KINEMATICS of MECHANICAL SYSTEMS

MINI-PROJECT

Helicopter Transmission

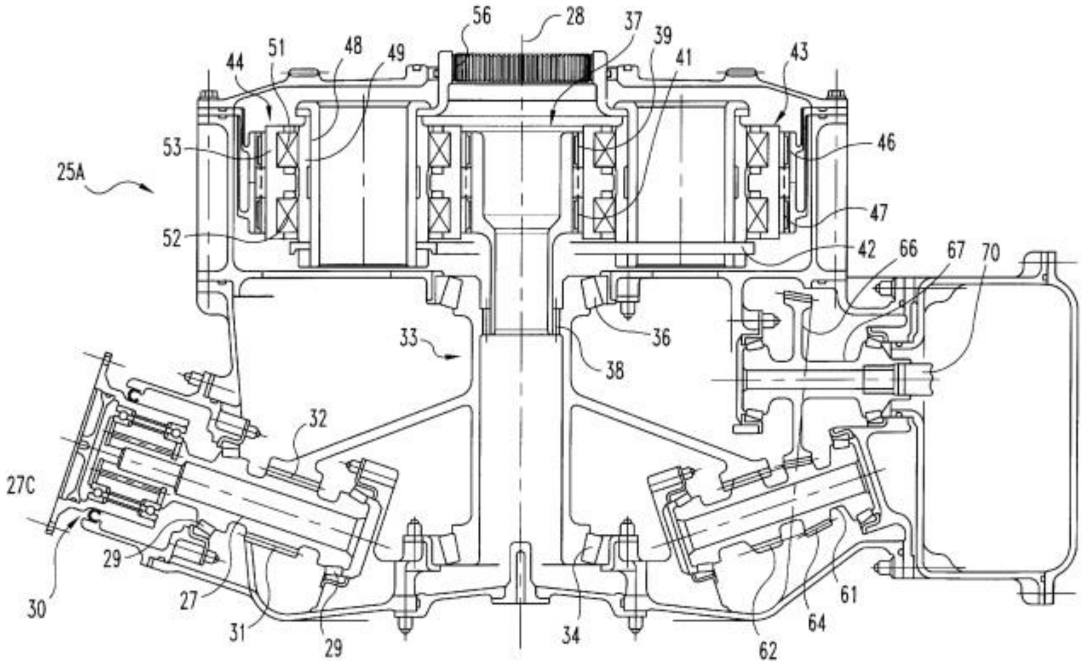

Fig. 3

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Questions:

a) Why do we need large speed reductions in this application?

The rotational speeds created by the gas turbines, which give the helicopter its propulsion, are too much for the rotor blades to handle. Thus a transmission (or gearbox) is placed to reduce the speed made by the turbine such that this would allow for a more manageable speed for the rotor blades.

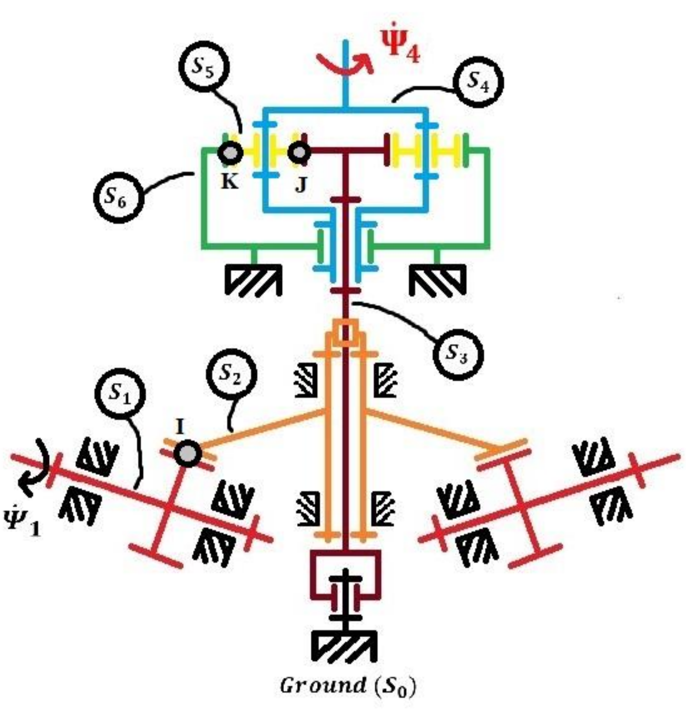
b) What is the interest of using turbines in helicopters?

