Analysis of a Contra-Rotating Propeller Driven Transport Aircraft

J. S. Vanderover* and K. D. Visser†
Clarkson University, Potsdam, New York, 13699-5725

The impact of a contra-rotating propulsion system on a medium sized passenger aircraft was examined numerically using Advanced Aircraft Analysis (AAA) software. A baseline model of a next generation Boeing 737-800 was first created with information from The Boeing Company. Contra-rotating propeller, or CRP, data was collected through a literature study, including information on fuel burn savings, weight penalties, noise radiation, and propeller efficiency of the CRP. The propulsion information of the 737-800 was then replaced with data representing a contra-rotating propeller system. The results indicated a 6000 lb reduction in the required fuel which represents a 17% reduction in fuel burn, for a 2000 nautical mile (nm) flight. It was observed that the optimum use for the CRP propulsion system is short range flights of around 2000 nm or less however, the fuel savings was also seen to increase at higher ranges as well. For a 3000 nm range case, 4000 lbs, or 9% fuel burn savings, was determined. At 6000 nm, the fuel burn savings increase to 22000 lbs or 13%. The literary study of historical CRP data was used to verify the accuracy of these results.

I. Background

CONTRA-ROTATING propellers have been studied for over 60 years as a more fuel efficient method of aircraft propulsion. A CRP consists of 2 sets of propeller blades, one directly behind the other in the axial direction, spinning in opposite directions as shown in Figure 1. Counter-rotating propellers spin in opposite directions, but are located on opposite sides of the fuselage. In order to illustrate the difference between contra-rotation and counter-rotation, Figure 2 has been included.

---

* Under Graduate Senior, Department of Mechanical and Aeronautical Engineering. Student Member AIAA
† Associate Professor, Department of Mechanical and Aeronautical Engineering. Senior Member AIAA

American Institute of Aeronautics and Astronautics
The fundamental premise behind CRPs is the elimination of the tangential velocity, which is considered to be a loss in performance and efficiency. Contra-rotating propellers can significantly reduce or even eliminate the tangential velocity of the propelled air, or swirl losses\(^2\), and also the torque produced by the engine. This leads to a more efficient and economical engine and less torsional loading on the wings.

The concept of contra-rotating propellers has been around since the 1930s. Benson\(^4\) and Betz\(^5\) wrote two of the first papers which examined the possibility of creating a contra-rotating propeller. Biermann and Gray\(^6\) conducted wind tunnel tests onto a model CRP which resulted in an 8 to 16% increase in the propeller efficiency depending on installation position. More Recently, Davenport, Colehour, and Sokhey\(^7\) showed a 6% increase in propeller efficiency at a 35% high power loading. This efficiency is shown in Figure 3 for both calculations and a test run Davenport et al. Citing Roskam\(^17\), 85% is a typical value for propeller efficiency, which substantiates the 6% efficiency increase over a single-rotation propeller.

The NASA-sponsored Advanced Prop-Fan Engine Technology (APET) Definition Study\(^8\) compared the benefits of using a single-rotating (SR) prop-fan over a turbofan. This study determined that an SRP calculated to a 21% fuel burn drop compared to the turbofan. Additionally, another NASA sponsored study\(^9\) showed a CR prop-fan to reduce fuel burn by 9% over the SR prop-fan. These two studies also showed a direct operating cost reduction of 10% for an SRP and another 3% improvement for a CRP. Jeracki and Mitchell\(^10\) show the variation of fuel burn savings with changes in both range and speed. Figure 4 shows the ascertained relationship. During the climb and descent dominated section, lower operating speeds cause a higher fuel burn savings over turbofan powered aircraft.

