

Design and Construction of Elastomeric Parts for the Azores OWC High Speed Stop Valve

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N.J. Caldwell, J. R. M. Taylor

University of Edinburgh, Scotland

ABSTRACT

As part of the EU Joule 3 programme, an Oscillating Water Column is being built on the island of Pico, in the Azores. Power takeoff is from a fixed and a variable pitch air turbine. Associated with the variable pitch turbine is a valve designed to block the airflow to the turbine to allow pseudo-reactive control ("latching"). The requirement for high speed and efficiency have prompted a novel design featuring an annular composite rubber/nylon membrane inflated by a hydraulically-latched resonant piston, with polyurethane rolling seals. A robotic lathe was built to machine male moulds from polystyrene foam and spray on elastomer coatings. The paper details the design of the components and production techniques developed.

1. INTRODUCTION

The European Pilot OWC Plant in the Azores features two power take off systems: a Wells turbine and a variable pitch turbine with high-speed stop valve. The chamber also has a bypass valve.

This combination should allow almost any control strategy which has been proposed for OWCs to be tried. The bypass valve allows experimentation with flow rate limiting the Wells turbine [1]. The variable pitch turbine allows constant pitch angle control to delay the onset of stall, and can work as a pump for part of the wave cycle to allow reactive loading [2]. The high speed valve allows experimentation with latching control strategies designed to maximise power output by forcing the chamber into resonance for a wider range of wave periods [3].

This paper presents an overview of the stop valve design but focuses on the production methods which have been developed for the critical elastomeric components. A separate paper describes the variable pitch turbine [4].

2. HIGH SPEED STOP VALVE

2.1 Introduction

When the stop valve is being used for latching control it will typically change state four times per wave cycle. The valve dissipates energy in the airflow when it is partly open. It is therefore important that the valve changes state as quickly as possible.

Salter [3] explained why current valve technologies were inadequate and presented a design for a high speed stop valve based on an elastomeric membrane inflated by a hydraulically latched piston. Most of the parts for the valve have now been built and tests on the full scale system should start in Lisbon at the start of 1999. While many design details have changed the device built is conceptually identical to that proposed in 1995.

2.2 Design Overview

Figure 1 shows the location of the valve in the OWC. Figure 2 is a sectioned view of the stop valve. A piston coaxial with the turbine slides in a cylinder with rolling seals. The air spaces behind and in front of the piston are closed; the piston behaves dynamically as a mass between two springs. A fast hydraulic brake can latch the piston in any position. The elastomeric membrane which seals the duct is inflated or deflated by the piston as shown in figure 3.

At time zero the piston is displaced away from the turbine by pumping air from the rear to the front chamber, and latched. By pumping air from the front to the rear chamber the membrane is sucked down onto its support structure and it conforms to the ideal duct geometry, allowing air to flow unimpeded. If the latching brake is released, the large pressure difference across the piston causes it to accelerate towards the turbine. It reaches maximum speed (around 20m/s) at the midpoint then starts to decelerate as pressure builds in the membrane chamber and falls in the rear chamber. At the point at which the piston has zero velocity it is again latched and the membrane has inflated to seal the duct. Similarly the valve can be deflated by releasing the latch and re-latching when the piston reaches zero velocity towards the rear chamber. If the timing of the brake is right then almost all of the actuation energy is stored for re-use in the next cycle.

The very high changeover speed (~2ms) of the brake is achieved using the minimum cylinder volume and a novel magnetically bistable low-mass spool valve with electro-pneumatic pilot.

At the time the project proposal was written it was anticipated that the latch would present the greatest difficulties. However it has been designed, built and tested with surprising speed by Dr. Richard Yemm. Developing the elastomeric parts and the process to make them has proved to be the most time consuming part of the project.

2.3 Elastomeric components

There are three crucial elastomeric components: one valve membrane and two 'belofram'-type rolling seals.

For prototypes of items 1 metre in diameter but only a few mm thick a closed injection mould process is clearly impractical. Making the components from stock sheet would have involved difficult and unreliable adhesive joins, even if large enough sheet could be found.

The process developed relies on the fact that some elastomers can be spray applied on to the surface of a male mould. The large volume (up

to 3m³) of the moulds dictated a low density material. Expanded polystyrene seemed ideal. The process to make the moulds had to be controllable, accurate and flexible enough to incorporate unforeseen design changes. We wanted to have the same control over spraying so the machine should do both jobs. As the components are volumes of revolution, this pointed towards a computer controlled lathe.

