Theoretical Formulation of Rotary Energy Absorbing Device Based on Model Testing

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1. INTRODUCTION

Rotary Energy Absorbing Device (READ) or fluid twister is an energy absorbing mechanism generally used during the launch of Unmanned Air Vehicles (UAV). This READ system along with other sub-systems like nylon tape, net, etc., is used effectively during emergency landing of manned aircrafts. This is a compact, maintenance free, low cost, highly reliable system for energy dissipation.

The energy absorption is a complex phenomenon and operates on the principle of fluid drag for absorption and dissipation of input energy. The energy is mainly absorbed by the drag generated due to vanes rotating in the fluid media. The energy absorbing capacity is a function of various parameters like quantity and type of fluid inside the drum, axial gap between the static and rotary vanes, dimensions of rotor vane, etc.

In this paper, an attempt has been made to derive the system equation for energy dissipation using experimental data.

2. BACKGROUND

Previous studies have been attempted to fully understand the energy absorption phenomena. In [1], the resisting torque generated by rotating vane has been derived without taking into account the parameters like quantity and type of fluid inside the drum, axial gap between the static and rotary vanes, etc. In [2], a theoretical integrated design approach of READ is discussed in detail for its intended application on Remotely Piloted Vehicle (RPV) launcher. In [3], a modified design approach using coupled non-linear differential equations of READ system for Rocket Assisted Launcher (RAL) is described. Reference [4] deals exclusively with the failure analysis of nylon tape and modifications of READ system to obtain the desired performance, as applicable to Hydro-Pneumatic Launcher (HPL).

In this paper, parameters like effect of type and quantity of fluid media, axial gap between the rotor and stator vanes, etc., are addressed. Hence, a model has been designed, fabricated, and extensive tests are conducted to arrive at meaningful conclusions.

3. CONSTRUCTIONAL DETAILS

Fig. 1 shows the solid model of fluid twister. A typical fluid twister consists of a number of moving and fixed vanes fixed on the shaft and the housing respectively. The vane assembly rotates in a housing filled with fluid. The moving vanes and fixed vanes are separated by a specified axial gap. From the literature and also as used in launcher, eight numbers of rotating vane and 9 numbers of fixed vane is selected. It is proposed to vary these numbers and study its effect subsequently. The energy of system to be dissipated is applied on the shaft of READ through a suitable pulley fixed on the shaft. The KE is absorbed by the fluid present in the housing by work done against the resisting torque of the vane system. The fluid travels back and forth between stator and rotor vane, there by absorbing energy.

4. EXPERIMENTAL SET-UP

Fig. 2 shows the experimental set-up. The shaft of the fluid twister is connected to the hydraulic motor through a love-joy coupling, which in turn gets energized by hydraulic power. The READ system has the provision to measure the temperature and pressure of the fluid media. A thermocouple and a pressure transducer are located inside the chamber to measure the fluid temperature and chamber pressure respectively. The variation of pressure is recorded online in computer whereas the rise in temperature is recorded manually at an interval of every 15 seconds. The milli-volt output from the sensors is converted to the pressure units by appropriate calibration. The RPM recording is carried out online by an arrangement of a permanent magnet and an energized coil. This data is further processed to obtain the RPM vs time plots.

5. TEST CONDITIONS

The experiments are conducted using a constant hydraulic pressure set-up of **100 bars** (P).

5.1) Varying the quantity of fluid media for a fixed axial gap of 2.8 mm

- Dry run (with no water)
- 100 % water (6.8 litres), 75% water (5.1 litres) and 50% water (3.4 litres)

5.2) Different types of fluids media for a fixed axial gap of 2.8 mm.

- 100 % water, 100 % SAE 40, 100 %SAE 10, 80:20 ratio of water(W) and ethylene glycol(GLY) and 60:40 ratio of water and ethylene glycol.

5.3) Variation of axial gap between stator and rotor blades with 100% water

- 2.8, 4.8 and 6.8 mm

6. ANALYSIS OF DATA

Fig. 3A shows the plot of RPM verses time of the rotor by varying the quantity of fluid media for a fixed axial gap of 2.8 mm. Similarly, Fig 3B, 3C shows the variation of RPM w.r.t for different types of fluids media for a fixed axial gap of 2.8 mm and variation of axial gap between stator and rotor blades respectively. The data for all the experiments is taken for 3 seconds. Following values are derived from configuration and figures.

6.1) Energy Supplied (E1) - Dry run

The energy supplied on dry run is calculated from the Fig. 3A.