The most problematic issue with contra-rotating propellers is the noise radiation produced. According to recent articles the noise produced by a CRP is very similar to single-rotating propellers (SRP) through the first harmonic.\(^11,12\) However, contrary to SRP trends, CRPs increase in noise level through the second harmonic and is often louder in the third than in the first. Harmonics of the fourth level and higher are not emitted in measurable levels by the SRP but the first few harmonics above the fourth harmonic still contain a detectable decibel level given off from the CRP. Figure 5\(^11\) presents the Average Sound Pressure Level, or SPL, noise radiation pattern of a contra-rotating propeller through the first 4 harmonics. The Overall Sounds Pressure Level, or OASPL, noise radiation patterns for the SRP and CRP are displayed in Figure 6.\(^11\) The noise radiation patterns show the SRP noise radiation decreases with distance, while the CRP produces alternating high and low bands of noise, most likely caused by blade interaction.

A comparison of the average sound pressure level of a CRP versus that of an SRP is presented in Figure 7.\(^12\) Both Figures 5 and 7 illustrate the increased noise level in the second and third harmonics from the first harmonic. The second harmonics appears to show the largest noise level increase by as much as 20 dB.

Also, it is important to note the noise radiation patterns vary significantly between the SRP and CRP\(^11\). The CRP tends to expel alternating band of high dB and low dBs in the tangential direction while the SRP tends to reduce sound level with distance elliptically. These alternating bands produced by the CRP are due to the propeller blades passing one another. However, while the tangential direction experiences these periodic bands, the axial direction exhibits a more consistent, but still higher noise level. Ultimately, the axial direction suffers as much as a 30 dB higher noise level, while the tangential direction doesn’t exceed much more than 10 dB.
One potential solution to the noise, that has been mildly examined, is a different number of propeller blades between the forward and aft propellers. This would cause the each blade to pass by another blade on the other propeller at separate times versus all at once if there is the same number of propellers. Block, Klatte, and Druez tested a 5x6 bladed CRP, meaning 5 blades on the forward propeller and 6 on the aft. It was determined that the noise generated by the CRP can be divided up into noise from each propeller and interaction tones.

Figure 5. Noise radiation patterns of a contra-rotating propeller (CRP) through the first four harmonics. (Ref 11)

Figure 6. Axial patterns for both (a) the SRP and (b) the CRP. (Ref 11)
Figure 7. Sound Pressure Level for both an SRP and a CRP with varying number of blades in the (1) axial direction (30 deg) and (2) in the tangential direction (100 deg). (Ref 12)
Heinig, Kennepohl, and Traub\textsuperscript{14} also examined this by comparing an 11x13, a 13x11, and a 12x12 CR propfan. It was found that there was no significance decrease in noise levels between the three setups. However, a 2x3 or a 3x5 might produce different results due to a larger percentage change between the number of propellers.

Other potential costs that could be incurred by using CRP over an SRP are higher acquisition costs, higher maintenance costs, and also a slight weight increase. Table 1 shows the percentage increase of these aspects. Also noted by Strack, etal,\textsuperscript{13} is for a 100 passenger aircraft, the Operational Empty Weight (OEW) should increase by around .37% between a SRP driven and a CRP driven aircraft.

Use of a Counter-Rotating Integrated Shrouded Prop-fan, or CRISP, can help reduce these noise levels. The shrouding and several controllable characteristics such as: tip speed, blade number, axial propeller spacing, and blade sweep can have a considerable impact on cabin noise. A well-designed contra-rotating propeller fitted for a 150-passenger aircraft should meet or exceed the ICAO Annex 16 noise limits.\textsuperscript{14}

One factor which was once a showstopper but is now diminishing in importance is gearbox complexity. The gearbox in a CRP can be required to withstand, depending on the setup, up to a 3 times higher power loading at 60% higher shaft speeds\textsuperscript{3}. When attempts to implement CRPs were first done, the gearboxes couldn’t stand up to the required loads. However, with ways of splitting the required load, using more advanced lubricants, and also strong materials, technology has eliminated issues with gearbox durability. A review of aircraft to date that have employed the use of contra-rotating propellers will show the progression with gearbox durability and will be presented in the next section.

