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A performance of Single Phase Switched Reluctance Motor having both Radial and Axial air gap

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Abstract - Switched Reluctance Motor has doubly salient poles in stator and rotor, windings are wound in just stator and no magnet or windings on the rotor. This configuration is robust mechanically and thermally.
The inverter of SRM is more robust than that of induction or brushless DC(BLDC) motor, but still its drive is comparatively expensive for home appliance . To drive the conventional three or four-phase SRM, 6 to 8 power switches are required when asymmetric bridge inverter is employed. Generally, more than 50% of the cost for the SRM drive is allocated to power devices and gate drives. This paper proposed single phase SRM that have both radial and axial air gaps. The stator and rotor were stacked with two types of stampings that have different diameters. This configuration is very effective to increase align inductance(Lmax). The high value of Lmax increases the motor efficiency and power density. The proposed single phase SRM(Claw SRM) can be driven by only two power switches. To show the validity of the proposed idea, the analysis using finite element method(FEM) and experimental works are carried out.
The proposed SPSRM can be driven with high efficiency and can be made compactly and inexpensively because of high value of align inductance and less number of switches. For the comparison, we used same stator for three-phase and single phase, and slightly different stator and rotor for proposed single phase SRM(Claw SRM).

I. INTRODUCTION

The characteristic of SRM are very similar to that of BLDC motor and comparatively inexpensive, but still it does not have cost merits compared to that of induction or universal motor. This is mainly due to the fact that inverter is required to drive the SRM. To cope with this problem, especially it is very important that engineer should consider both sides of motor and electronics to optimize the overall drive system for certain applications. In this paper, efficient SPSRM that is driven with low cost inverter is proposed. Conventional 6/4 shaped 3 phases SRM produce 3 different inductance profiles that are shifted by 120 electrical degrees each other. However, this SPSRM generate only one inductance profile, so there are some problems such as starting and negative torque. To solve these problems, the parking magnet attached on stator pole can be employed and this parking magnet settle the rotor always at predetermined position [1]. Another patent[2] suggested stator poles arranged irregularly to avoid starting problem.

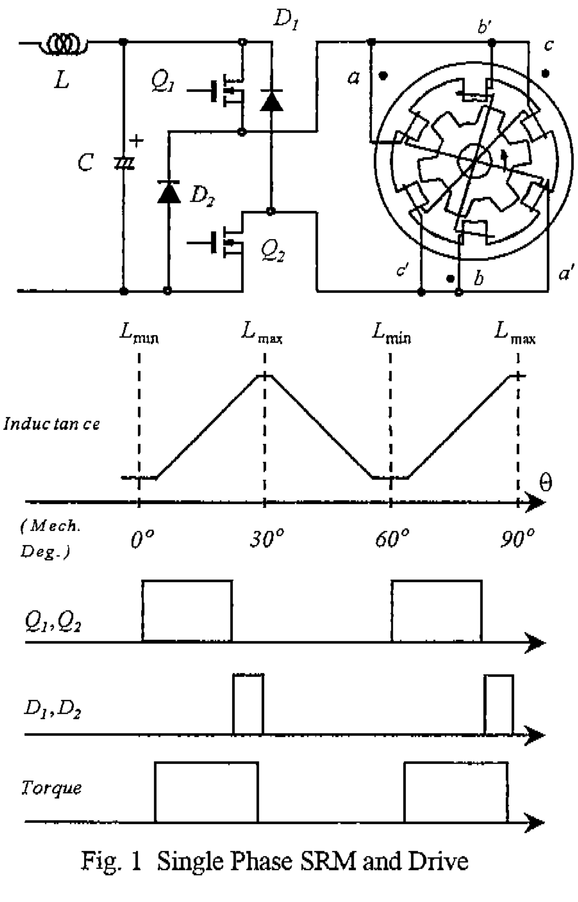
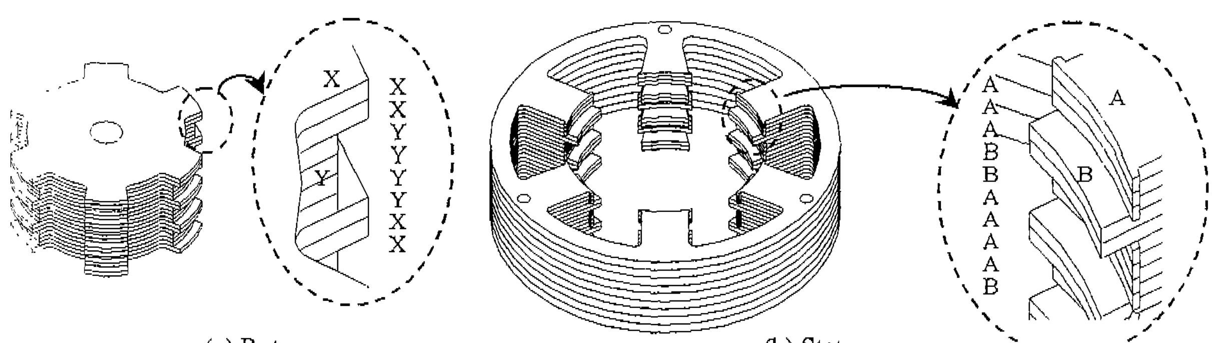