Torque supplied (T)= Input pressure (P)* Volumetric displacement (v)

$$T = 100\,e^{5}*(1.52*2.54^{3}) / (100^{3}*2*\Pi) = 39.64 \text{ Nm}$$

Energy supplied (E1) (250 rev. in 3 seconds) = 6.226 X 10^4 Nm (Dry run)

6.2) Virtual Inertia (Ev)

Here, Ev = 0.5*Iv* ω^2 . Where, Iv = Mass M.I. and ω angular velocity of rotating fluid.

6.3) Energy supplied by motor with fluid inside the drum (E2)

Energy supplied (E2) for 3 seconds = Torque supplied (T) * angular displacement

6.4) Energy dissipated (Ed)

Ed is obtained by subtracting (E2+Ev) from E1.

7. FORMULATION OF SYSTEM EQUATION

The resisting torque (T) developed depends upon dynamic viscosity (μ), wetted area(A), density(ρ), angular velocity(ω) and axial gap between stator and rotor vanes(x). Hence, T=ϕ (μ, A,ρ,ω, x). From Buckingham π theorem, it can be written as $\pi_1=\phi(\pi_2,\pi_3)$---(1). The selection of A, ω and ρ as repeating variables respectively gives

$$\pi_1=[\rho]^{a1}[\omega]^{b1}[A]^{c1}T\text{--(2)},\ \pi_2=[\rho]^{a2}[\omega]^{b2}[A]^{c2}\mu\text{--(3)},\ \pi_3=[\rho]^{a3}[\omega]^{b3}[A]^{c3}x\text{--(4)}$$

Solving (2), (3) and (4), we get $\pi_1= T/(\rho\,\omega^2 A^{2.5})$ --(5), $\pi_2 = \mu / (\rho A \omega)$ --(6), $\pi_3 = x / (\sqrt{A})$ ---(7)

Substituting and rearranging in equation (1), $T=\rho\,\omega^2 A^{2.5}\,\phi(\mu / \rho A \omega, x / \sqrt{A})$. Reynold's number (Re) for rotational motion = $\rho\ A\ \omega/\mu$. Hence, $T = \rho*\omega^2*A^{2.5}\ \phi(1/Re,\ x/\sqrt{A})$. Energy equation is obtained by integrating as $Ed=\int T*\omega\ dt$ and if it is assumed that ω is not varying w.r.t., then, $Ed=T*\omega*t$ and substituting T, $\mathbf{Ed=\rho*\omega^3*A^{2.5}*t*\phi(1/Re,\ x/\sqrt{A})}$ **—(8)**

Equation (8) in function form, is converted into algebraic form by the following method.

7.1) Case-I: Keeping (1/Re) constant and varying $(x/\sqrt{A})$

The equation (8) gets modified as, $Ed = \mu*\omega^2*A^{1.5}*t*\phi(x/\sqrt{A})$ ---(9)

Equation (9) implies that the energy dissipated is not dependent on density, violating the experimental result. **Hence this relationship is not considered for further analysis.**

7.2) Case-II: Keeping $(x/\sqrt{A})$ constant and varying (1/Re)

The equation (8) gets modified as, $Ed= \rho*\omega^3*A^2*t*x*\phi(1/Re)$ ---(10)

Equation (10) satisfies the experimental results and hence is considered for further analysis.

From equation (10), the required relationship in algebraic form is obtained by plotting (1/Re) on X-axis and $(Ed/\rho*\omega^3*A^2*t*x*)$ on Y-axis and is shown in Fig. 4. The values for the plot is calculated from five experimental data points for five different kind of fluid media selected for experimentation and is shown in Table 4. The value of A is calculated based on the rotating fin dimensions multiplied by number of vanes (in this case 8) and is taken as 0.00452 m^2. Also, the values of x(axial gap) and t(time) is taken as 2.8mm and 3 seconds respectively.

