SHOCKLESS-REACTIONLESS VALVE

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by

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ABSTRACT

PMP Industries, sponsoring company for this project, is one of the world's leaders in the production of gearboxes, and in the last few years the company has been investing intensively into research and development to create a new hydraulic line of products. The company already produces swing drive gearboxes, used in swinging construction machinery, and the hydraulic motors that drive them. The only components missing for this swing drive system in order to be fully produced by PMP Industries were the valves that regulate the hydraulic motor's behavior, and therefore regulate the behavior of the swinging construction machinery.

The valves currently available in the market that solve this problem are four for each hydraulic motor. These valves are technically called shockless, that damps the start and stop of the swing, and reactionless, that eliminates vibrations at the end of the swing, valves. Each motor has two shockless and two reactionless valves. The target for this project is to develop an innovative valve that does the job of both a shockless valve and a reactionless valve. This would bring the total number of valves in the system from four to two.

The way the solution was found was to first analyze the current valves in the market and then create a new valve that mimics their behavior. The factors that had to be considered were working pressures, pressure location into the valve, orifices sizes, spring characteristics, overall size, and cost. After an iterative design process repeated eighteen times, a valve that meets all the requirement was found.

The valve designed behaves both like a shockless and a reactionless valve. The valve has a lower cost, estimated around 60% of the one of the competitor's. The valve's strict tolerances allow for minimum and ignorable differences between each of them so that the product is always reliable and consistent. The valve is assembled using only standard tooling and fittings to allow for a quick and easy assembly. In order to have a standard shockless behavior in the system, the valve's working pressures are adjustable through loading or unloading a spring. In case of malfunction the valve is easily replaceable without the need to replace the whole hydraulic motor.

INTRODUCTION

BACKGROUND

In heavy swinging construction machinery there are two main issues that have to be addressed: the shocks happening in the hydraulic system and the precise positioning of the machinery. The shocks in the hydraulic systems are peaks of pressure that can have several causes. These causes are usually related to extreme demand from the operator, or an extreme demand from the load conditions. The precise positioning is an issue because during breaking conditions there are reacting pressures that build up in the hydraulic motor and these pressures have to be managed. These two issues in the modern machines are addressed with two types of valves: shockless valve and reactionless valve.

