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PRELIMINARY DESIGN, FABRICATION AND TESTING OF THE FW-350 LUNAR FLEXIBLE WHEEL PROTOTYPE

ABSTRACT

This paper presents the design, fabrication and field testing of the third generation FW-350 Lunar earth analogue flexible wheel prototype which is 24 inches in diameter and designed for a 300-Kg four-wheeled rover class. A set of four lunar wheels were manufactured, assembled and field tested. Wheel prototypes were installed on the PUD-II prototype rover and tested at the CSA’s Mars Emulation Terrain (MET).

All the wheel prototype structure components performed as per functional specification: Tread, side wall bands, beads, rim clamps, rims, and fastener system. Some grousers deformed while driving over rocks under severe testing. Those are being reinforced. While performance and reliability goals were identified early on in the concept design phase, future work will focus on verification aspects.

1. INTRODUCTION

As part of the CSA drive to develop expertise in planetary rovers it became clear that rover wheels is a critical technology which needs to be developed to enable the design of reliable and robust rovers featuring the flexibility to perform a variety of planetary missions.

This paper describes the development of the FW-350 flexible metal lunar rover wheel using fast-prototyping techniques. Such techniques are normally used to advance a system from concept stage to field testing stage in a short period to enable better understanding of the overall technology and develop more practical long term technology development plans. This work is being carried out at the CSA by the robotics group as a contribution to a technology development partnership agreement between CSA, academia (university of McGill) and industry (Neptec Inc) on Lunar Traction. This activity so far has generated a wealth of information in the area of planetary traction including various wheel designs and prototypes, wheel test rigs, modeling, wheel performance and soil simulation software [3, 5].

The main focus of this R&D activity is on investigating if the traction capabilities of a heavy 4-wheeled rover could be extended so that the wheel can operate at low ground pressures in the range of 1 to 1.6 psi. If this can be achieved it would reduce the number of wheels heavy planetary rover normally requires (6 to 8), hence improving mass and rover reliability. If we want to stick to wheels rather than tracks, there are many arguments to support this approach [1] then it is obvious that we need to significantly increase the area of the wheel contact patch. This is the reason why the flexible wheel approach was selected.

This particular lunar flexible wheel concept (FW-100 & FW-350) is based on emulating the pneumatic radial tire design, Fig-1, in function and by modifying or replacing components or materials which can not survive the lunar environments.

The rationale to this approach is that the current car tire
designs, although had accelerated development in the last 100 years, have been evolving for thousands of years before. It makes sense to pay attention and reuse proven design heritage. Off-road vehicles traction is of particular interest because of the closeness of rough and sandy operational terrain to planetary terrain.

Pneumatic radial wheel functions were first decomposed then the initial wheel design, FW-100, Fig-2, was synthesized to emulate functions and their interaction.

As shown in Fig-1 the pneumatic radial tire relies on air pressure to transmit the car load to the ground through the rim outer surface. The tread is the tire ground interface which performs two basic functions: transmitting vehicle load to ground and producing traction through friction with ground. Other functions include expelling water and enabling turn maneuver.

Body ply is the main structure that holds the tire together and it is mainly responsible, in combination with the side walls, for transmitting torque from rim to tread and to protect the side of the wheel as well as producing wheel forward and lateral stiffness. Steel belts provide the strength and base for the tread and hold the wheel circular shape, important to reduce energy consumption inside the wheel.

Wheel bead is the interface between the rim and body ply and side wall. The bead helps the rubber around it to seal the air inside the tire as well as providing a good path for torque transmission without slippage. The chafer provides further side protection for the wheel. Inside liner provides air pressure containment. In general the tread provides the high frequency compliance required for traction on the road while the side walls and body ply provide lower frequency compliance of the wheel.

The driving requirements for the FW-100 and FW-350 prototype wheel design concept are:

- Wheel loads 50 to 100 Kg in earth analogue.
- Very light construction.
- High traction.
- Power efficient.
- Low ground pressure terrain.
- Sandy terrain with some rocks.
- Path to flight design.
- Reuse of pneumatic radial wheel design heritage.
- Reliable, 100 Km operation.

2. FW-100 WHEEL DEVELOPMENT

FW-100 wheel Fig-2, was the first completed wheel prototype, in our development, to mimic radial tire design. The wheel uses blue tempered spring steel instead of rubber. Side walls, chafer and body ply were replaced by radial bands see Fig-3; the bead function is performed by two rim belts which fasten the inside of the radial bands to the rim.

For a tread belt function two spring steel sheets are used and are fastened to the radial bands. A V-spring inside each radial band combined with side springs, Fig-3, emulated air pressure inside a tire. This allows also controlling wheel lateral stiffness.
The spring constant of the two side springs and V-spring of the radial band are the variables that the designer can control to suit a particular rover traction requirement.