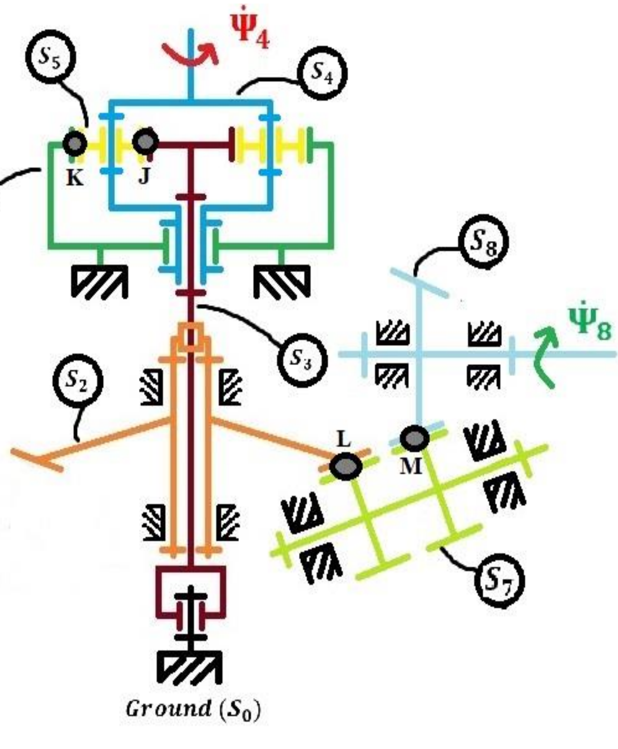
As advances in technology are made, more efficient machines are created which allow for improvements of previous iterations. The motors utilized by cars, (the piston engines) lack the horsepower needed to allow for bigger and faster helicopters to fly. Thus a machine which has a higher performance is used, the turboshaft. Unlike a jet turbine (which converts fuel to thrust), a turboshaft utilizes its fuel to create a shaft power which is transmitted to the rotor blades of the helicopter through a gearbox for the previously explained reason.

There are more benefits for helicopters to utilize gas turbines than piston engines as these are lighter, produce more power and are more reliable.

c) Based on the diagrams and data in the patent, propose a kinematic model of the two-stage transmission.

This kinematic model is based off of figure 3 of the patent.





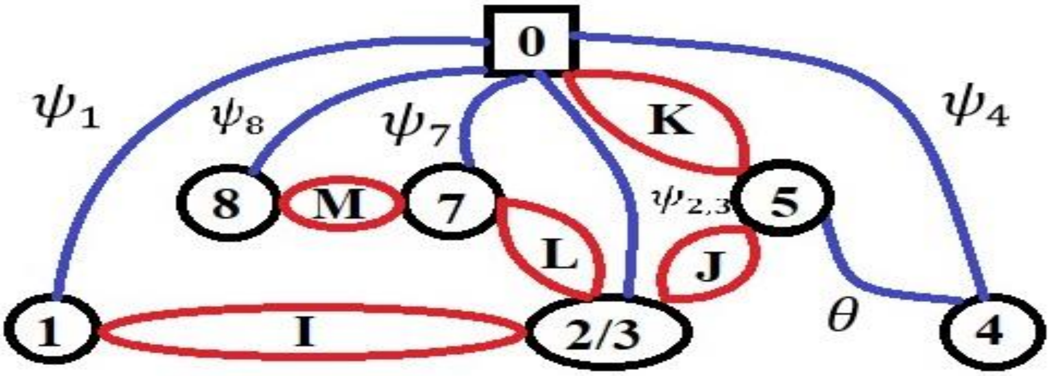
Parameters:

$1/0 \rightarrow \psi_1$ $2/0 \rightarrow \psi_2$ $3/0 \rightarrow \psi_3$ $4/0 \rightarrow \psi_4$ $5/4 \rightarrow \theta$

$7/0 \rightarrow \psi_7$ $8/0 \rightarrow \psi_8$

Graph of Links:

Every point of contact (I, J, K, L and M) has a no slipping condition such that the meshed gears can function correctly.