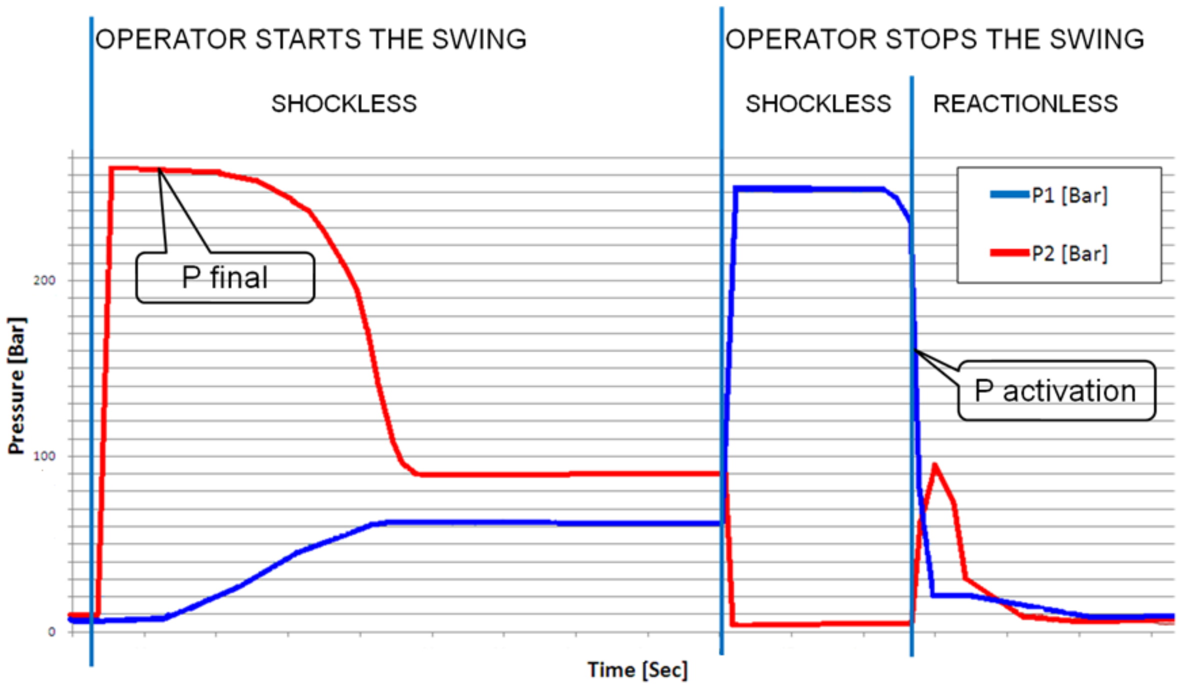


Figure 1- Pressure behavior

The best way to understand how both valves work is by analyzing the pressure behavior in the hydraulic motor when the valves operate. Figure 1 describes the pressure behavior in the system from the moment the operator of the swinging construction machinery starts the swing to the moment the machinery comes to a stop. In the system there are two pressures, P1 and P2, that could be either high or low depending on which way the machine is swinging. As Figure 1 shows, when the operator starts the swing there is a rapid increase of pressure P2. This rapid increase in pressure happens because the system is trying to overcome the inertia of the machinery. When this peak of pressure reaches P_{final} the shockless valve acts like a relief valve. During the acceleration phase Pressure P2 gradually decreases until constant velocity is reached. The next thing to happen during the swing is the braking phase. At the point where the operator stops the swing, he/she therefore stops the pressure signal that drives the motor, there is a rapid increase in pressure at the other side of the motor, now trying to stop the machinery. The inertia of the machinery makes it overshoot and the shockless valve allows this for a brief moment, until the machine slows down. At this point it is the reactionless valve that comes into action. During the pressure drop the reactionless valve, at $P_{activation}$, opens the channels and equilibrates the two pressures. This allows a smooth and vibration-free stop. What the valves do is, therefore, to allow for a smooth acceleration and for a smooth stop of the swinging machinery.

The target of this project is to create a valve that does the job of both the shockless and reactionless valves. This would enable the making of a cheaper and smaller system bringing down the number of valves from four (two shockless and two reactionless) to two (two shockless-reactionless combined). The valves are now four because one shockless and one reactionless are used for the two swinging directions (1). The project is sponsored by PMP Industries, one of the world leaders in the production of mechanical transmissions, hydraulic transmissions, heavy metal fabrications and dedusting systems.

CURRENT MOST COMPLETE SOLUTION IN THE MARKET

The current best solution in the market is shown in Figure 2.