<table>
<thead>
<tr>
<th>Table 1. Comparison of SR and CR Propellers. (Ref 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRP</strong></td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Acquisition Cost</td>
</tr>
<tr>
<td>Maintenance Cost</td>
</tr>
<tr>
<td>Shaft Hp/D\textsuperscript{2}</td>
</tr>
</tbody>
</table>

The following is for a 100 Passenger aircraft traveling at M = 0.8 at 35,000 with a 1300nm range

| Operational Empty Weight (lb) | 55756 | + .37% |
| Takeoff Weight (lb) | 75666 | - .65% |
| Shaft Hp | 1.120 | - 2.1% |
| Block Fuel (lb) | 3373 | - 8.1% |
| V\textsubscript{TP} (ft/s) | 800 | 750 |

**Figure 8.** Example of a Counter-Rotating Integrated Shrouded Prop-fan. (Ref.14)

II. Historical Overview

The Convair XFY-1 Pogo was a prime example of gearbox durability issues. In 1948 the US Navy issued a proposal requesting an aircraft capable of vertical take off and landing (VTOL). In order to do this, the Convair XFY, along with the Lockheed XFV, used one of the most unique concepts that ever incorporated the CRP. Standing upright, a vertical takeoff resembled that of a helicopter takeoff as can be seen from Figure 9. The very little torque produced by the CRP allowed the vertical take off without the stabilizing rotor to counter any rotation as seen on the vast majority of helicopters. Both aircraft were completed by late 1953 and conducted flight testing throughout most of 1954.
While flight testing, the XFV-1 transitioned from horizontal flight to vertical flight several times and in November 1954, the XFV actually managed to vertically take off and land a few times. However, the VTOL aircraft were never pursued further due to difficulty controlling decent rate and gearbox wear. After a few months of flight tests, the gearbox began to expel slivers of metal from wear and tear. The only XFV-1 still in existence is on currently being restored at the International Sport Aviation Museum in Lakeland Florida and the last XFV is at the National Air and Space Museum but not currently on display.

Several other aircraft throughout the years have integrated the CRP into their designs. One of the more famous CRP driven aircraft was the XF-11 flown by Howard Hughes. On the maiden voyage in July of 1946, an unfortunate engine malfunction caused the XF-11 to crash. The only other prototype was then refitted with a single-rotating propeller. Figure 9 shows an example of first prototype of the XF-11.

Figure 9. Pictures of the (a) Lockheed XFV-1 Salmon and (b) Convair XFV-1 Pogo. (Ref 16)

The XB-35, an early flying wing bomber, had a similar gearbox problem to the XFV and it too was altered from CRPs to SRPs. Several other aircraft that used CRPs include, but are not limited to, the Avro Shackleton MR MK3, the Fairey Gannet, XB-42, and XB-42. Some unique features to these aircraft include the Fairey Gannet’s tri-folding wings, and the XB-42 and XB-35’s pusher configuration.

Figure 10. First prototype of the XF-11 still fitted with contra-rotating propellers. (Ref 16)

Figure 11. Examples of the (a) Fairey Gannet, (b) XB-35, flying wing, (c) XB-42, and finally (d) the Avro Shackleton MR MK3. (Ref. 16)
The Tupolev Tu-95, or “The Bear,” is one of the most well known contra-rotating propeller driven aircraft in the world and is still in used today. The Tu-95 is a Soviet bomber mounted with four CRP driven engines. Its design first began in the early 1950s with a first flight in late 1952. After a few years of testing, service entry for the Tu-95 began in early 1955. One of the biggest technological improvements between the Tu-95 and any other propeller driven aircraft of the time was the 35° sweep angle. The sweep angle enabled the aircraft to reach speeds in excess of 875 km/h, or Mach 0.83, at cruise altitude.