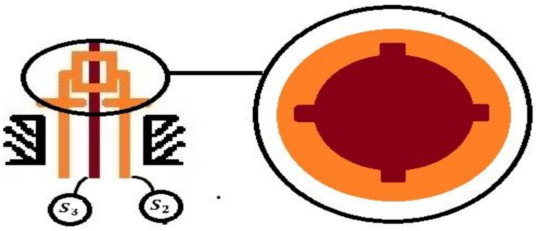
Description:

The model on the left represents a "front" view (so to speak) of the gearbox where the rotation of two input shafts (from two turboshafts and right angle nose gearboxes) are transmitted to the main rotor shaft of the helicopter. While the model on the right represents a "left" view which has the same intermediate member of the previous model which transmits its rotation to the tail rotor shaft. Equal rotational speed must be transmitted from both input shafts to allow the system to have a stable operation.

This gearbox has two stages: the first is a speed reduction caused by a face gear (Solid 1 and 2) and the second by a planetary gear (Solid 3, 4, 5 and 6).

Solid 0 is the housing of the helicopter and is considered the "ground" of the system.

Solid 1 is composed of a shaft (27) and a one-way overrunning clutch (30) and a face gear (31) which is straddle mounted (which means that its gear is in between 2 bearings) to a tapered rolling bearing set (29); this solid acts as the main input of the whole system. Solid 2 is composed of a face gear (32) on an intermediate drive member (33), which has the shape of an umbrella, is also straddle mounted to a tapered rolling bearing set (34 and 36) that allows its rotation.



Solid 3 is composed of a torque transmitting tube (37) which is splined at its bottom (as illustrated in the diagram) to Solid 2. The number of "spline teeth" depends on the study of the material, thus this is only for illustration. Thus $\psi_2 = \psi_3$.

Also, solid 3 has two helical gear teeth rings near its upper end (39 and 41).

Solid 3 acts as the sun gear of the planetary gear system.

Solid 4 is the planet carrier (42) which has an internal spline (56) that couples with the main rotor shaft (57), thus acting as the output member of the system. Solid 5 is the planet gears (43, 44) that are each composed of a hub fixed to the carrier (48) which supports an inner race (49) of a double row roller bearing set (51 and 52) that support the outer race (53) with two rings of helical gear teeth mounted on it.

This rings are in mesh with the sun gears' rows of helical teeth (39 and 41) and the ring gears' row of helical teeth (46 and 47) which is Solid 6 that is fixed to the housing of the helicopter. Thus Solid 6 = Solid 0 and has no angle parameter.

Solid 7 is oriented 90º from Solid 1 and is composed of a shaft (61) and a gear (62) which is in mesh with the gear teeth of solid 2 (32), this shaft also has another gear (64) which is in mesh with Solid 8. Both of these gears are straddle mounted to a set of tapered rolling bearings.

Solid 8 is composed of an accessory output driver (67) that is splined to the accessory output shaft (70) which has a gear (66) that is in mesh with a gear of Solid 7 (64). The output shaft (70) gives the tail of the helicopter its rotation, which is needed to counteract the torque of the main rotor and allow the helicopter to be held straight.

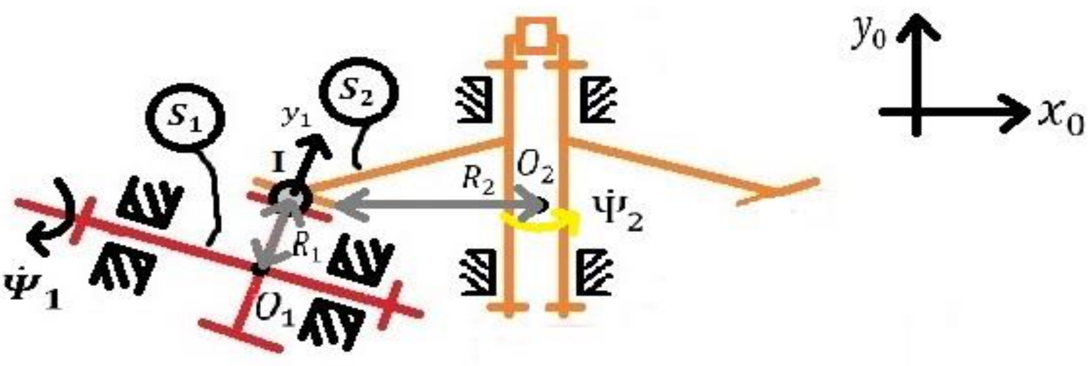
d) Assuming that the technical drawings are to scale, find the speed ratio between the input and the main rotor based on direct measurements of distance on the drawings (possibly combined with some of the data in the tables). Comments.