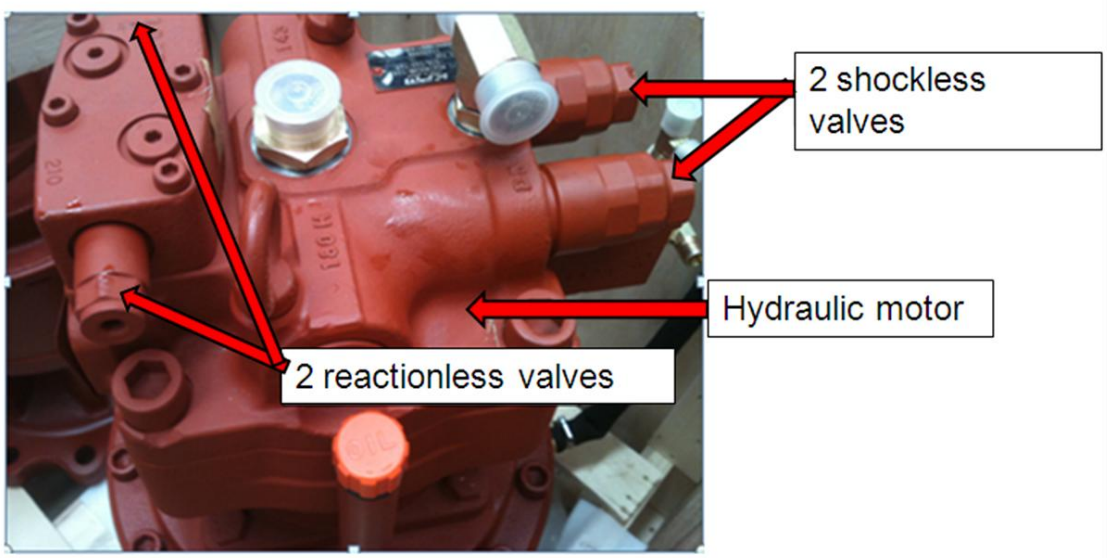


Figure 2 – Current option in the market

There are currently two options in the market: two shockless valves or two shockless plus two reactionless valves. In Figure 2 it is possible to see the most complete package with the four valves. By eliminating two valves, the size, the weight, and the cost of the hydraulics valves will immediately decrease.

CUSTOMER FEEDBACK, FEATURES, AND OBJECTIVES

SURVEY ANALYSIS

In order to determine the importance of the product features a survey was distributed. The survey was done by people working at PMP Industries. The number of surveys returned was 22. The people that completed the survey where six from the Engineering department, four from the R&D department, eight from the Sales department, and four from the Purchasing department. The survey has a list of features and the people taking the survey were asked to give their opinion on how important each feature was. The scale was from 1 to 5, where 1 means low importance and 5 high importance. The following is the list of features with the average importance for each one of them.
The following are the results in order of importance:

Low cost	4,91
Reliability	4,82
Precision	4,64
Innovation	4,59
Adjustability	4,27
Safety	4,23
Ease of assembly	4,14
Size	3,86
Ease of replacing	3,05

Table 1- Survey results listed by importance

From the survey's results what stands out as the most important feature is the cost of the valves, and the least important feature is the ease of replacing of the valves. During the design process the focus was, then, on the small details of the valve. That is what ensures a good reliability and precision, but the cost factor played a major role in the design keeping the dimensions as small as possible, selecting the right materials and avoiding unnecessary machining.

From Table 2, a segment of the QFD (appendix C), it is possible to see that the main improvements, designer's multiplier column, will be made on the Size, and on the cost. The other features do not need improvement since the current valves in the market are already satisfactory (2).

	Customer importance	Designer's Multiplier	Current Satisfaction	Planned Satisfaction
Low cost	4,91	1,5	3,05	4,90
Reliability	4,82	1,0	4,05	4,80
Precision	4,64	1,0	4,73	4,75
Innovation	4,59	1,0	3,86	4,80
Adjustability	4,27	1,0	4,39	4,40
Safety	4,23	1,0	4,68	5,00
Ease of assembly	4,14	1,0	3,85	4,50
Size	3,86	1,5	3,18	4,50
Ease of replacing	3,05	1,0	2,64	3,00

Table 2- QFD segment

PRODUCT OBJECTIVES

The following is a list of product objectives and how they are obtained or measured to ensure that the goal of the project is met. Meeting these product objectives is very important for the success of the project. For every feature there is a brief description on how each feature has been satisfied. The percentage in parentheses is the relative weight ratio taken from the QFD (Appendix C).

Low cost (22%):

_ The combination valves + hydraulic motor will be cheaper than the one of the competitors' of comparable quality.

Size (15%):

_ The number of valves will be brought down from four to two.

_ The valve will not interfere with any other piece of equipment of the machinery.

Reliability (11%):

_ Components and materials will be consistent with company's knowhow to ensure reliability.

_ The valve will have to work at least as long as the rest of the hydraulic transmission does (company's know-how and cycle test of prototype).

Innovation (11%):

_ The product will be new in the market.