3. CNC POLYSTYRENE LATHE

3.1 Hardware

The lathe was based on an existing three-axis Cartesian robot. A steel frame was designed and built to support the robot, and a spindle added which is effectively a fourth axis (Figure 4). Drive to the axes is by DC servo motors, and position feedback is by optical encoders. The robot travel is 2m along the spindle axis, 1m vertically and 1m horizontally. Objects up to 2.4m in diameter may be mounted on the spindle.

Due to the dangerous nature of the chemicals involved, the lathe is enclosed in a polythene tent and is supplied with powerful fume extraction.

3.2 Software

All axes are controlled by a PMAC motion control card mounted in a host PC. This allows all four axes to execute complex moves, under full position and velocity control. The card can be loaded with standard CAM programs (G-code) as produced by the RayCAM package. The operator draws the desired mould shape in a CAD environment, and the G-code file to drive the robot is automatically generated.

Control over machining parameters (spindle speed, feed rate, tool offsets etc.) is available in real time using the custom Windows software, written in Visual C++ (Figure 5). This also displays the tool position, status of the machine and details of the program which is currently running. Three hand-wheel encoders on the control box can be configured to control the position of the robot axes directly, for setting up offsets and performing manual operations. Another hand-wheel on the machine control box can be configured to control any machining parameter in real time.

3.3 Spray Equipment

Liquid elastomers are sprayed with a pneumatically powered reciprocating pump. A pressure regulator allows inlet air pressure to be varied from 0 to 9 bar, which produces up to 200 bar fluid pressure. The spray head mounted on the robot arm has a nozzle orifice diameter adjustable in the range 0 to 600 microns. The spray head has two valves: one controls flow to the nozzle, and the other clears nozzle blockages by momentarily increasing the nozzle orifice size. These valves are remotely operated by buttons on the control box.

4. MAKING THE MOULD

4.1 Material

Expanded polystyrene of density 25 kg/m^3 has a complete lack of voids, with good adhesion between grains. It is supplied in blocks $2400\text{mm} \times 1200\text{mm} \times 600\text{mm}$, so it is necessary to make the mould blanks by gluing together two blocks. Blocks are cut using a hot-wire attachment on the robot arm, and glued with 3M Spray77, a spray contact adhesive which is unusual in not attacking polystyrene. Fibreboard plates glued to each end support the block between centres of the lathe.

4.2 Rough machining

Mould blanks are turned into a roughly cylindrical form with a hot wire arranged parallel to the spindle axis. An angle grinder is attached to the robot arm with its axis parallel to the spindle axis, and mounted with a wire brush. At a spindle speed of 60rpm, this allows deep cuts (up to 100mm) at high speed (120 mm/min), by removing the material in whole grains. The mould is left about 10mm oversize.

4.3 Machining the profile

Accurate machining of a mould with CAM demands that the tool have a well-defined shape, so that cutter radius compensation may be used. Initially, hot-wire cutting was chosen for final machining of the desired profile, using a thick wire bent into a U shape. This produced a good surface finish but was very slow (full scale moulds would take 100 hours) and was difficult to accomplish accurately. Grinding polystyrene produces a rougher finish but is much faster (1 hour for a full-scale mould) and more accurate. The preferred method involves a standard reinforced grinding disk, diameter 125mm and thickness 6.35mm, coaxial with the spindle (Figure 6 and 7). The disk is diamond-dressed to give an accurate semicircular edge, allowing the software to compensate for the tool radius.

Pre-finish cuts are at 60 rpm, cut depth 6mm, feed-rate 60 mm/min. A finish cut at 15 rpm, 2mm depth at 15mm/min leaves the best attainable surface finish. Accuracy on diameter is $\pm 0.5\text{mm}$.

The surface is smoothed with a cement-based filler and sanded. A thin layer of Araldite 5052 low viscosity epoxy is painted on and sanded down. This protects the mould from the aggressive MEK solvent in the polyurethane. Finally Allcosil No.2 silicone mould release coating is sprayed on. This cures to a thin silicone rubber layer, avoiding the transfer problems of wet silicone mould release agents.

5. THE ROLLING SEALS

5.1 Design

The piston to cylinder seal must seal a circumference of over 3 metres against pressures of up to 1.5 bar with low leakage. At the same time seal friction must be kept low to reduce losses in the valve cycle. The cylinder is rolled from steel plate so surface finish and roundness of the cylinder could not be guaranteed to the tolerance required of sliding seals without a very expensive machining operation. Under these conditions sliding losses would be too high and seal life would be too low.