Many variants have been created throughout the years ranging from the Tu-95A to the Tu-95H, including a variant passenger aircraft known as the Tu-114, or ‘the cleat.’ This is one of the only medium sized commercial transport aircraft to include the use of CRPs. While for a 140 to 220 passenger aircraft, it had a relatively high take-off weight, the performance matched or exceeded every other aircraft being produced at the time. In the early 1960s, the Tu-114 also set and still holds a world speed record for a commercial turboprop driven aircraft. The Tu-114 has set speed records for payloads from 1000 to 30000 kg and 1000 to 10000 km with speeds of up to 877 km/h at 12000m or Mach 0.83. Coincidentally, this matches or exceeds the cruise speeds set for most commercial airliners today. Also, the range of the Tu-114 remains in a competitive limit of today’s aircraft. This, once again, shows the feasibility of contra-rotating propellers in today’s commercial market.

![Figure 12. Examples of the (a) Tupolev Tu-95 Bear G and (b) Tupolev Tu-114 Cleat. (Ref 16)](image)

One of the newest applications, expecting to enter the market in 2006, for the CRP is the Antonov AN-70. Once flight testing and certification has been completed, the performance results of the AN-70 could potentially persuade the aviation market to consider using CRPs for their fuel saving benefits. This short takeoff and landing (STOL) aircraft is the largest military aircraft using contra-rotating propellers to be tested since the TU-95 in the 1950s.

![Figure 13. Pictures of the Antonov AN-70. (Ref 16)](image)

The purpose of this study was to investigate the benefits of substituting a CFM-56 with a CRP driven engine. Through a literary review, numerical data for both fuel burn savings and efficiency boosts were gathered and then substituted for the actual data from a Boeing 737-800. Once this substitution took place, fuel weight reductions were then used to determine the fuel burn savings.

III. Numerical Model

The fundamental objective of this study was to investigate the potential benefits of using contra-rotating driven engines instead of standard jet engines on a commercial transport aircraft. The Advanced Aircraft Analysis, or
AAA, software developed by DARCorp, based on preliminary aircraft design methods from Roskam,\textsuperscript{17} was employed to compute the benefits derived from using the CRP and to determine optimized conditions where a CRP will produce the most favorable fuel savings. The AAA software uses an iterative process that computes a takeoff weight based on several mission segment specifications and three input parameters.

The strategy utilized was to create a model of an existing aircraft, determine the takeoff weight, and compare the computed takeoff weight to known data on the model Boeing 737-800. Using an iterative process, input values would be modified, starting from typical values,\textsuperscript{15} until the generated values matched the known data. The Boeing 737-800 was selected due to its similar passenger capacity and speed as the Tu-114 as shown in Table 2. Although over 30 years of technological advancements exist between these aircraft, the Tu-95 has undergone several advancements and still remains competitive with today’s aircraft. A typical mission consisting of several sections including warm up, taxi, takeoff, climb, cruise, descent, and landing/taxi was used for the AAA model. Each mission segment contained a fuel fraction which was determined from observed data from Roskam\textsuperscript{17} or from the Breguet range and endurance equations. These fuel fractions represent the percent of fuel used for each segment and are shown in Table 3. Roskam’s\textsuperscript{17} empirical tables are used for calculating all segments excluding climb and cruise. Both climb and cruise are determined from estimated values for L/D specific fuel consumption (SFC), speed (rate of climb for climb segment), and range (distance to climb for climb segment). Before adding the contra-rotating propellers, a baseline model had to be created and calibrated using an iterative process as previously stated. Specific fuel consumption, L/D, and rate of climb for the baseline model were estimated from typical transport jet aircraft data\textsuperscript{17} and then slightly modified so the concluded takeoff weight would match with the takeoff weight as stated from the manufacturer.