Fig. 1 Single Phase SRM and Drive

To increase torque, Lmax should be increased because Lmin can not be controlled easily.(Fig. 7) If a designer increase the number of turns to obtain higher static torque, not only Lmax but also Lmin and winding resistant increased. Theorforc, even if static torque is increased, dynamic performance will be degraded. The conventional SRM uses only one side inductance term (radial or axial), but proposed single phase SRM use both radial and axial inductance term as like equation (3) because of axial contacting area between rotor



(a) Rotor (b) Stator

Fig.2 Stack of proposed SPSRM(claw SRM)

Table 1.Motor Dimension and Spec.

Out dia. of Rotor		Inner dia. of Stator	
X	50.0 mm	A	50.6 mm
Y	46.0 mm	B	46.6 mm

Air Gap (mm)	Radial : 0.3 Axial : 0.5
Number of Turns : 160 / Pole	
Winding Resistance : 1.3 Ω / Pole 0.87 Ω / Total	

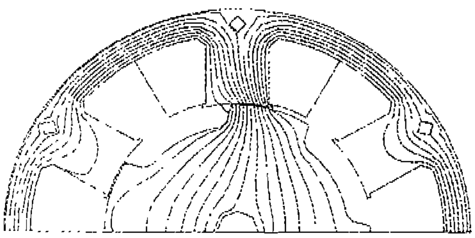


Fig.3 6/4 3phases SRM

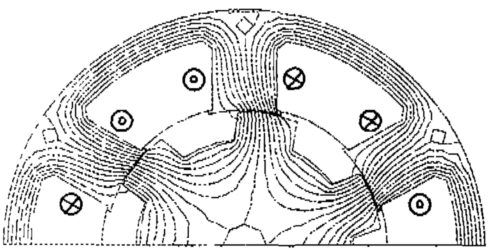


Fig.4 6/6 SRM Simulation (radial)

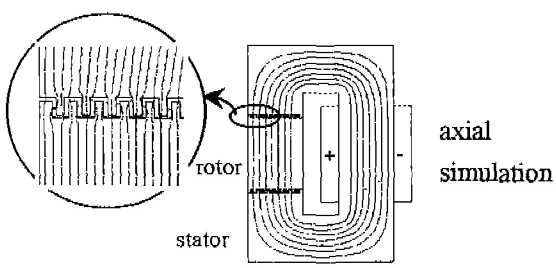


Fig.5 Proposed 6/6 SRM Simulation (axial)

$$T = \frac{1}{2} \cdot i^2 \frac{dL}{d\theta} \tag{1}$$

$$\frac{dL}{d\theta} \approx \frac{L_{max} - L_{min}}{\pi / 6} \tag{2}$$

$$L_{max} \approx \frac{\mu_0 \cdot N^2 \cdot A_r}{l_{gr}} + \frac{\mu_0 \cdot N^2 \cdot A_a}{l_{ga}} \tag{3}$$

$$(\mu >> \mu_0)$$

$$L_{min} \approx K \cdot N^2 \tag{4}$$

μ_0 : permeability of air
μ : permeability of magnetic material
l_{gr} : radial air gap length (m)
l_{ga} : axial air gap length (m)
N : number of turns (two poles)
A_r : effective radial contact area of rotor and stator
A_a : effective axial contact area of rotor and stator
K : proportional constant

and stator laminations.