Instead, a pair of rolling seals can do the job with lower losses. Each seal looks like a stocking which has been folded back on itself. The inside end is clamped to the piston while the outside end is clamped to the cylinder. The space in the middle between the two seals is kept at low pressure. When the piston moves relative to the cylinder, the seals roll rather like stockings. Because the seals are rolling rather than sliding, wear and friction are much reduced.

The rolling seal material needs high strain capability to stretch from the piston to the cylinder diameter, good abrasion resistance for long life and enough strength to contain the chamber pressures. The process developed involves spraying cold-curing polyurethane (Irathane155) onto male moulds as a thin continuous layer. Termination details for clamping the ends of the seals can be made as integral features so no adhesive bonds are required.

5.2 Production Process

Irathane 155 is a two part cold curing elastomer. It is mixed before spraying and carried in MEK solvent. This solvent is toxic so the whole lathe had to be covered in a plastic tent with fume extraction. Many tests with combinations of flow rate, feed-rate and recoat time were carried out to get accurate thickness and good surface finish.

Both the rolling seals and the valve membranes require thicker, wedge shaped termination details for clamping

and sealing. We wanted to spray these as an integral part of the component, so that the bond between the termination and the main body of the membrane or rolling seal was as strong as possible.

First we tried to create thickness variations by controlling the speed at which the spray gun advanced over the mould. However we found that the detail required for the terminations could not be achieved with this method due to the finite width of the spray pattern.

The next idea was to spray depressions on the mould with layers of polyurethane until filled to the same level as the rest of the mould. In between coats excess was removed with a spatula.

Once filled to the same level the whole mould was sprayed with a number of coats to form the main body of the rolling seal. With careful control of the time between coats this proved to be a success. If the main body is sprayed with 4 hours of forming the terminations then they bond together into one homogenous part. The strength of this bond is indistinguishable from the strength of the rest of the component.

Figure 8 shows a completed rolling seal being removed from its mould.

6. STOP VALVE MEMBRANE

6.1 Membrane Specification

The stop valve is essentially a digital device. It has two states- inflated to seal the duct, and deflated to allow air to flow past. The transition between these states takes place in less than 100ms.

It is important that when deflated the valve has a smooth surface to offer the least possible resistance to the airflow to reduce losses. As it is positioned close to the turbine, it has to conform to the ideal geometry to maintain uniform duct cross-section to avoid affecting air velocity or introducing vortices. This shape is something like the stem of a chess piece. When inflated it must "bulge out" to adopt a predictable and stable shape independent of varying internal or duct pressure. Internal pressure of 1 Bar gauge will allow the valve to block the duct for all conceivable waves, but 0.5 Bar will suffice for all but the roughest conditions.

6.2 Problems with polyurethane

The polyurethane elastomer used for the rolling seals has properties which make it unsuitable for the membrane. The most important of these

is serious short-term creep under moderate stress. At 2N/mm^2 (one tenth of UTS) at 20°C the material has crept by 100% after two hours. This is twice the initial elastic strain. Therefore this material cannot be relied upon to stay the same shape when under moderate stress. Also, the relatively high internal damping of the material would cause a significant temperature rise at the very high strain rates encountered in the valve- probably making the creep problem worse.

6.3 A New Material

The circumference of the contact patch (the ring of material which touches the outer duct when inflated) must increase by 50 % when inflated. The length along the membrane parallel to the turbine axis must increase by 27% when inflated. However, it is desirable that once this extension has taken place the valve stiffen so that further increases in internal pressure cause only very small changes of geometry. The valve should operate in this stiff zone so that fluctuations of pressure either inside the membrane or in the duct do not cause significant changes of geometry.

This sudden stiffening after a set extension is achieved by laying reinforcing fibres in convolutions, parallel to the turbine axis. As the valve inflates the convolutions start to straighten out, adding very little stiffness to the elastomeric matrix. However, once the convolutions are fully straight there can be no more extension without stretching the reinforcing cords. These cords are very much less extensible than the elastomer matrix so the axial stiffness of the composite suddenly becomes very much higher (figure 9 below). The extension at which this transition occurs can be controlled by varying the amplitude of the convolutions on the mould. As the lathe is computer controlled, these convolutions can easily be incorporated into the mould design.

