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Hydraulic Force and Impeller Evaluation of a Centrifugal Heart Pump

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Abstract : A rig was constructed to test the performance characteristics and compare the hydraulic forces exerted on a centrifugal type artificial heart impeller. A conventional shaft, seal and bearing system, while driven by a small electric motor, supported the impeller which was separated from the pump casing by a six degree of freedom force transducer (JR3 Inc). Radial (x,y) and axial (z) hydraulic forces were recorded and compared. At physiological operating conditions, the results indicate that the double entry/exit centrifugal pump encounters a smaller radial force and significantly reduced axial thrust. These experimental results are valuable in the design of a magnetic bearing system to suspend the impeller of a centrifugal artificial heart pump. This experimental technique may also be applied to evaluate the required capacity and predict the lifetime of contact bearings in marine pumps.

Key words : Artificial Heart, Centrifugal Pump, Hydraulic Forces, LVAD.

1. Introduction and background

Investigators at QUT and TPCH have been researching artificial heart devices since 1996 leading to the development of a prototype pump. This 3rd generation centrifugal type pump aims to use latest magnetic technology to drive and levitate the non-contacting and rotating impeller within the device. A technique employed by most of the latest generation artificial heart pumps[2-5]. Unlike industrial centrifugal pumps, care must be taken not to impose damage to the pumping medium, i.e. blood. Therefore, this system eliminates the need for shafts or seals, common sites for damage to occur to the delicate blood cells[3]. Additionally, the implanted pump must operate without failure or regular maintenance for an extended period of time. The non-contacting magnetic configuration of

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** The Prince Charles Hospital (TPCH), Brisbane, Australia this pump eliminates component wear and allows for a mechanical life expectancy of up to 10 years[6]. The purpose of this investigation was to evaluate and compare the characteristics of the first two prototype iterations (Single entry/exit and double entry/exit centrifugal pumps) and assess their suitability to an artificial heart application.

The most important parameters under investigation were pump performance characteristics and hydraulic forces imposed on the impeller. The flow and pressure head performance characteristics are vital in determining the ability of the designed pump to meet the physiological circulation requirements of the body. Determination of hydraulic forces encountered by the impeller due to pressure differentials within the pump 〔*Fig. 1*〕 are essential in deciding the capacity requirements of the magnetic bearings to keep the impeller suspended and prevent impeller touchdown. In the case of marine pumps, knowledge of such forces aids in the determination of contact bearing capacities and bearing lifetime.

The force on the impeller is a direct result of the pressure distribution within the pump and the change of fluids momentum. Equations are used to calculate the radial force 〔*Eq. 1*〕 and axial force 〔*Eq. 2*〕.

$$T_r = 9794(KHD_2B_2) \tag{1}$$

Where:

T_r = Resultant radial thrust (Newton)
H = Head (Meter)
D_2 = Impeller diameter (Meter)
B_2 = Impeller width (meter)
K = Constant(varies with pump capacity)

$$T_a = (A_2 - A_s)\left[H_v - \frac{1}{8}\frac{\left(u_2^{\,2} - u_s^{\,2}\right)}{2g}\right]\gamma - (A_2 - A_1)\frac{H_v}{2}\gamma \tag{2}$$

Where:

T_a = Resultant axial thrust
A_2 = Area under impeller 〔*Fig. 1*〕
A_1 = Area Inner diameter 〔*Fig. 1*〕
A_s = Shaft area 〔*Fig. 1*〕
H_v = Output head 〔*Fig. 1*〕
U_2 = Impeller tip speed
Us = Shaft tip speed
γ = Specific Gravity

The following hydraulic forces were calculated using these modified equations from(1) and consulting the relevant graphs in(1) to obtain values for the coefficient K corresponding to a single or double pump arrangement 〔*Table. 1*〕.

Table 1 Theoretical Force Values

	Single Pump	Double Pump
Axial(z)	10.4(N)	0(N)
Radial Frce(x.y)	0.96(N)	0.2(N)

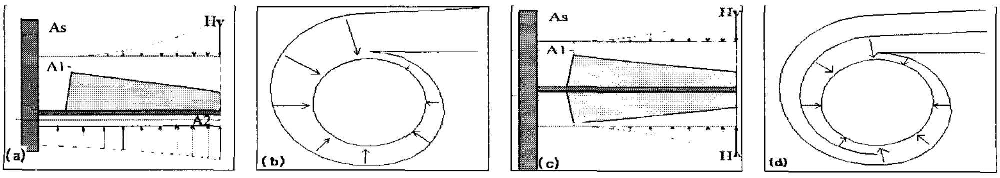

Fig. 1 Axial (a,c) and Radial (b,d) forces in a single and double sided centrifugal pump

The theoretical values presented describe the forces produced on the impeller of a centrifugal pump as a result of asymmetric pressure distributions within the pump.