II. SIMULATION

Fig.1 shows configuration of proposed SPSRM and its drive. In this motor three individual windings ,each windings has serial connection of diagonal poles (a-a',b-b',c-c'), are connected with parallel. The windings have a polarity to make short flux path as shown in Fig.4. Otherwise one of stator back yoke can be concentrated with magnetic flux three times of normal amount flux. There are several different ways to make short flux path but this paper use the connection method as shown in Fig.1 to use same stator with 3phase and conventional single phase in the experiment. The stacking method employed for the proposed SPSRM is shown in Fig. 2. The proposed SPSRM consisted of two types of rotor and stator stampings with 0.5mm thickness as shown in Fig. 2. This SRM can be assembled on the full

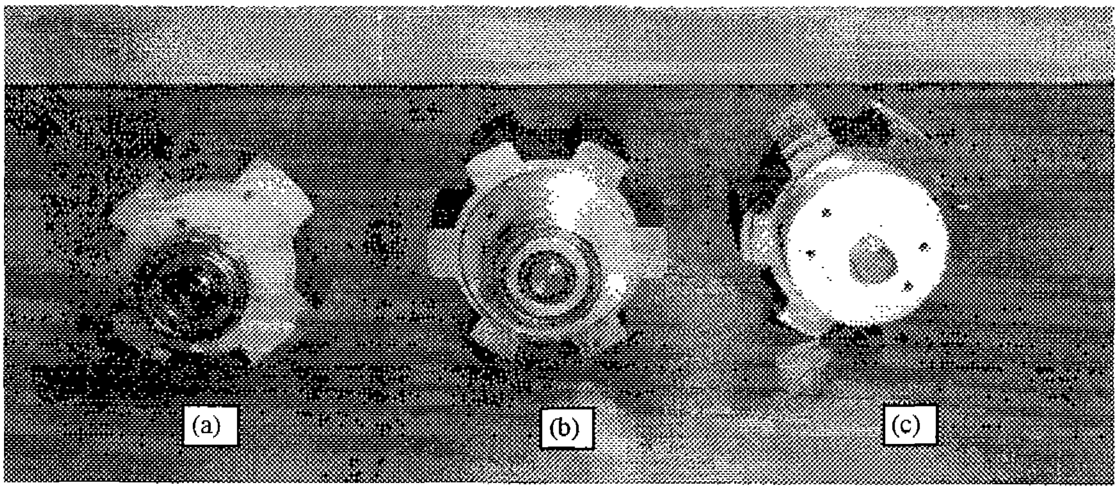


Fig.6. 6/4,3phase(a), 6/6SPSRM(b), proposed 6/6 proposed SPSRM(c) rotor picture

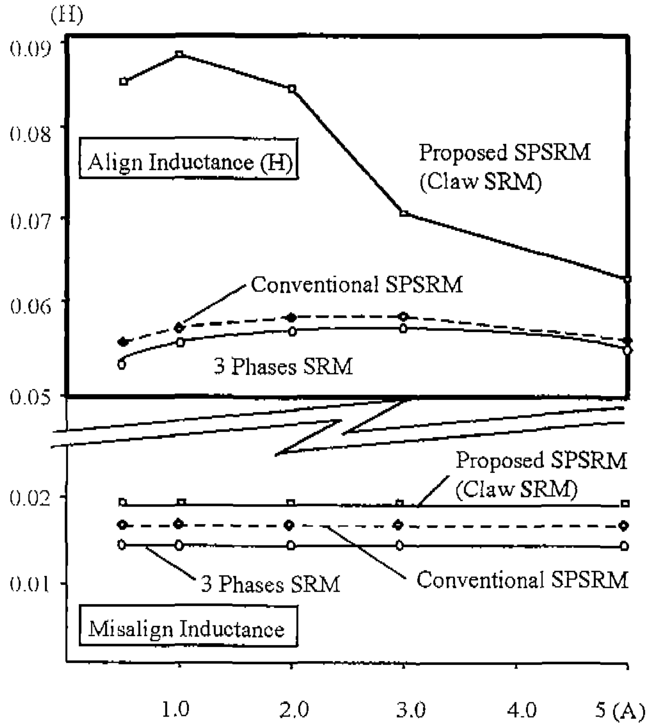


Fig.7 Comparison of inductance (simulation)