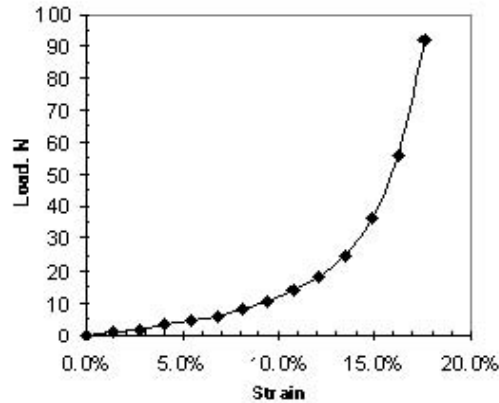


Figure 9: Axial stiffness increase as corrugations straighten, 25mm wide sample.

As the fibres are laid parallel to the turbine axis, the membrane is free to expand in hoop to the full 50 % extension required. Once the convolutions are straight, the membrane behaves very much like a radial-belted car tyre. All the pressure forces are taken by the reinforcement.

If the cord were given a uniform coat of elastomer, these convolutions (which take the form of a rounded zig-zag of wavelength 30mm and amplitude 11mm) would cause considerable disturbance to the duct air flow when the valve was deflated. This problem is overcome by filling the valleys between the convolutions with elastomer, so that when deflated the valve presents a smooth outer surface to the duct airflow. A side effect is that these filled valleys become ripples on the outer surface when the valve is inflated.

6.4 Matrix

Natural rubber has the lowest internal damping of all the rubbers, has a very low creep rate and is resistant to tearing and abrasion. It can be spray applied as a latex to the mould, the component being built up in many thin layers. In its untreated state it is susceptible to environmental attack, but this can be greatly improved by additives. The completed valve membrane is protected against UV with 4% carbon black, oxidation with Aquanox anti-oxidant and ozone cracking by Novazone, a mixed diaryl p-phenylenediamine with high molecular weight to prevent water leeching.

6.5 Reinforcement Material

The similarity of the membrane to a radial car tyre and the use of a rubber matrix led us to investigate the fabrics used in tyre production. These are usually high strength nylon or rayon, and take the form of 0.7mm diameter twisted cords, spaced at 12 cords per cm. They are pre-stretched then allowed to relax to prevent creep, and are coated to encourage adhesion to rubber. Breaking load for nylon cord is around 210N at 22%, and for rayon cord is around 180N at 13%. The choice between high strength or high modulus was difficult. Dunlop Textiles in Rochdale, UK were kind enough to supply us with rolls of nylon and rayon tyre cord. After tests we decided on the nylon as the lower modulus would lead to better load sharing between the fibres. The cord was laid up onto the mould before being coated with rubber (figure 10). Samples of the reinforced rubber have been tested to a load equivalent to 6 Bar gauge internal pressure (figure 11 below).

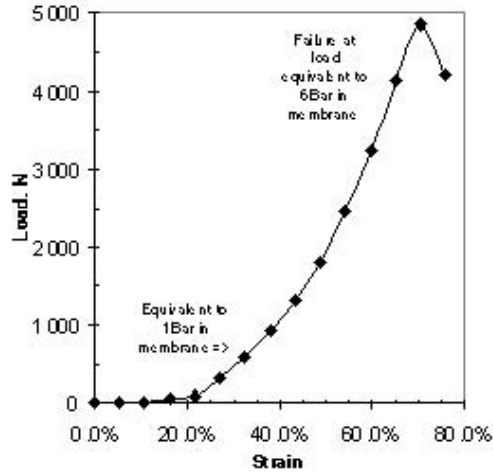


Figure 11: Testing 25mm sample until failure

6.6 Terminations

The load in the fibres is transferred to the structure through the terminations, analogous to the bead in a car tyre. These are thicker wedge-shaped edges of the membrane which allow it clamped to the structure. The lower modulus of the natural rubber would have led to clamping failure, so we decided to use the high modulus Irtthane 155 in this region of the component. This also has excellent adhesion to the reinforcing cord. After laying up the fibres, the polyurethane is sprayed in layers into the termination depression in the mould and levelled in the same way as for the rolling seals.

Samples of these terminations have been tested to find the optimum clamp geometry and clamping pressure.

7. MODEL TESTS

A one third scale model of the membrane was built before the full size one. This served as a test bed for production techniques, as well as confirming the convolution size necessary for the desired inflated shape. The model showed the expected stiffness increase as the convolutions straightened out (figure 12 below).