Precision (9%):

_ There will be used tolerances consistent with industry practice in designing the valve to avoid unwanted oil leakages or unwanted pressure drops.

_ Iterative tests will be conducted until the design will meet the desired characteristics. Characteristics are a damping time that will be within a 50% difference from the competitors’, actuating pressures and threshold pressures within a 20% difference from the competitors’.

Ease of assembly (9%):

_ Standard tooling will be used in assembling the valve.

_ Every component that has to be tightened will have a standard tool fitting.

Safety (8%):

_ The valve will be located inside an hydraulic motor which is located at several feet from any human being.

_ The valve will be secured in place by screwing it in the motor using a standard high torque setting.

Adjustability (8%):

_ When assembling, a ferrule will be used to calibrate the main spring which controls the behavior of the shockless side of the valve.

Ease of replacing (7%):

_ In case of malfunctioning (extreme situation) the valve will be possible to unscrew from the motor and replaced with a new one without the need of replacing the whole hydraulic system.

_ This substitution will only be done by a skilled employee of the company.

Table 3 shows the Engineering characteristics that determined the importance weights in the designing of the product.

Size (cm^3)
Number of components
Weight (kg)
Material
Screwing torque (Nm)
Roughness of components (μm)
Spring constant (N/mm)
Assembly time (s)
Cost (€)
Product is new (yes/no)
life expectancy (hours)
Spring preload (N)

Table 3- Engineering characteristics

DESIGN ALTERNATIVES AND SELECTION

The first step in the designing process was to analyze the best valves in the market and measure their main characteristics like areas on which pressure acts, location of high pressure and low pressure, springs' characteristics, orifices sizes, overall size. The next step was to create a valve that does both the shockless and reactionless jobs and that performs the same way the analyzed valves do.

The main principle at the bases of the design is the area differential principle. Figure 3 shows how this principle works. If a pressure acts on a piston through two areas, in this case A1 and A2, the resulting are on which the pressure acts is given by the difference between the areas, therefore $A_{differential} = A1\text{-}A2$. Also, the pressure at which the piston gets activated is $P_{activation} = F_{spring}/A_{differential}$. What the area differential principle allows is the use of smaller springs since it is possible to reduce the area on which the pressure acts. This helps keeping the size of the valve within certain dimensions. This area differential principle, a total of four pistons, three springs, and the right pressure locations, allow to open and close ports to cause damping and pressure equilibration.

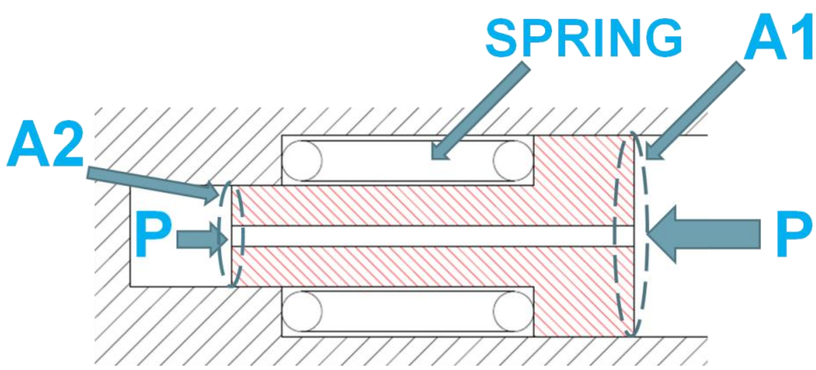


Figure 3- area differential principle

The designing process was very iterative because even small changes required a complete redesign of the valve. This designing cycle is represented in Figure 4. The first step was to create a design and determine the various areas, pressure locations, springs, and overall size. Once the design was completed it was analyzed in detail and all the strengths and problems of the design were found. Example of problems are the size, springs impossible to find, problems related to manufacturing and assembly, wrong pressure locations, or simply wrong concept. This cycle was repeated eighteen times until the valve did not have any issues.