Table 2. Tupolev and Boeing Aircraft Performance. (Ref 15)

<table>
<thead>
<tr>
<th></th>
<th>Wing Sweep (deg)</th>
<th>Passenger Capacity</th>
<th>Takeoff Weight (lb.)</th>
<th>Fuel (lb.)</th>
<th>Weight (lb.)</th>
<th>Speed (mph)</th>
<th>Range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tupolev Tu-114</td>
<td>35</td>
<td>140-220</td>
<td>361560</td>
<td>134000</td>
<td>540</td>
<td>5560</td>
<td></td>
</tr>
<tr>
<td>Boeing 737-800</td>
<td>25</td>
<td>162-189</td>
<td>176433</td>
<td>43137</td>
<td>530</td>
<td>3060</td>
<td></td>
</tr>
</tbody>
</table>

With accurate input variables, conversion to the CRP driven engine was executed by altering the specific fuel consumption and efficiency characteristics to match the performance boosts predicted throughout the literature review. Averaging fuel burn and efficiency values from several literature references on the performance of contra-rotating propulsion, conservative estimates of a 20% decrease in fuel consumption and a 4% increase in propeller efficiency over typical turboprop driven aircraft\textsuperscript{17} were utilized.

The aircraft analyzed was one of the next generations Boeing 737s. The 737-800 was chosen because it is a midsized transport jet that can have a range varying from 2000 to 3000 nm, providing a difference for performance comparisons. Ranges outside of the 2000 to 3000 nm scope were studied to determine where fuel saving optimization for the CR propulsion system lies.

IV. Results

To ensure accuracy of the base model Boeing 737-800, the values determined through use of the AAA software, both the takeoff weight and the fuel weight, were compared with the official manufacturers’ weights, as stated from Boeing. As can be seen from Table 4, the calculated weights and actual weights are within a 5% margin of error. Due to inconsistencies between the real world and an approximation, the fuel weight and the takeoff weight could not be matched simultaneously and therefore had to be chosen to produce a small 5% error. Actual aircraft could acquire the values due to discrepancies between manufacturing, components, or any weight imperfections.

Table 3. Mission Segment Fuel Fractions

<table>
<thead>
<tr>
<th>Mission Profile</th>
<th>Mission Segment Fuel Fraction, $M_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warmup</td>
<td>0.99</td>
</tr>
<tr>
<td>Taxi</td>
<td>0.99</td>
</tr>
<tr>
<td>Takeoff</td>
<td>0.995</td>
</tr>
<tr>
<td>Climb</td>
<td>0.9844</td>
</tr>
<tr>
<td>Cruise</td>
<td>0.8013</td>
</tr>
<tr>
<td>Descent</td>
<td>0.99</td>
</tr>
<tr>
<td>Landing/Taxi</td>
<td>0.992</td>
</tr>
</tbody>
</table>
Table 4. Comparison of Boeing 737-800 historical data to AAA computed data. (Ref 15)

<table>
<thead>
<tr>
<th></th>
<th>Range = 1990 nm</th>
<th></th>
<th>Range = 3060 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B737-800</td>
<td>Calculated</td>
<td>% Error</td>
</tr>
<tr>
<td>Takeoff Weight (lbs)</td>
<td>155500</td>
<td>158787</td>
<td>2.11</td>
</tr>
<tr>
<td>Fuel Weight (lbs)</td>
<td>35000</td>
<td>34645</td>
<td>1.01</td>
</tr>
</tbody>
</table>

With the results of the AAA software for the base model found, the next step in the procedure was to substitute in a contra-rotating propeller for the previously given jet engines. Keeping all other values the same, the values for the specific fuel consumption were changed and values for the propeller efficiency were added to simulate the CRP engines. Empirical data gathered from Roskam\textsuperscript{17} states that typical values for SRP regional jet efficiency and fuel consumption are $\eta_p = 85\%$ and $c_i = 0.4$ to 0.6 lb/hr/hp, respectively. To adjust for the CRP benefits, a fuel burn reduction and efficiency increase need to be added. To estimate conservatively, efficiency was increased by 3\%, versus 6\% suggested by Reference 7. Also, a 9\% fuel burn reduction for a CRP over an SRP was used, as stated by reference 9. The estimates used for the CRP engine data were therefore, $c_i = 0.36$ lb/hr/hp for the specific fuel consumption, $c_p$, and an efficiency, $\eta_p = 88\%$.