Throughout the wheel development the stiffness of individual radial bands elements were estimated by assuming that they are one of three configurations of leaf spring: circular, semi-elliptical and quarter elliptic according to equations (1) and (2).

\[ F = kx \text{ (Hooke’s law)} \]  
\[ k = \frac{MEdt^3}{d^3} \]  

Where:
- E = Modulus of Elasticity
- M = 4 for a circular flat spring
- M = 8/3 for semi-elliptic leaf spring
- M = 1/6 for quarter elliptic leaf spring
- b = width of spring
- t = thickness of material
- d = diameter of circle or span
- F = Force
- x = Deformation
- k = spring constant

It was assumed that i) the tread contribution to wheel deflection under vertical load is negligible and ii) that most of the contribution is due to the individual radial bands. Top and bottom elements of individual radial bands are assumed to be rigid and depending on required wheel patch deflection, internal wheel preload, top and bottom radial bands are each allocated a deflection.

Edge and main grousers, made of aluminium, on each radial band simulate the pneumatic wheel tread. Grousers have walls across to improve wheel’s lateral stability.

The concept of traction employed is based on trapping regolith between grousers at the wheel contact patch. This effectively makes the regolith or soil to be part of the bottom part of the wheel tread. Such mechanism produces soil to soil coefficient of friction which is high. Also Grousers (cleats) under wheel pressure shear soil off and carry sand between causing shear displacement to occur, and thus shear strength to develop along surface. In the open space behind the last grouser a much longer shearing surface is produced, yielding greater thrust development [2].

As seen in Fig-3 and Fig-4 the FW-100 edge grousers are inclined at an angle relative to main grouser to give the wheel a suitable radius to reduce turning loads. An of-the-shelf all-terrain vehicle (ATV) rim is used.

The prototype wheel components are fastened using bolts and lock nuts. This enabled the testing of various grouser and radial band systems. Also a single point fastening enabled wheel components to slide against each other producing a friction damping in the wheel.

Various tests on the FW-100 revealed brittleness issues in using the blue tempered spring steel material. The straight grouser design also suffers from a reduced lateral stability and reduced traction on the wheel sides hence reducing effective wheel width. Another challenge was the fact that the wheel was complex to manufacture since the radial bands were manufactured individually. Another issue was that torque was transmitted from rim to radial bands by friction which depended on the rim belts pressure, making the wheel susceptible to slip on the rim. The main grouser being rigid limited the flexibility of the tread which affected traction.

3. FW-350 DEVELOPMENT

After going through several design iterations the FW-350 flexible wheel prototype, Fig-5, Table-1, was produced.
The wheel is cut from a 0.025 inch spring stainless steel sheet. In this new design we implemented the lessons learnt from the FW-100 and subsequent prototyping iterations. To address manufacturing complexity the whole new wheel was cut from a single spring stainless steel sheet. The new grousers are flexible and are arranged in a closed V-configuration. The function of a V-grouser is not the same as in the pneumatic tire where the V-tread function is to pump water away from the wheel. The closed V-grouser traps soil for traction and provide lateral stability to the wheel on hill side driving. The exit of the V is blocked by two walls at the edges of the tread belt, see Fig-5. The wall also protects the sides of the two thin tread belts when the wheel sides are in contact with rocks. The walls also add to lateral stability. The fact that the grousers are flexible makes the wheel flexible in its six degrees of freedom thus enabling better traction on rough terrain.

To ensure no slip, torque transmission from rim to radial bands, side bands are connected to a bead-lock carbon fibre rim. The new bead is similar to that of the tire using an aircraft multi-strand cable which interconnects all side bands together inside. The radial band V-spring was replaced by an “OO” shaped pillow like spring. This ensures better load distribution along the inside of the rim and also more lateral stiffness of the wheel. These links were designed to be preloaded during assembly to create wheel pressure, just like in a normal tire, see Fig-7. The geometry of the abovementioned links also prevents local components flexing beyond elastic range.

Grousers were later reinforced in such away to make them more robust when working in a rocky terrain. A special configuration of wire mesh, made from aircraft multi-strand cable, linked all the grousers together, see Fig-5. The resulting tread –grousers became very robust yet still flexible.

<table>
<thead>
<tr>
<th>Wheel Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.63 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Mass</td>
<td>15 Kg</td>
</tr>
<tr>
<td>Speed (maximum)</td>
<td>10 Km/hr</td>
</tr>
<tr>
<td>Load (nominal)</td>
<td>70 Kg</td>
</tr>
<tr>
<td>Load (maximum)</td>
<td>100 Kg</td>
</tr>
<tr>
<td>Operational Terrain</td>
<td>Regolith/sand</td>
</tr>
<tr>
<td>Deformation (maximum)</td>
<td>2Xno-load contact patch area</td>
</tr>
<tr>
<td>Grousers type</td>
<td>Flexible, closed V-shaped</td>
</tr>
<tr>
<td>Grouser with</td>
<td>0.19 m</td>
</tr>
<tr>
<td>Grouser depth</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Rim</td>
<td>Bead lock-8” x 10”</td>
</tr>
<tr>
<td>Bolt pattern</td>
<td>4x112 mm</td>
</tr>
</tbody>
</table>

Table-1 FW-350 Wheel Specifications

4. MANUFACTURING

The single sheet stainless steel wheel cutting was performed by a water jet rather than laser to avoid excessive heat generation during cutting and preserve spring material properties. The resulting single sheet structure was folded and bent to form the wheel, see Fig-6. The grousers were cut from the same single sheet and were bent separately in large batches. Standard pressbrake and specialized jigs were used to bend and form the wheel structure and grousers. Four copies of the wheel were manufactured.