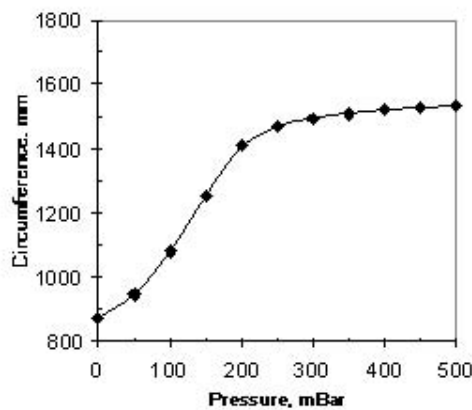


Figure 12: Membrane inflation

A series of tests with a sealing test rig (Figure 13) studied how valve sealing performance varied with internal pressure and contact patch size. As a result the final membrane (Figure 14) was designed so that the circumference of the contact patch when the membrane is inflated in free space is 5% more than the

circumference of the duct. Indications from these trials are that 1 bar in the membrane will contain 700 mbar in the duct.

8. CONCLUSIONS

The polystyrene lathe has proved to be a powerful and flexible tool. Materials tests showed that while polyurethane was suitable for the rolling seals, the membrane required a composite construction. The rolling seals and membrane components have been built at full scale. The high speed hydraulic brake has been completed. Successful tests of the scale model membrane are encouraging. Tests on the full scale valve system will commence in Lisbon at the start of 1999 prior to installing in the Azores OWC.

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Stephen Salter has done much of the analysis and mechanical design for the stop valve.

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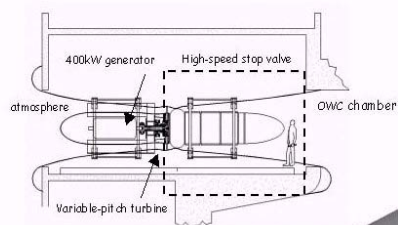


Figure 1: Location of valve

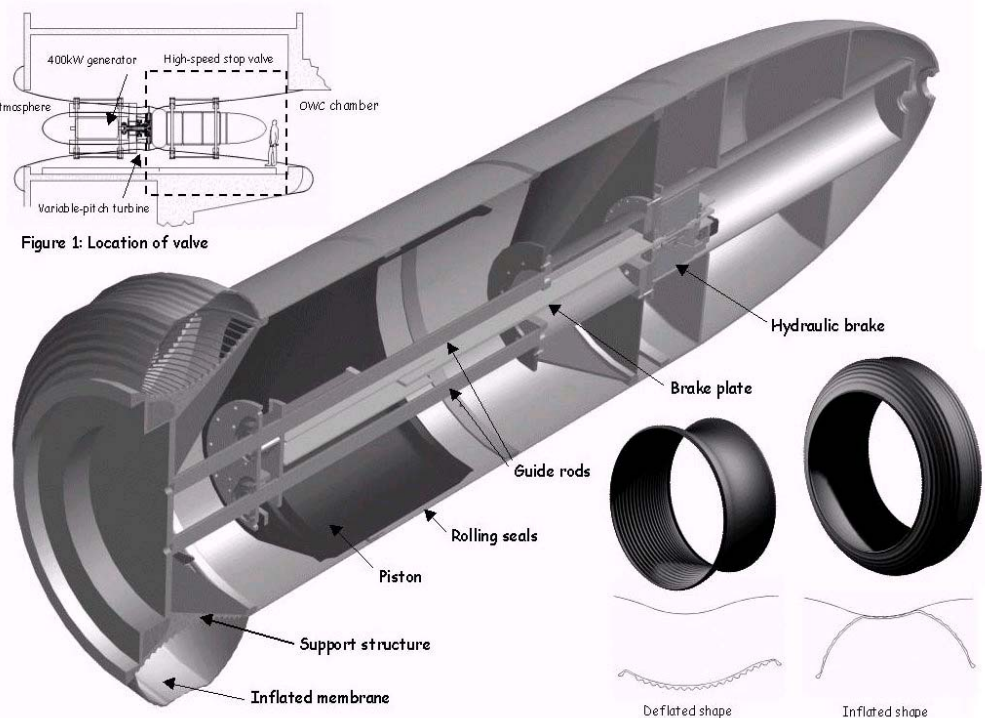


Figure 2: Section view of High-Speed Stop Valve



Figure 3: Membrane inflated and deflated shape