The following final equation for energy dissipation is obtained by using MATLAB.

$$\mathbf{Ed = \rho*\omega^3*A^2*t*x*1e^8\ (6.483/Re^2 - 0.0085/Re + 0.000013)} \quad \text{---(11)}$$

$$\text{Or } \mathbf{Ed = \rho*\omega^3*A^2*t*x*1e^8\ (6.483*\mu^2/\rho^2*\omega^2*A^2 - 0.0085*\mu/\rho*\omega*A + 0.000013)} \quad \text{---(12)}$$

8. RESULTS AND DISCUSSIONS

Equation (12) can be written in terms of Torque (T) by dividing the dissipated energy (Ed) by time (t) and angular velocity;

$$\mathbf{T = 1e^8\ [6.483*\mu^2*x/\rho - 0.0085*x*\mu*A*\omega + 0.000013*\rho*x*A^2*\omega^2]} \quad \text{---(13)}$$

Which, can further be written in condensed form as, $\mathbf{T = a - b*\omega + c*\omega^2}$ ---(14)

Where, $\mathbf{a = 1e^8*[6.483*\mu^2*x/\rho],\ b = 1e^8*[0.0085*x*\mu*A],\ c = 1e^8*[0.000013*\rho*x*A^2]}$

To validate equation (12), ω is estimated by substituting all the values of dependent variables. This value of ω is then compared with that obtained from experiments and is shown in Tables 5, 6 and 7. It is seen that error is between the estimated and the experimental RPM is comparable for this kind of complex phenomena.

9. CONCLUSIONS

- Experiments were carried out to evaluate the effect of axial gap between stator and rotor vanes, effect of quantity and type of fluid in the housing on the resisting torque generated and the energy dissipated.
- The resisting torque (T) is a function of wetted area of the rotating vane (A), properties of fluid used like dynamic viscosity (μ) and mass density (ρ), axial gap between the rotor and stator vane (x) and angular velocity (ω).
- There is an optimum value of axial gap, for which energy absorbing capacity is maximum, when other parameters are kept constant.
- The % quantity of fluid is most important parameter for effective working of the system.

10. REFERENCES

[1] JRN Reddy and AS Reddy, "Theoretical studies and model testing of Rotary Energy Absorbing Device", ADE report No. ADE/TR/90-86(a), Jan 1990.

[2] AS Reddy, "Integrated design of Rotary Energy Absorbing Device for Launcher", Design Engineering, Proceedings of National Conference on Design Engineering - NACOMM 91, Madras.

[3] AS Reddy, Vasanth Sastry & TN Balasubramanyam, "Rotary Energy Absorbing Device for Launcher - A concept put into practice", National COnference on Machines and Mechanism (NACOMM) - 95, CMERI, Durgapur.

[4] Vasanth Sastry, AS Reddy and J Jayaraman, "Rotary Energy Absorbing Device for Launcher - A case study", 24th National System Conference (NSC) - 2000, ISRO, Bangalore.

Table 1: Varying the quantity of fluid media (water) for a fixed axial gap of 2.8 mm

Sl.No.	Qty. of fluid	Rise Time, (s)	Max. RPM	Ev (N-m)	E2 (N-m)	E=E1-E2 (N-m)	Ed=E-Ev (N-m)
1.	100 %	0.05	625	20.99	7718	54550	54530
2.	75%	0.08	700	19.747	8601	53670	53650
3.	50%	0.10	1000	26.867	12329	49940	49910

Table 2: Types of fluid media for a fixed axial gap of 2.8 mm

Sl.No. o.	Type of fluid	Rise Time (s)	Max. RPM	Ev (N-m)	E2 (N-m)	E=E1-E2 (N-m)	Ed=E-Ev (N-m)
1.	Water	0.05	625	20.99	7718	54550	54530
2.	SAE 40	0.10	665	21.576	8143	54120	54100
3.	SAE 10	0.10	665	20.745	8143	54120	54100
4.	60W:40GLY	0.05	600	19.925	7285	54980	54960
5.	80W:20GLY	0.05	565	18.526	6871	55390	55370

Table 3: Varying the axial Gap for 100 % WATER

Sl.No.	Axial Gap(mm)	Rise Time (s)	Max. RPM	Ev (N-m)	E2 (N-m)	E=E1-E2 (N-m)	Ed=E-Ev (N-m)
1.	2.8	0.05	625	20.99	7718	54550	54530
2.	4.8	0.06	485	12.64	6596	55670	53650
3.	6.8	0.06	535	15.38	5979	56280	56270

TABLE 4: Experimental data points for five different kind of fluid media

SL. NO.	MEDIA	Density kg/m^3	Dynamic viscosity N-s/m^2	$X=\mu/\rho*A*\omega$	$Y=E_d/\rho*\omega^3*A^2*t*x$
1	Water	1000	8.74e-4	0.003e-3	1.133e3
2	SAE40	908	2366e-4	0.828e-3	1.028e3
3	SAE10	873	938e-4	0.341e-3	1.069e3
4	W60-40G	1080	40.8e-4	0.013e-3	1.195e3
5	W80-20G	1030	24.77e-4	0.009e-3	1.513e3