An additional factor that was also included in the analysis was the additional weight of a CRP engine over an SRP engine. This was accounted for in the Operational Empty Weight. As stated previously, a CRP weighs on average about 17\% more than an SRP engine. This translates to about a .37 \% OEW increase. For the given aircraft, this was only a few hundred pound weight increase for the medium range models. On a side note, the AAA software automatically accounts for weight differences between SRP and jet engines using estimation methods from Roskam.\textsuperscript{17} Even the extended range models didn’t exceed 1000 lbs. A final issue that should be accounted for is, due to greater complexity over SRP, the maintenance and acquisition costs are expected to be slightly higher by 34\% and 27\% respectively. These costs should be included into a cost estimate in order to calculate potential savings but are not expected to render the fuel reduction benefits null and void.

Once the CRP data had been substituted for the jet data, several range cases were examined to determine optimal CRP applications. The B737-800 is designed for ranges of 1990 and 3060 nm. For the high and low design range cases the fuel burn savings are 3,820 lbs (17\%) and 5877 lbs (8.86\%) respectively. These two cases represent savings that would be yielded if applied to an actual aircraft. The several additional ranges represent the same aircraft refitted for additional fuel while keeping the same payload. Optimized ranges occur at the lower range and higher range cases. This compares to trends from the literary review as shown previously in Figure 4.\textsuperscript{10} The contra-rotating propeller driven aircraft produces almost 20\% fuel burn savings over the jet driven aircraft at the optimized ranges. Figure 14 shows the relationship trend between the fuel burn savings and the range.

A reduction in required fuel will cause the aircraft’s takeoff weight to diminish as well. This reduction in takeoff weight is accounted for through an iterative process automatically done with the AAA software. Therefore, addition of a CRP will result in a lower takeoff weight. Figure 15 shows the reduction of takeoff weight from use of a jet

![Figure 14. Fuel Savings determined for several range cases.](chart-url)
Figure 15. Fuel Savings determined for several range cases.

range of 3850 nm. Evaluated against the Boeing 737-800 with 162 passengers, the longer range model with 140 passengers represents a closer match for comparison.

The effect on the range of propeller aircraft versus jet aircraft is a significant figure. The only value changed between all the cases listed was the corresponding change in range. Sensitivities calculated by the AAA software show around a 30 lb increase for each additional nautical mile of range for the 3000 nm range case. The value derived from the actual change shown in Table 5 is only an average of 20 lbs/nm. Using the information from Table 5, sensitivities of takeoff and fuel weight were calculated as shown in Table 6. The sensitivities show, on average, a 4 lb/nm smaller fuel weight sensitivity to range for the CRP driven aircraft over the jet driven aircraft.

Table 5. Fuel Savings determined for several range cases.

<table>
<thead>
<tr>
<th>Range (nm)</th>
<th>$W_{TO}$ (lb)</th>
<th>$W_{F}$ (lb)</th>
<th>$M_{FF}$</th>
<th>$W_{TO}$ (lb)</th>
<th>$W_{F}$ (lb)</th>
<th>$M_{FF}$</th>
<th>$W_{F}$ (lb)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>122720</td>
<td>17409</td>
<td>0.9102</td>
<td>117639</td>
<td>14138</td>
<td>0.9193</td>
<td>3271</td>
<td>18.79</td>
</tr>
<tr>
<td>1900</td>
<td>158787</td>
<td>34645</td>
<td>0.8292</td>
<td>153863</td>
<td>28768</td>
<td>0.8458</td>
<td>5877</td>
<td>16.96</td>
</tr>
<tr>
<td>3060</td>
<td>176433</td>
<td>43137</td>
<td>0.8013</td>
<td>168838</td>
<td>39317</td>
<td>0.8068</td>
<td>3820</td>
<td>8.86</td>
</tr>
<tr>
<td>4000</td>
<td>222497</td>
<td>65455</td>
<td>0.7486</td>
<td>209798</td>
<td>59121</td>
<td>0.7554</td>
<td>6334</td>
<td>9.68</td>
</tr>
<tr>
<td>5000</td>
<td>297604</td>
<td>102217</td>
<td>0.6964</td>
<td>274568</td>
<td>90736</td>
<td>0.7042</td>
<td>11481</td>
<td>11.23</td>
</tr>
<tr>
<td>6000</td>
<td>426000</td>
<td>165849</td>
<td>0.6477</td>
<td>380355</td>
<td>142963</td>
<td>0.6565</td>
<td>22886</td>
<td>13.80</td>
</tr>
<tr>
<td>7000</td>
<td>680789</td>
<td>294062</td>
<td>0.6025</td>
<td>575832</td>
<td>240819</td>
<td>0.612</td>
<td>53243</td>
<td>18.11</td>
</tr>
</tbody>
</table>