These calculations are based off of figure 3 of the patent.

The rotational speed from the gas turbines will be considered to be 21,160 rpm, it is connected to a right-angle nose gearbox which has a speed ratio of 2.13:1 thus resulting in a rotational speed of 9,934 rpm. This will be considered the input of the system:

$$\dot{\psi}_1 = 9{,}934\ rpm$$

First stage speed reduction:



$$\vec{V}_2^1(I) = \vec{V}_2^0(I) - \vec{V}_1^0(I) \qquad \textbf{Equation 1}$$

By using the Chasles relation, the Moving Basis Formula and the no slipping condition at I ($\vec{V}_2^1(I) = \vec{0}$), equation 1 becomes:

$$\vec{0} = \left[\vec{V}_2^0(O_2) + \vec{\Omega}_2^0 \times \overrightarrow{O_2 I}\right] - \left[\vec{V}_1^0(O_1) + \times\, \vec{\Omega}_1^0 \times \overrightarrow{O_1 I}\right]$$

As the velocity at the origin of a gear is nil: $\vec{V}_2^0(O_2) = \vec{V}_1^0(O_1) = \vec{0}$

$$\vec{0} = \begin{bmatrix} 0 \\ \dot{\psi}_2 \\ 0 \end{bmatrix}_0 \times \begin{bmatrix} -R_2 \\ 0 \\ 0 \end{bmatrix}_0 - \begin{bmatrix} \dot{\psi}_1 \\ 0 \\ 0 \end{bmatrix}_1 \times \begin{bmatrix} 0 \\ R_1 \\ 0 \end{bmatrix}_1 = \begin{bmatrix} 0 \\ 0 \\ R_2\dot{\psi}_2 - R_1\dot{\psi}_1 \end{bmatrix}_{0/1}$$

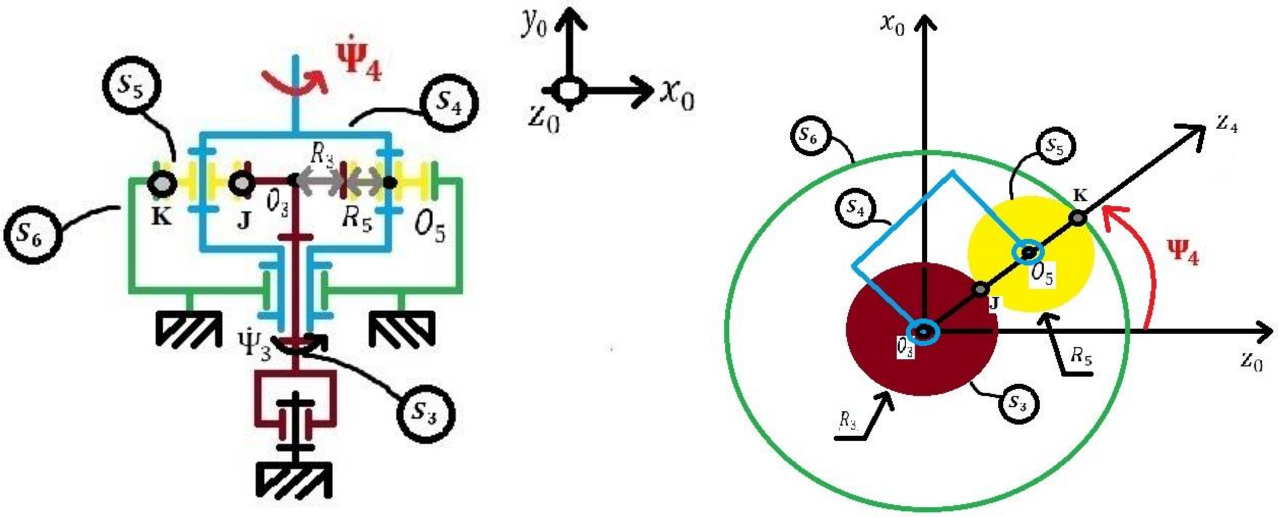
$$/\vec{z}_0 : 0 = R_2\dot{\psi}_2 - R_1\dot{\psi}_1 \rightarrow \frac{\dot{\psi}_2}{\dot{\psi}_1} = \frac{R_1}{R_2}$$

As the patent is considered to be in scale, in an A4 format: $R_1 = 0.7\ cm,\ R_2 = 4.2\ cm$

Thus equation 1 results in: $\dot{\psi}_2 = \dot{\psi}_1 \cdot \frac{R_1}{R_2} = 9{,}934 \cdot \frac{0.7}{4.2} = 1{,}656\ rpm \cdot \vec{z}_0$

A speed reduction of 6:1 is achieved in the first stage.