TABLE 5: Comparison of ω for variation of qty. of fluid media for an axial gap of 2.8 mm

SL. NO.	Quantity of Fluid (water)	Energy dissipated (N-m)	Experimental RPM	Theoretical RPM (Estimated)	% error
1	100 %	54527	625	597	4.48%
2	75 %	53645	700	720	-2.8%
3	50 %	49911	1000	921	7.9%

TABLE 6: Comparison of ω for various fluid media (100%) for a fixed axial gap of 2.8 mm

Sl.No.	Media	Energy Dissipated (N-m)	Experimental RPM	Theoretical RPM (Estimated)	error%
1	Water	54527	625	597	4.48%
2	SAE40	54101	665	662	0.45%
3	SAE10	54102	665	662	0.45%
4	W60-40G	54961	600	585	2.5%
5	W80-20G	55377	565	595	-5.3%

TABLE 7: Comparison of w for different axial Gap for 100 % water

SL. NO.	Axial Gap (mm)	Energy dissipated (N-m)	Experimental RPM	Theoretical RPM	% error
1	2.8	54527	625	597	4.48%
2	6.8	55655	535	447	16.4%
3	4.8	56274	485	504	- 3.9%

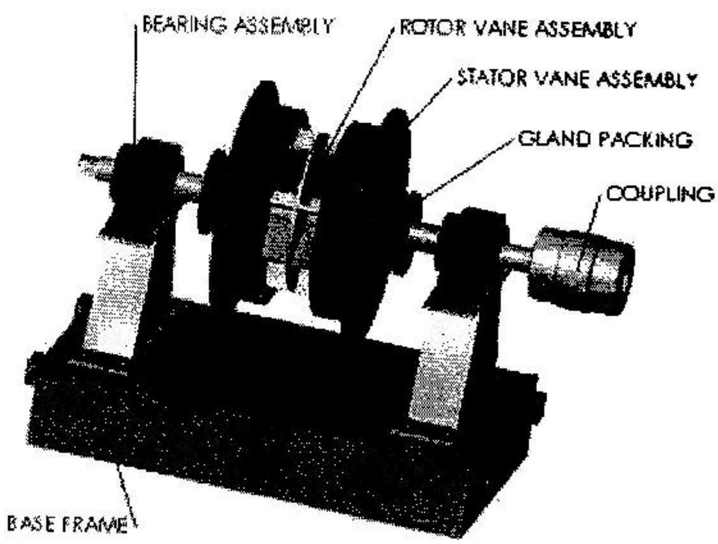

Fig 1 Solid model of READ

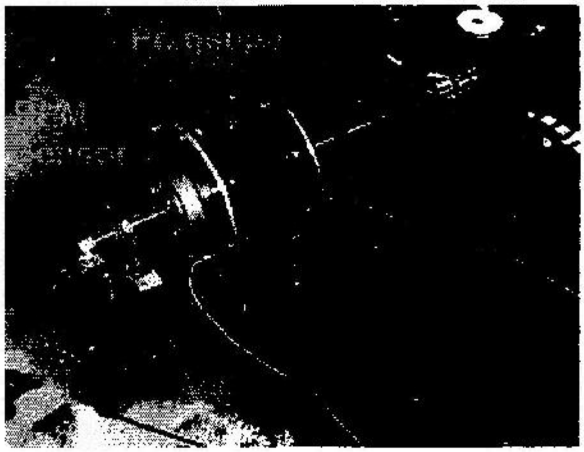

Fig 2 Experimental set-up-READ with sensors

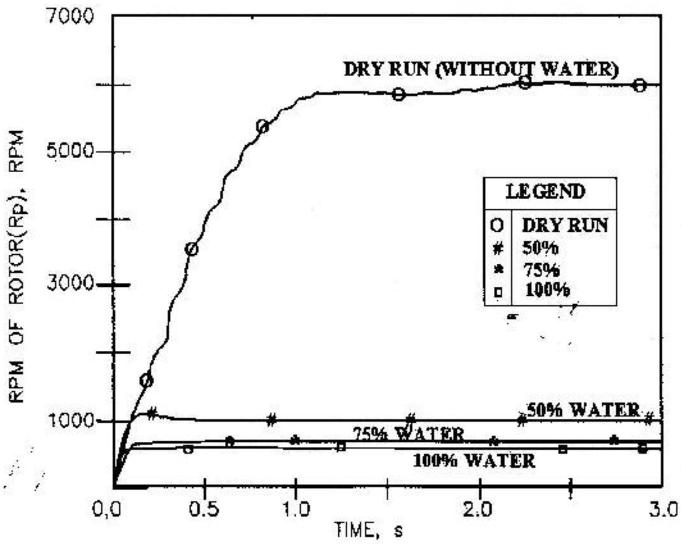

Fig 3A RPM vs. Time for variation in quantity of fluid

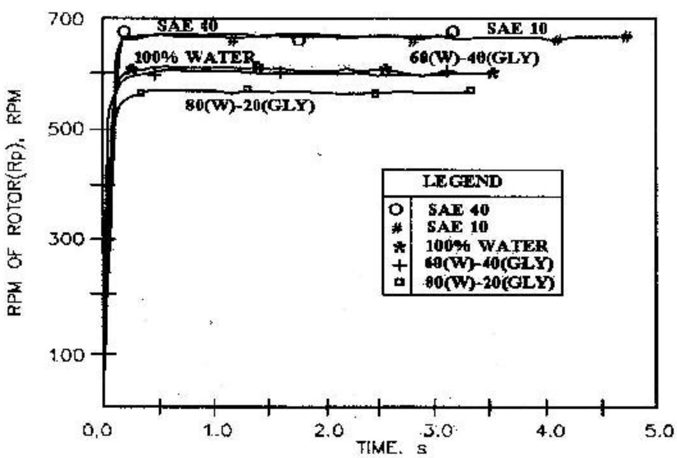

Fig 3B RPM vs. Time for various types of fluid

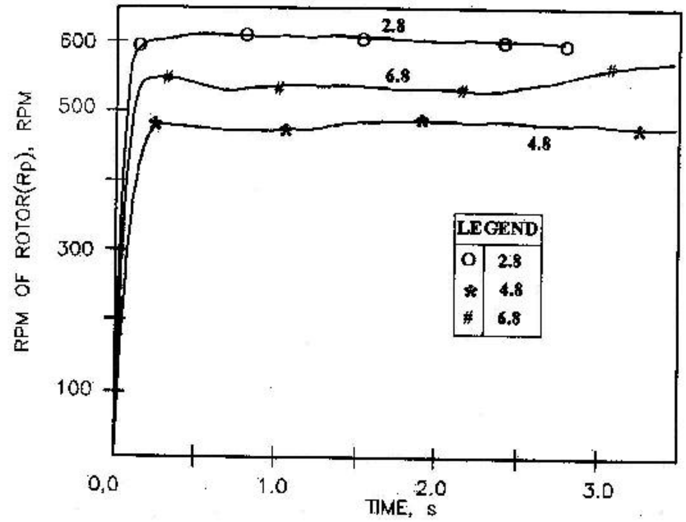

Fig 3C RPM vs. Time for variation of axial gap between stator and rotor blades

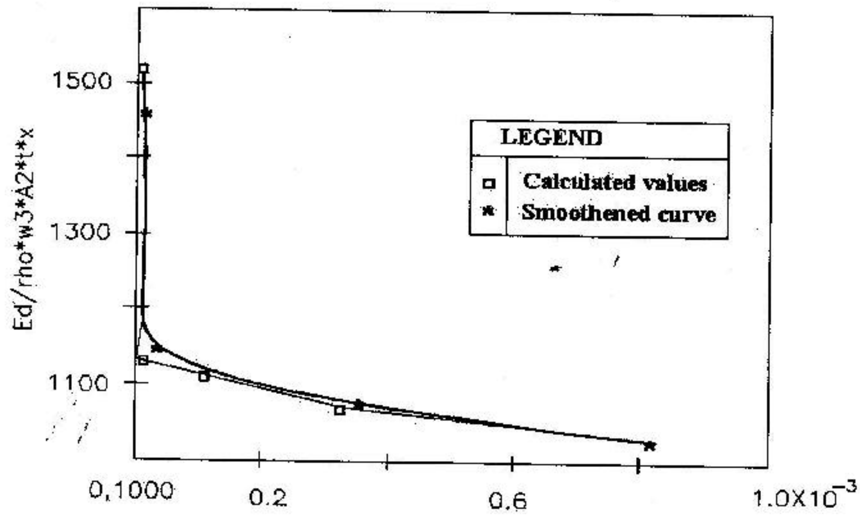

Fig 4 Development of equation for energy dissipation (Ed)

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