Fig-6 FW-350 Wheel single sheet bending

Assembling the wheel on the bead-lock rim required a wheel preloading rig to be made see Fig-7. After assembly, the grousers’ tips were bent to take two cables each. The grousers were linked together by a wire net which effectively limited the deflection of the grouser components, Fig-5.

Fig-7 FW-350 Preloading rig
5. LABORATORY TESTING

Various tests were performed on spring material and completed assemblies to validate collective behaviour and estimation of spring constant. Specifically this was carried out to test behaviour of models of the radial band and internal reinforcement configurations.

Fig-8 FW-350 Preloading rig

As for the tire performance two quantities were the focus of the testing, namely the Drawbar-Pull and the wheel rolling resistance. These were measured using the single wheel test bed shown in Fig-8 and test process and procedures developed as part of CSA, academia (McGill University, and industry (Neptec Inc) partnership [1,2,4].

The power consumption and coefficient of rolling resistance for the wheel was characterised by driving the wheel over the sand bed for a specific distance at various constant velocities for a given wheel loads. The power was measured from the speed controller motor with calibration applied. Equation (3) was used to calculate the coefficient of rolling resistance

\[ Cr = \frac{P}{Wv} \]  

where

- \( Cr \) = Coefficient of rolling resistance [1]
- \( P \) = Power consumed by the wheel [W]
- \( W \) = Total weight on the wheel [N]
- \( v \) = Wheel linear velocity [m/s]

The test data indicate that the FW-350 Cr values compare well with an inflated rubber wheel used as a standard reference for testing. Also the curve indicates that the FW-350 becomes more efficient as it is loaded.

The Drawbar Pull test was performed on the same test bed using 100% slip. The load was measured by a load cell at different wheel loads. The early favourable FW-350 wheel traction results indicated that the sand grouser concept really works.

6. FIELD TESTING

Four FW-350 wheels were installed on the PUD-II experimental prototype rover [4], see Fig-9, and field tested at the CSA new extended Mars Emulation Terrain (MET).

Tests demonstrated that the wheel was operating at required patch size, producing adequate traction and transmitting torque from rim to tread without rim-tread relative slip.

Two problems were identified during field testing: The grouser individual links were bending when negotiating rough rock fields. Also the inside “OO” pillow links of the radial bands were becoming misaligned.

Grousers were then reinforced using a cable net which limited the individual grouser elements from over bending See Fig-5. The radial band sides and inside pillow link were riveted together to limit misalignment. Subsequent field tests demonstrated that both problems were fixed.

Both bead, radial band bead interface and the bead lock mechanism held well. Stress relief interface point
between radial band and tread belt were examined regularly. The tread side walls functioned well and protected the two thin tread belts. The bolt-lock nut fastening was adequate and flexible when there was a need to dismantle a wheel component.

Several wheel imprints on sand were regularly inspected. They showed that wheel loads are evenly distributed across the wheel and that the sand is contained within the wheel tread as per design.

7. DISCUSSION AND CONCLUSION

The paper described an on-going planetary wheel development activity which examined the potential of extending single wheel traction and low ground pressure capabilities. Such extended capabilities would enable the development of heavy duty wheeled planetary rovers without the need to have a track or number of wheels increased beyond four. Early laboratory and field tests were promising and performance measured equalled and surpassed in some areas that of a standard off-road pneumatic wheel.

Tests indicate that the grouser system which relied on the concept of soil to soil contact friction is working well. However it was found that light grouser strength is driven by the rock content of the drive profile. A unique method to strengthen grousers was developed. Light multi-strand cables were employed to interconnect all the grouser system elements and make them function in a collective manner without losing flexibility.

Thin single sheet-metal construction simplified the manufacturing processes of complex wheel designs and enabled the scalability of the design to meet different rover loads and performance. Wheel flexible elements spring constant can be modified by changing material, width, length and thickness. Thin tread protection mechanisms functions were successfully demonstrated during field tests.

Emulating radial pneumatic wheel functions ensured that wheel design heritage was reused. Emulating pneumatic wheel air pressure function through the use preloaded inner radial band “OO” pillows was a simple and successful solution.

The use of bead-lock rims simplified the rim to side wall torque path interface and wheel assembly. However, the rim, though made of carbon fibre still accounted for half of the wheel mass.

Fast prototyping technique proved valuable in allowing a relatively small multidiscipline team to react quickly to enable retooling and building new expertise to support the evolving plans and needs of a space organization.

8. FUTURE WORK

The development iterations of the FW-350 have identified many problems which were dealt with. To set the current concept on a space flight path the following need to be done:

Further rigorous field and laboratory testing is required to identify the wheel failure modes and reliability over extended operations. CSA is already involving industry and academia in modelling and testing the reliability of rover components including wheels.

Different wheel materials need to be examined to further reduce the wheel mass and be compatible with lunar environment.

9. ACKNOWLEDGMENT

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10. REFERENCES


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