail rotor magnets at 2600RPM.

Therefore n = 29,998,800

Ex. TR_RPM = 29,998,800 / 11538 = 2600

To determine correlation, it is not necessary to display tail rotor RPM measurement directly, so in order to save computational time arriving at the subsequent correlation determination, the tail rotor RPM can be measured in terms of main rotor RPM. Do this by modifying the constant to provide a result relative to the Main Rotor RPM:

TR_RPM_OVER5 = 5,999,760 / TBM — where TBM = time between magnets in uS, is given directly from ATOM measurement. The constant 5,999,760 was derived by the following formula:

$$520 = \frac{n}{11{,}538}$$

where 520 is main rotor RPM at 100%,
11,538 is time between two tail rotor magnets at 2600RPM.

Therefore n = 5,999,760

Ex. TR_RPM_OVER5 = 5,999,760 / 11538 = 520

Rotor RPM correlation:

This result, although an erroneous tail rotor RPM value, is proportional to the main rotor RPM. RPM correlation between the main rotor and tail rotor, within a specific band, can be arrived at very rapidly by truncating the two or three least significant bits of both measurements with a fast binary 'AND' operation, and executing an equality test.

Ex. **X = MR_RPM AND $fffd** **'truncate 2 LSB's from MR_RPM**
Y = TR_RPM_OVER5 AND $fffd **'truncate 2 LSB's from TR_RPM**

Perform an equality test between the two.

Ex. **If X <> Y then … 'belt slip indicated if not equal**

This procedure is an efficient means of correlating the Tail Rotor RPM and Main Rotor RPM, and might possibly be accurate enough to measure dynamic belt stretch.

Preliminary tests indicate that the RPM measurements and correlation calculations can be executed in approximately 1mS, which should allow plenty of time for a main loop to execute and perform other measurements and housekeeping.

Background:

The PULSIN command uses a 16-bit register to accumulate 1uS internal counts. The function returns a zero if the TBM count overflows the 16-bit register, or if there is no activity during the 65,535uS in which the PULSIN command is active.

RPM is an inverse function of time. This means that as the RPM increases, the time between magnets becomes shorter and the smaller the TBM count. As the main rotor RPM increases, there comes a point at which the TBM is 65,535 which is the **largest number** the PULSIN command can accommodate.

With the maximum 16-bit count, and four magnets on the main rotor shaft, this 65,535 count would resolve to a minimum main rotor RPM of approximately 229 RPM.

Ex. 14,994,200 / 65,535 = 229 RPM

Theoretically, the maximum main rotor RPM that can be represented would be 14,994,200 RPM.

Ex. 14,994,200 / 1 = 14,994,200 RPM

In the case of the tail rotor with two magnets, the minimum resolvable RPM is approximately 463 RPM. At a tail rotor speed of 2340 RPM (2600 – 10%), the TBM is 12,820 counts. At a tail rotor speed of 2860 RPM (2600 + 10%), the TBM is 10,489 counts. Both of these values are well within the range of the PULSIN command to measure with more than adequate resolution.

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Implementation of a low rotor RPM horn:
The main rotor of a helicopter must maintain a nominal 100% RPM for proper and safe flight. In a typical turbine engine helicopter this is done automatically and requires little, if any, intervention by the pilot.

In a typical piston-powered helicopter, the pilot must manage the throttle, which is controlled with the left hand, much like a motorcycle throttle, under varying load conditions, to maintain a nominal 100% rotor RPM.

If the rotor RPM gets too low, also called under-speed, the blades cannot produce enough lift for the helicopter to fly efficiently, and the tail rotor cannot produce adequate anti-torque.

If the rotor RPM gets too high, also called over-speed, damage to the rotor hub and associated components can occur from excessive centrifugal forces.

All helicopters have a rotor tachometer that indicates rotor RPM at all times. As a redundant safety item, some helicopters have a “horn” of sufficient audible intensity to warn the pilot of under and over-speed conditions.

Once the main rotor RPM is determined from the methods described above, it is a relatively simple matter to sound an audible alarm any time the rotor RPM falls within certain critical RPM bands.

Realistically, the main rotor RPM range we are interested in is 520 RPM +/- 10% (approximately), ranging between 468 to 572 RPM. The TBM for these two boundaries are 32,051 and 26,244 counts (or microseconds) respectively. Both of these values are well within the range of the PULSIN command to measure with more than adequate resolution.

While the main rotor is not turning, and during spool-up the TBM count returned from the PULSIN command will return a zero count until the rotor speed reaches about 229 RPM. Any rotor speed below 350 or so can probably be regarded as spool-up or spool-down, and so can be disregarded by the rotor RPM horn algorithm.

Any time the rotor speed is between 350 and 468 it should be considered either dangerously low or a spool-up/down cycle. Either way the low rotor RPM horn should sound an alarm during this interval. In the former case the alarm will warn the pilot, precisely as it is intended to do. In the latter case, then the brief alarm during spool-up/down will assure the pilot prior to every lift-off and during every spool down that the alarm is functional.

The RPM band between 468 and 572 can be considered normal operating range, and the software can branch around the alarm routine.

Rotor speed above 572 is over-speeding the rotor and the rotor RPM horn should also sound an alarm to alert pilot of possible damage to the rotor system.

A digitally controlled throttle governor:
A feature of turbine powered helicopters is the FADEC (Fully Automated Digital Engine Control) control system. This system maintains 100% main rotor RPM automatically as a function of turbine engine control, which relieves the pilot of this burden. Once the turbine is spooled up to operating speed and the FADEC is engaged, the pilot can ignore Main rotor RPM.

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Some small piston-powered helicopters offer what is called a governor, which serves a similar function. The governor maintains 100% main rotor RPM by physically twisting the throttle linkage slightly, in response to changes in main rotor RPM imposed by varying load conditions.

At least one, and possibly the only input required for such a governor is main rotor RPM. As rotor RPM decays or increases slightly in response to varying load conditions, the ATOM micro-controller, which can easily monitor rotor RPM, as demonstrated above, could then control a servo motor mechanism which would then tweak the throttle control to dynamically adjust throttle.

Some control loop theory would need to be implemented to tune the system, and manual over-ride ability would need to be incorporated to rapidly arrest any in-flight governor mal-function. The main rotor cannot change RPM very rapidly due to Newton's 1st law: an object in motion tends to stay in motion, etc. Although the pilot would need to respond quickly, a governor malfunction could be intercepted.

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About This AppNote

Author : J. Mark Wolf

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