Table 6. Sensitivities of Takeoff and fuel weight to range.

<table>
<thead>
<tr>
<th>Range (nm)</th>
<th>$\Delta W_{TO}$</th>
<th>$\Delta W_{F}$</th>
<th>$\Delta W_{TO}$</th>
<th>$\Delta W_{F}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>36.43131</td>
<td>17.4101</td>
<td>29.51919</td>
<td>14.77778</td>
</tr>
<tr>
<td>1900</td>
<td>16.49159</td>
<td>7.936449</td>
<td>20.53738</td>
<td>9.858879</td>
</tr>
<tr>
<td>3060</td>
<td>49.00426</td>
<td>23.74255</td>
<td>43.57447</td>
<td>21.06809</td>
</tr>
<tr>
<td>4000</td>
<td>75.107</td>
<td>36.762</td>
<td>64.77</td>
<td>31.615</td>
</tr>
<tr>
<td>5000</td>
<td>128.396</td>
<td>63.632</td>
<td>105.787</td>
<td>52.227</td>
</tr>
</tbody>
</table>

engine to a CRP driven engine. A trend line has been added to show the trend between increased range and takeoff weight. A Tu-114 has been added to the plot to compare to of the results. The Tu-114 shown in Figure 15 has a range of 5560 nm and is carrying a payload of 140 passengers. This isn’t the maximum payload but is a potential configuration for the Tu-114 used to maximize the range capabilities. A fully loaded Tu-114 will weigh 380000 lbs (220 passengers) and have a
Another method to analyze the benefits of adding a CRP is additional range instead of reduced fuel load. With the sensitivities known for the range to takeoff weight and the differences in takeoff weight between the aircraft, an extended range for the CRP driven B737-800 can be calculated. As seen from Table 7 below, the reduced weight can also add, in all cases, over 100 nm to the range of the aircraft.

Table 7. Additional range possibilities instead of Reduced weight.

<table>
<thead>
<tr>
<th>Reduction in Weight (lbs)</th>
<th>Additional Range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5081</td>
<td>138.8635</td>
</tr>
<tr>
<td>4924</td>
<td>351.8317</td>
</tr>
<tr>
<td>7595</td>
<td>174.2993</td>
</tr>
<tr>
<td>12699</td>
<td>196.063</td>
</tr>
<tr>
<td>23036</td>
<td>217.7583</td>
</tr>
</tbody>
</table>

V. Conclusion

A contra-rotating propeller was integrated on a Boeing 737-800 to determine the possible benefits the transport airline industry could obtain. Addition of a CRP can reduce fuel burn by at least 8% and up to at least 20%. Both very short range (less than 2000nm) and very long range (more than 4000nm) appear to be the optimized areas under which a CRP driven aircraft will give the largest returns. Although issues with contra-rotating propulsions systems still exist, in this time of rising fuel costs alternative fuel saving methods should be given a more thorough glimpse. These results shown could provide considerable savings throughout the airline industry every year.

References