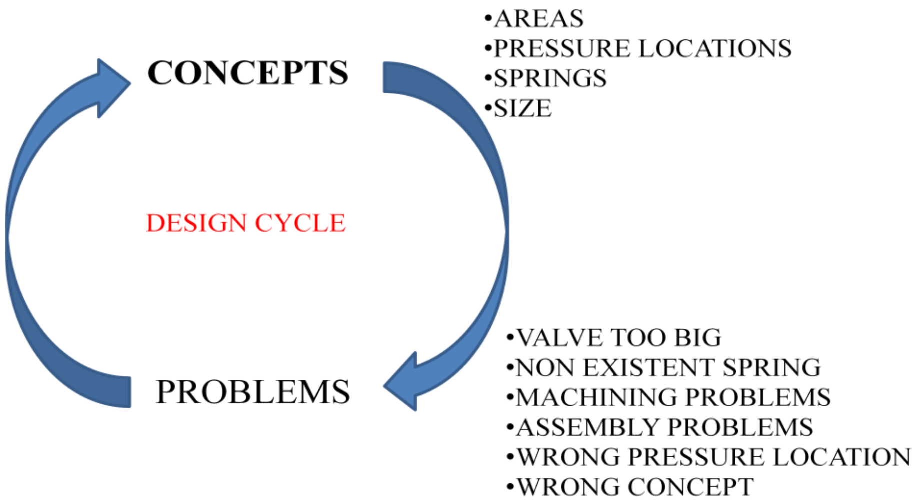


Figure 4-designing cycle

CALCULATIONS

All the calculations of areas, springs, and operating pressures were done using an excel spreadsheet. According to the calculations the shockless valve will have a P_{final} of 269.1 bar, and the reactionless will have a $P_{activation}$ of 168.3 bar. The calculations cannot be shown for proprietary reasons.

FINAL DESIGN

After all the iterations a final design was achieved. Figure 5 shows the 3D drawing of the final design. Detailed drawings and shop drawings are not shown for proprietary reasons.

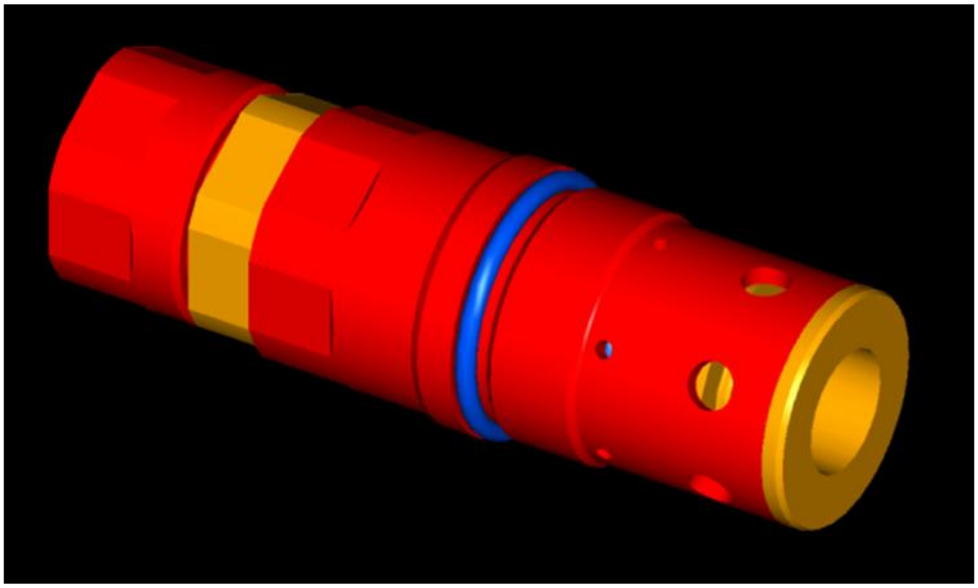


Figure 5 - 3D of final design

The materials of which the valve is made of are cast iron and steel. The main material is steel, every component but two (two components will be made of cast iron) will be made of steel. The prototypes are made only of steel (except for the O-Rings). There are different types of steel used in the valve that were selected based on PMP Industries’ know-how. The specific types of steel are not present in this report for proprietary reasons.