<u>Second stage speed reduction (planetary gear):</u>



$$\vec{V}_5^3(J) = \vec{V}_5^4(J) + \vec{V}_4^0(J) - \vec{V}_3^0(J) \quad \textbf{Equation 2}$$

By using the Chasles relation, the Moving Basis Formula and the no slipping condition at J ($\vec{V}_5^3(J) = \vec{0}$), equation 2 becomes:

$$\vec{0} = \left[\vec{V}_5^4(O_5) + \vec{\Omega}_5^4 \times \overrightarrow{O_5 J}\right] + \left[\vec{V}_4^0(O_3) + \vec{\Omega}_4^0 \times \overrightarrow{O_3 J}\right] - \left[\vec{V}_3^0(O_3) + \vec{\Omega}_3^0 \times \overrightarrow{O_3 J}\right]$$

As the velocity at the origin of a gear is nil: $\vec{V}_5^4(O_5) = \vec{V}_4^0(O_3) = \vec{V}_3^0(O_3) = \vec{0}$

$$\vec{0} = \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix}_{0/3/4/5} \times \begin{bmatrix} -R_5 \\ 0 \\ 0 \end{bmatrix}_4 + \begin{bmatrix} 0 \\ \dot{\psi}_4 \\ 0 \end{bmatrix}_{0/3/4} \times \begin{bmatrix} R_3 \\ 0 \\ 0 \end{bmatrix}_4 - \begin{bmatrix} 0 \\ \dot{\psi}_3 \\ 0 \end{bmatrix}_{0/3/4} \times \begin{bmatrix} R_3 \\ 0 \\ 0 \end{bmatrix}_4$$

$$\therefore 0 = \left[R_5 \cdot \dot{\theta} + R_3(\dot{\psi}_3 - \dot{\psi}_4)\right] \cdot \vec{z}_4$$

$$\vec{V}_5^0(K) = \vec{V}_5^4(K) + \vec{V}_4^0(K) \quad \textbf{Equation 3}$$

By using the Chasles relation, the Moving Basis Formula and the no slipping condition at J ($\vec{V}_5^0(K) = \vec{0}$), equation 2 becomes:

$$\vec{0} = \left[\vec{V}_5^4(O_5) + \vec{\Omega}_5^4 \times \overrightarrow{O_5K}\right] + \left[\vec{V}_4^0(O_3) + \vec{\Omega}_4^0 \times \overrightarrow{O_3K}\right]$$

As the velocity at the origin of a gear is nil: $\vec{V}_5^4(O_5) = \vec{V}_4^0(O_3) = \vec{0}$

$$\vec{0} = \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix}_{0/3/4/5} \times \begin{bmatrix} R_5 \\ 0 \\ 0 \end{bmatrix}_4 + \begin{bmatrix} 0 \\ \dot{\psi}_4 \\ 0 \end{bmatrix}_{0/3/4} \times \begin{bmatrix} R_3 + 2 \cdot R_5 \\ 0 \\ 0 \end{bmatrix}_4$$

$$\therefore 0 = [-R_5 \cdot \dot{\theta} - (R_3 + 2 \cdot R_5)\dot{\psi}_4] \cdot \vec{z}_4$$

By adding the results of both equation 2 and 3, one can obtain the speed ratio between the planet carrier and the sun gear:

$$Equation\ 2 + Equation\ 3 = \ [R_5 \cdot \dot{\theta} + R_3(\dot{\psi}_3 - \dot{\psi}_4) - R_5 \cdot \dot{\theta} - (R_3 + 2 \cdot R_5)\dot{\psi}_4] \cdot \vec{z}_4$$

$$/\vec{z}_4 : 0 = R_3 \cdot \dot{\psi}_3 + \dot{\psi}_4(-2 \cdot R_5 - 2R_3) \rightarrow \frac{\dot{\psi}_4}{\dot{\psi}_3} = \frac{R_3}{2(R_5 + R_3)} \quad \textbf{Equation 4}$$