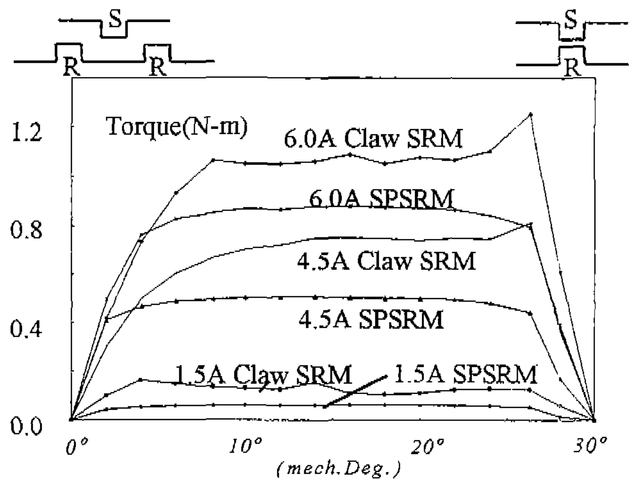


Fig.8 Static Torque w.r.t Constant Current (experiment)

misalign position and push down the rotor to z-direction (perpendicular to paper), and it is possible only in the case that rotor and stator has a integer multiple tooth ratio. This condition is generally satisfied in single phase SRM. In conventional SRM design, a precise simulation results can be obtained using only two-dimensional analysis with ignoring fringe field effect and assuming magnetic flux flow only x-y plane. Fig.3 and Fig.4 show the conventional FEM analysis of two dimensional plane.

This proposed SPSRM(Claw SRM) has a z-direction magnetic flux considerabl. The proposed SPSRM should be analyzed with three-dimensional FEM tool, but similar result can be obtained by executing two times of two-dimensional analysis, axial and radial direction respectively. From this simulation, The Inducatnce ratio of the flat gap (conventional) to claw gap(proposed) can be obtained.

The increased inductance value can be found out as shown Fig.7. Usually SRM with a same number of winding turns has a similar misalign inductance(Lmin). In Fig. 7 Inductance of three different types of SRM are compared at the position of Lmax and Lmin. Both conventional SPSRM (flat type)and three phases SRM have a almost same Lmax but proposed SPSRM has a 50% higher align inductance value comparing with conventional type. In the Fig.8 static torque is compared between flat type SPSRM and Claw SRM with same constant current. Proposed single phase SRM(Claw SRM) produces higher static torque by 25% at 6A, by 35% at 4.5A, by 35% at 1.5A. The static torque difference between flat and claw SRM is small in higher current because of magnetic saturation.

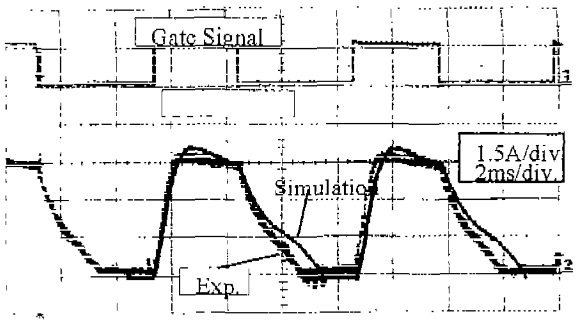


Fig.9 Flat Type SPSRM Simulation & experiment (Conventional SPSRM) 1400rpm

Simulated and experimented current wave-forms are shown in the Fig. 9 for the flat type SPSRM. For the case of conventional SRM precise simulation result can be obtained in both static and dynamic simulation, but in the case of claw SRM same simulation is almost impossible with two-dimensional FEM analysis.

There is large difference in current shape between flat type(Fig. 9) and claw type(Fig. 10(d)) in high speed fan load. In spite of magnetic saturation which begins at a lower current for claw SRM as shown in Fig.7, still the gap more than 10% in efficiency is maintained as shown in Fig. 12.