TESTING

Figure 6 shows the testing bench layout. The valves are mounted on the hydraulic motor that will be powered by a pump. The motor is connected to an electric motor that acts as a swinging machine, delivering resistance to motion when needed. The pressures, flow rates, and temperatures are measured by a measuring device that will be connected to a computer. The plots will determine whether or not the valves are working properly.

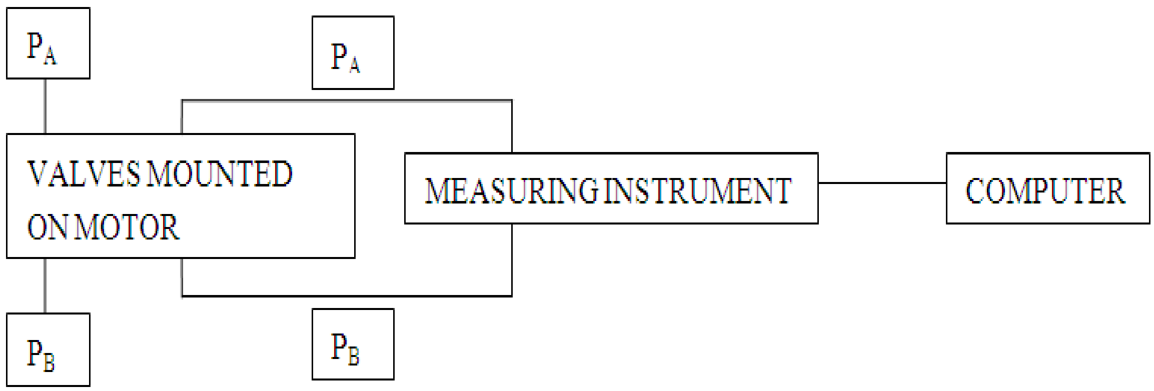


Figure 6- testing bench idea

After the valve has been tested using the bench and no issues are apparent, the valve will be mounted on an excavator and this will be the final testing to prove that the valve works as desired.

Preliminary tests show that the valve behaves according to design. The valves working pressures are the ones desired for both the shockless and the reactionless part. The shockless valve opens at around 270 bar and with a damping delay time of around 0.2 seconds, as planned. There is a difference of ±8% between each spring purchased for the prototypes and the spring regulation system has been proven to work because it was able to compensate for this differences. The reactionless valve eliminates the vibrations as desired. The valve so far has been tested by mounting it only ones on an excavator and the plots taken confirm the correct behavior. Plots cannot be shown on this report for proprietary reasons. The future testing will be a life test of the valves on the testing bench. After this test shows positive results the valves will be mounted on an excavator for several weeks to make sure they will operate with no problems in actual working conditions.

SCHEDULE AND BUDGET

The project has been developed over a nine months period. The following are the milestone dates:
Proof of Design Agreement and Concept sketches 11/23
Break 12/11 – 12/31 (no design tasks over break - only SW drawings)
5 th week 1/29 - 2/4 design freeze
Last week 3/4 - 3/10 report
Last week 5/27 - 6/2 report

The following is the schedule for the overall project where green is the current schedule and the yellow was the planned one:

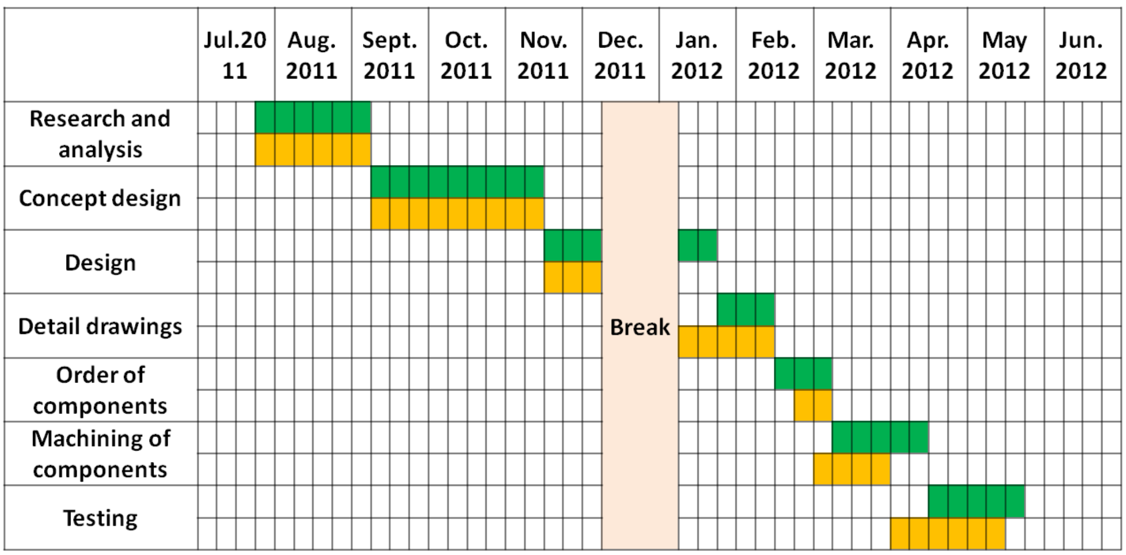


Figure 7-schedule

For the budget of this project the estimated amount is $1392 (appendix D). This includes components, machining, and labor. The final amount spent is $1340 which takes the project slightly below budget.

FORECASTED	
Material, Components or Labor	**Amount**
Machined components	$100
Springs, bolts and ferrules	$60
Labor (assuming 50 man hours)	$1000
Miscellaneous (20%)	$232
Total	$1392
ACTUAL	
Material, Components or Labor	**Amount**
Purchased components (x10 valves)	$610
Labor (30 man hours)	$600
Shipping to the US	$130
Total	$1340

Table3 - budget

CONCLUSION

The investment made by PMP Industries in order to develop a new and innovative valve has been proven to be fruitful. The valve has been behaving as expected and only minor changes will have to be made in the future. These changes are needed to make sure that when the valve goes into production no machining time is wasted and that every single component is machined as efficiently as possible. Also, several life tests will be conducted before the valve goes into production. The plan for the future is to end testing and have a finished valve by the end of 2012 and begin production in 2013.

REFERENCES

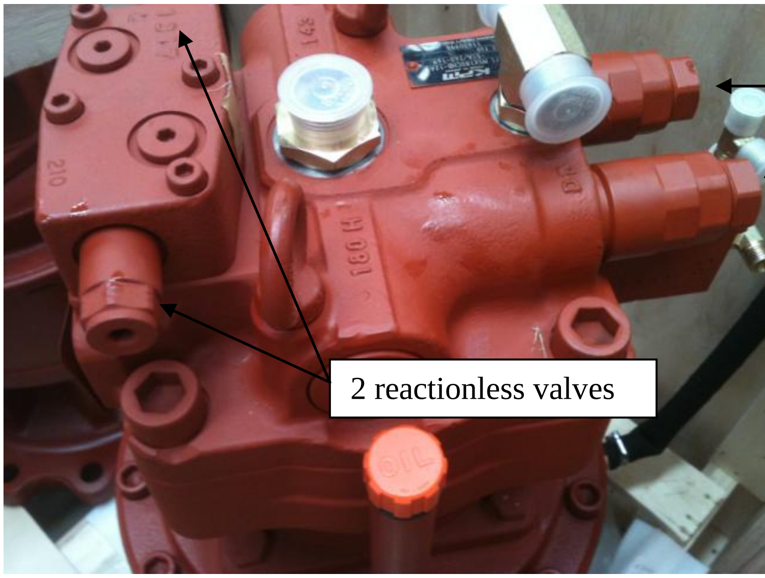
1. **Lanza, Alessandro.** *Engineer.* Coseano, 23 September 2011.
2. **Bonera, Andrea.** *Sales manager.* Coseano, 9 September 2011.