As the patent is considered to be in scale, in an A4 format:

$R_3 = 1.175\ cm,\ R_5 = 2.125\ cm$

As explained in the description of the kinematic model, the rotational speed of Solid 2 is the same as the one for Solid 3. Thus: $\dot{\psi}_2 = \dot{\psi}_3 = 1{,}656\ rpm$

Thus equation 4 results in: $\dot{\psi}_4 = \dot{\psi}_3 \cdot \frac{R_3}{2(R_5 + R_3)} = 1{,}656 \cdot \frac{1.175}{2(2.125 + 1.175)} = 295\ rpm \cdot \vec{z}_4$

A speed ratio of approximately 5.6:1 is achieved with this planetary gear set as describe in the patent, 4 gears can fit into this setup.

Another method of calculating this speed ratios can be done by using the number of teeth of the given gears, for example in the first stage speed reduction the number of teeth for the gear (31) of the input shaft (27) has 18 while for the intermediate drive member (33) gear has 109. Since gears have to have the same module to mesh one can obtain the following:

$m = \frac{dp_1}{z_1} = \frac{dp_2}{z_2} \rightarrow \frac{R_1}{2 \cdot z_1} = \frac{R_2}{2 \cdot z_2} \rightarrow \frac{R_1}{R_2} = \frac{z_1}{z_2}$ where dp is the pitch diameter of the gear.

Thus Equation 1 becomes: $\frac{\dot{\psi}_2}{\dot{\psi}_1} = \frac{z_1}{z_2} \rightarrow \dot{\psi}_2 = \frac{18}{109} \cdot 9{,}934 = 1{,}640\ rpm$

Resulting in a speed reduction of approximately 6:1 for the first stage.

The same can be done for the second stage, however the respective radius is replaced with the respective number of teeth. $\therefore R_3 = z_3 = 30$ and $R_5 = z_5 = 54$

Thus equation 4 becomes: $\dot{\psi}_4 = \dot{\psi}_3 \cdot \frac{z_3}{2(z_5 + z_3)} = 1{,}640 \cdot \frac{30}{2(30 + 54)} = 293\ rpm$

Which is a speed ratio of approximately 5.6:1.

The description given to figure 4 is such that the main difference between this and figure 3 is the kind of gear used by the input shaft (27) and the intermediate drive member (33). Where in figure 3 the design uses a face gear (31 and 32) for transmission, this figures input shaft (68) is slightly different in terms of angle and uses a face-milled or face-hobbed bevel gear (69) that engages with another face-milled or face hobbed bevel gear (71). This change has no immediate effect on the speed reduction. There is no change in the planetary gear setup.

For figure 5, the main difference between figures 3 and 4 is that the ring gear (76) fixed to the gearbox (78) has only one ring (77) of helical teeth instead of the two in figures 3 and 4. Consequently, so do the planets and the sun gear. All four planets (78) now have a single set of helical teeth as well as the sun gear (79), which engage to the ring gear (76).

All of this changes have no immediate effect on the calculations already done.

In all design, the two input shafts from the first gearbox and turboshafts have a speed reduction through the two-stage gearbox and output through the gear carrier in the planetary gear which splines with the main rotor shaft of the helicopter.

e) What is the claimed interest of this patent?

By using a small amount of space, the claims that a speed reduction of greater than 30:1 can be achieved by using these designs, where the first stage produces a speed reduction of 5.5:1 into an epicyclical gear train second stage ratio of about 6:1. According to my calculations, a speed reduction of approximately 33:1 is achieved by a first stage speed reduction of 6:1 and a second stage speed reduction of 5.5:1.

Thus with this interpretation the objective of a greater than 30:1 speed reduction is achieved, however not as described; where the first stage has a greater speed reduction than the second one.

Additionally, A great deal of different factors have varying effects on the design of this gearbox, such as the noise the gears could produce, the material needed for gears to withstand the contact forces created by the high rotational speeds of the turboshaft, etc.

References:

- John M. Hawkins, (2001), US 6,302,356 B1, retrieved from: http://www.freepatentsonline.com/6302356.pdf