III. EXPERIMENTAL RESULT

To increase Lmax, reducing of air gap length is used generally, but it is limited by mechanical tolerance. And increasing the number of turns is another choice, but this also increase copper losses in a same motor volume. Therefore machine designer should decide optimum condition between turns and resistance of winding. Proposed SPSRM has higher align inductance (Lmax) at the same winding resistance because of large air gap area. Since align inductance(Lmax) of proposed SPSRM is larger than that of conventional air gap SRM, proposed SPSRM produces larger torque at the same current. And this proposed SPSRM and its drive can be made compactly, because of high Lmax in the motor side and less number of power devices in the drive side. In Fig. 10 is shown summation of current of a-a',b-b',c-c'[Fig.1] and gate signal applied by voltage control with fixed advance angle. In this paper two IGBT power devices was used for the asymmetric bridge converter. This paper does not mention about the starting condition. If supposes that the motor is running condition, starting problem or zero torque problem does not break out any trouble because of fan inertia Over the 1200rpm, it can be known from Fig. 10 that sharp peak current shape appears at turn-off position (12 mech. degree before align) because of magnetic saturation. Magnetic saturation affect the efficiency of motor because permeability of iron decrease, but still claw SRM has advantage in motor efficiency compared with conventional

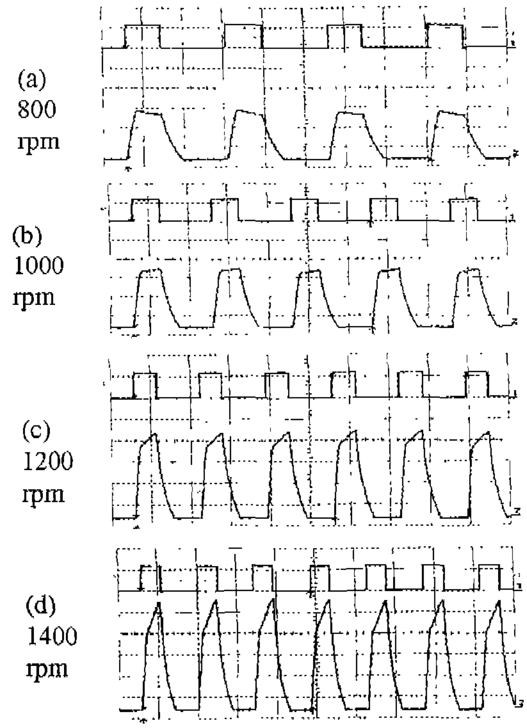


Fig.10 Total Current vs. Speed (Claw SRM)
(Fixed Advance Angle , 1A/div. , 5ms/div.)

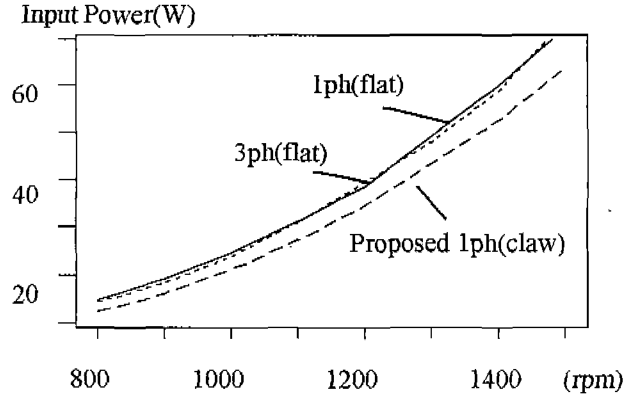


Fig.11 Comparison of Input Power

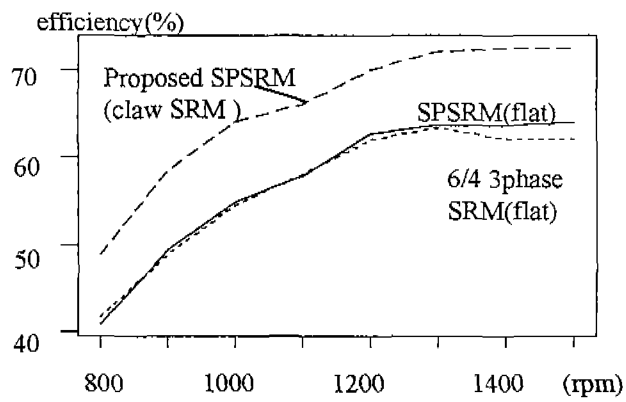


Fig.12 Comparison of Efficiency

single or three phase SRM even at 1400rpm based on the experiment result of Fig.12. So, this claw SRM has superior performance throughout all running condition and has a good power density. The flux path of SPSRM is shorter than that of conventional 6/4 three phases SRM. This short flux path reduces the losses on iron part. So proposed SPSRM is more efficient. Fig.11 shows the comparison of input powers to run a fan at the each same speed of 3 different SRM including claw SRM. The difference of input power is 3 watts at 800rpm and 12 watts at 1500rpm, from which it can be known claw SRM has much smaller input in all running condition. Fig.12 shows the comparison of efficiency. Claw SRM has higher efficiency by more than 10% at a operating speed. This paper also compared both efficiency and input power of proposed SPSRM with those of conventional SRM in Fig. 11 and Fig. 12. It is proved that propose SPSRM has