2. Materials and methods

An experimental rig was constructed to compare the performance characteristics and the magnitude of hydraulic forces encountered by the impeller of the first and second iteration centrifugal pump. The centrifugal pump was constructed using stereo lithography technology (QMI, Brisbane). The impeller of each pump was supported by a conventional shaft and bearing system, and driven by a small 20W electric motor. The impeller, shaft, bearing and motor assembly (grey) was separated from the pump casing (black) by a six degree of freedom force transducer (JR3 Inc, Woodland, USA) and two flexible couplings (to prevent transferral of impeller forces to the casing) [*Fig 2*]. Thus, any forces imposed on the impeller were transferred through the shaft and resisted by the force transducer. The stiffness of the transducer was extremely high, preventing impeller movement and retaining a central position. A circulation loop was constructed incorporating a flow meter, pressure gauges and valves to enable testing and measurement [*Fig. 3*].

The pumps were operated at a range of outlet resistances. Recording flow rates and heads at various rotational speeds created pump performance curves. Radial (x,y) and Axial (z) forces were recorded and compared at physiological operating conditions of 5L/min and 100mmHg, and validated with theoretical values [*Table 1*].

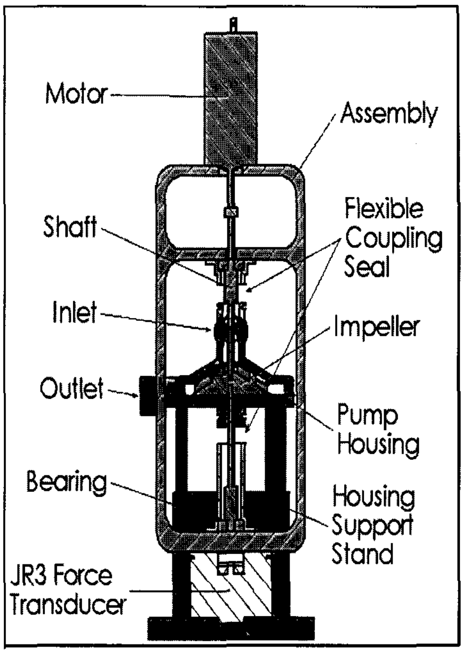

Fig. 2 Force Test Rig

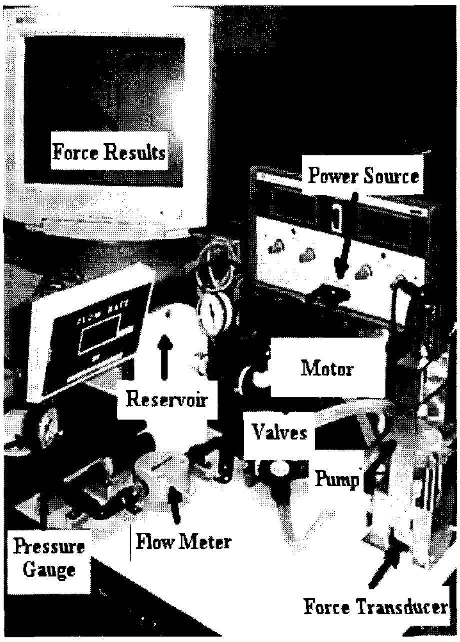

Fig. 3 Experimental circulation loop.

3. Results

A study of the pumps performance characteristics recorded the following performance curves at 1800 rpm and 2100 rpm. From these data, the design condition required for physiological circulation (5L/min, 100mmHg) was identified and achieved while testing the single and double pumps at rotational speeds of 2000 rpm and 2100 rpm respectively [*Fig 4&5*].