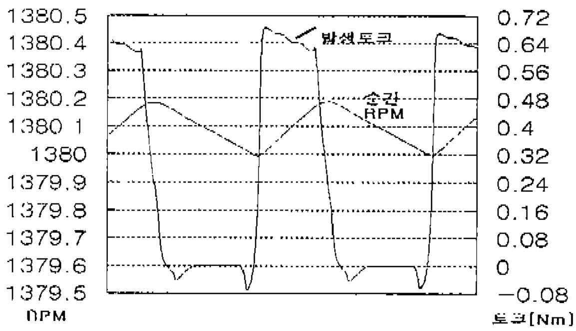


Fig.13 Simulation of Speed Ripple

higher efficiency than that of 6/4 or conventional SPSRM. Through the experimental works, it can be concluded that proposed SPSRM shows the advantages such as the higher torque to weight ratio and efficiency.

IV. FAN LOAD

Instantaneous motor speed can be decided based on the produced torque and load and inertia.

$$T_e - T_L = J\frac{d\omega}{dt} \quad (5)$$

$$T_L = k_1 + k_2 \cdot \omega^a + k_3 \cdot \omega^b \quad (6)$$

T_e : instantaneous motor torque

T_L : load torque

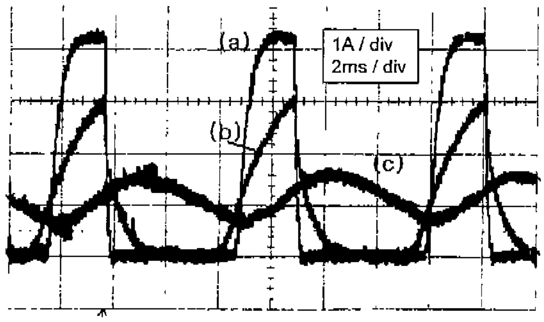
J : inertia of fan and rotor

ω : angular speed (rad/sec)

k_1, k_2, k_3, a, b : fan load constant ($k_1 \cong 0$)

Zero-torque problem in SPSRM can be simply solved in case of fan load because fan requires only small friction torque at starting, and rotates in uni-directionally. And because fan also has big inertia generally, it reduce torque ripple considerably like Low Pass Filter. So, it is suitable load for SPSRM.

As shown in Fig. 13 which illustrates speed variation by torque pulsation, its speed ripple is smaller than 0.1 rpm because of large inertia of fan.



(a) : C=1500μF without L
(b) : C=5000μF without L
(c) : C=1500μF L=16mH
Fig.14 DC Link Current Ripple

V. CURRENT RIPPLE from DC SUPPLY

Because all windings are activated simultaneously in SPSRM, voltage and current ripples of the DC link capacitor are higher than those of the DC link capacitor for 3 phase SRM. So, in this experiment, small series inductor was added at the front of DC link capacitor as shown in Fig. 1. The added inductor can smooth the current ripple very effectively than adding big capacitor, and it is cost effective.

VI. CONCLUSION

This paper proposed an efficient SPSRM(Claw SRM having both radial and axial air gaps. Moreover, the drive circuitry has only two power devices. Both motor and drive electronics can be made compactly, so inverter of proposed SPSRM can be made with considerably low cost compared with conventional three phase SRM inverter.

The proposed SPSRM is suitable for fan applications because the inherent starting problem does not critical and fan inertia can reduce torque ripple for this applications. For the proposed SPSRM, the noise and vibration problems of motor, voltage and current ripples in DC link capacitor should be studied further.

VII. REFERENCES

[1] Swedish Patent Number 9004168-2
[2] Peter Lurkens, United States Patent, Patent Number - 5,428,257, 1995