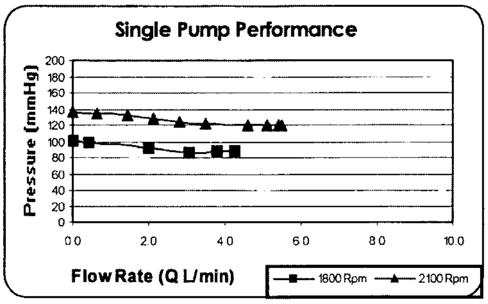

Fig. 4 Single Pump Performance

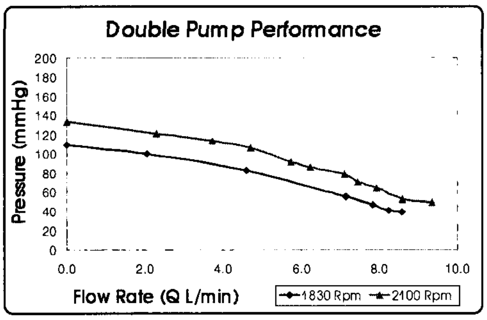

Fig. 5 Double Pump Performance

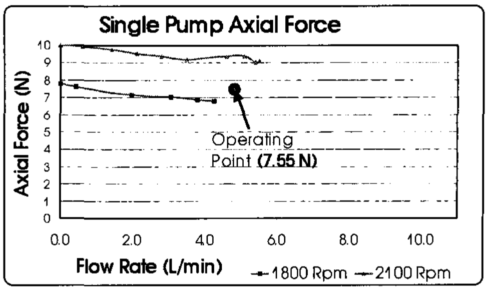

Fig. 6 Single Pump Axial Force

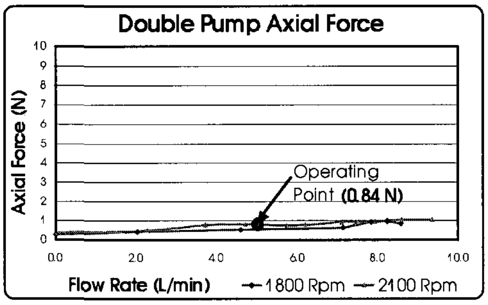

Fig. 7 Double Pump Axial Force

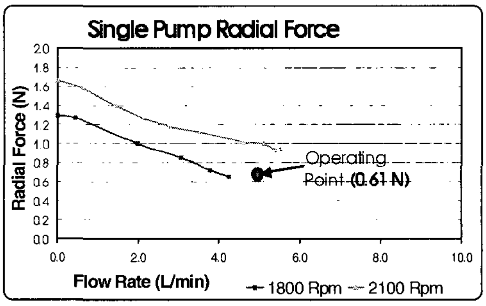

Fig. 8 Single Pump Radial Force

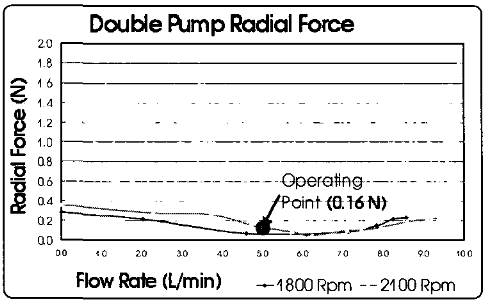

Fig. 9 Double Pump Radial Force

At the identified physiological operating conditions, the theoretical force values of the single entry/exit pump impeller were expected at 10.4N axial thrust (Z) and 0.96N radial load (X,Y). The experimentally measured axial force was 7.55N (Z) [Fig 6] and the radial force was 0.611N [*Fig. 8*]. The double entry/exit pump expected a theoretical axial thrust of 0N and a radial load of 0.2N. Practical measurements recorded an axial force of 0.84N (Z) [*Fig. 7*] and a radial force of 0.16N [*Fig. 9*].

4. Discussion

The first iteration single entry/exit centrifugal pump encountered large axial and radial forces due to the asymmetric pressure distribution within the pump. These forces act to displace the impeller off centre and must be counteracted by the magnetic levitation system to prevent impeller-casing touchdown.

These results prompted the importance of reducing those forces to reduce the size of the magnetic bearing. While running the pump at physiological operating conditions, it is essential to minimize the axial and radial force. A reduced hydraulic force increases the impeller suspension capacity of magnetically and hydro-dynamically suspended blood pumps. The lifetime of pivot bearing systems would also be potentially increased due to a decrease in frictional wear. By identifying the magnitude and direction of these forces, an optimum magnetic bearing current stiffness can be designed to handle these expected forces. Such a system would require less power to maintain impeller suspension and centering, thus efficiency would improve with a reduction in power consumption.

Acknowledging these design objectives, a second iteration centrifugal pump incorporating a double entry to balance axial thrust and a double volute casing to reduce radial force was developed. Running this pump at physiological operating conditions produced a 90% reduction in axial force, and a 75% reduced radial force.

Both iterations were able to meet the physiological requirements of the body at a relatively lower rotational speed than that of axial flow devices.

Reasonable correlation was found between practical and theoretical results. Errors are attributed to the approximate nature of the theoretical equations for radial and axial thrust[7]. It is envisaged that these experiments will aid in refining such equations for the application of a centrifugal blood pump. By modelling the forces encountered by a centrifugal blood pump impeller, it is possible to employ techniques to minimise such forces to the benefit of a magnetic motor or pivot bearing system.

5. Conclusion

The technique employed to measure impeller forces proved an accurate method to characterise hydraulic forces encountered by a centrifugal pump. This procedure may also be used to determine forces imposed on impellers of marine pumps. This analysis is beneficial to the design of magnetic bearing systems for centrifugal pumps, as well as for the prediction of wear characteristics in shaft and pivot supported systems.

The results indicate that both iterations of centrifugal pumps are able to meet the physiological output conditions required by the human body at a relatively low rotational speed. The impeller of the single entry/exit pump encounters a resultant radial force as well as a significant axial thrust, which must be countered to keep the impeller central. This would lead to an increased power consumption of a magnetic bearing, or increased wear in a contact bearing system. On the other hand, the double entry/exit centrifugal pump encounters a lower resultant radial force as well as a significantly reduced axial thrust, to the benefit of the future levitation system.

This evidence supports the investigation of an innovative centrifugal pump as a magnetically suspended centrifugal blood pump which can minimise these axial and radial thrust forces, thus improving efficiency and increasing operational lifetime. Further design refinements and iterations are required to improve the device for the application to destination artificial heart therapy.

6. References

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