APPENDIX A – RESEARCH

Closest MET project: Gasoline-styled high pressure valve, Andrew Tenhundfeld (2000).

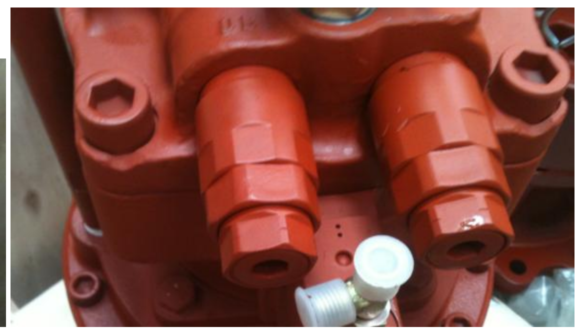
Interview with Andrea Bonera, Global Sales Manager at PMP Industries, Sept. 9, 2011.
e-mail: a.bonera@pmp-industries.com
Right now we are able to sell a full range of slew drives.
We could be even more aggressive in the market if we had the hydraulic motor to accompany our slew drives, giving the costumers a full transmission package.
We are now producing hydraulic motors for other gearboxes but not yet for our slew drives.
This kind of gear boxes control the rotation of a device or structure.
There is a need for a hydraulic motor fitted with a valve that allows precision in the rotation of the structure.
We have the technology for the hydraulic motor and not yet for the valve component.
Buying a valve from other companies is not a good option for us because, even though the products are of high quality, the lead times are very long. The already existing valves are also very large in size and we want to offer our customers a product smaller in size.
Developing our own valve would allow us to create a complete transmission package keeping the production costs low and therefore attracting a really large number of costumers.

Interview with Alessandro Lanza, Design Engineer at PMP Industries, Sept. 23, 2011.
e-mail: a.lanza@pmp-industries.com
The current solutions in the market are two:
Solution 1: hydraulic motor for slew drives fitted with 2 shockless valves
Solution 2: hydraulic motor for slew drives fitted with 2 shockless valves and 2 reactionless valves.
A shockless valve avoids pressure peaks in the system.
A reactionless valve allows a more precise and smooth positioning of the rotating structure.
There are currently about 10 companies in the world that make shockless valves and only one that makes reactionless valves.



Reactionless valves close up

Shockless valves close up



Current most complete solution in the market: 2 shockless valves and 2 reactionless valves.
Very large in size.
Expensive.
Only KPM makes reactionless valves.
Very good control of the rotating structure.
Long lead times.

APPENDIX B – SURVEY

**SHOCKLESS-REACTIONLESS VALVE
CUSTOMER SURVEY**

This project is to develop a combined valve. This valve will serve as a substitute for both the shockless and reactionless valves in the market and these valves will be combined into one.

From the following list please determine how important each feature is to you for the design of the shockless-reactionless valve.
Please circle the appropriate answer. 1 = low importance 5 = high importance

							Avg
Safety	1	2	3(3)	4(11)	5(8)	N/A	4.23
Adjustability	1	2(2)	3(2)	4(6)	5(12)	N/A	4.27
Precision	1	2	3(1)	4(6)	5(15)	N/A	4.64
Size	1	2(1)	3(8)	4(6)	5(7)	N/A	3.86
Reliability	1	2	3	4(4)	5(18)	N/A	4.82
Ease of assembly	1	2	3(3)	4(13)	5(6)	N/A	4.14
Ease of replacing	1(1)	2(2)	3(14)	4(5)	5	N/A	3.05
Innovation	1	2	3	4(9)	5(13)	N/A	4.59
Low cost	1	2	3	4(2)	5(20)	N/A	4.91

How would you rate the following features for the current shockless and reactionless valves in the market (for the case of shockless-reactionless combination)?
Please circle the appropriate answer. 1 = very bad 5 = very good

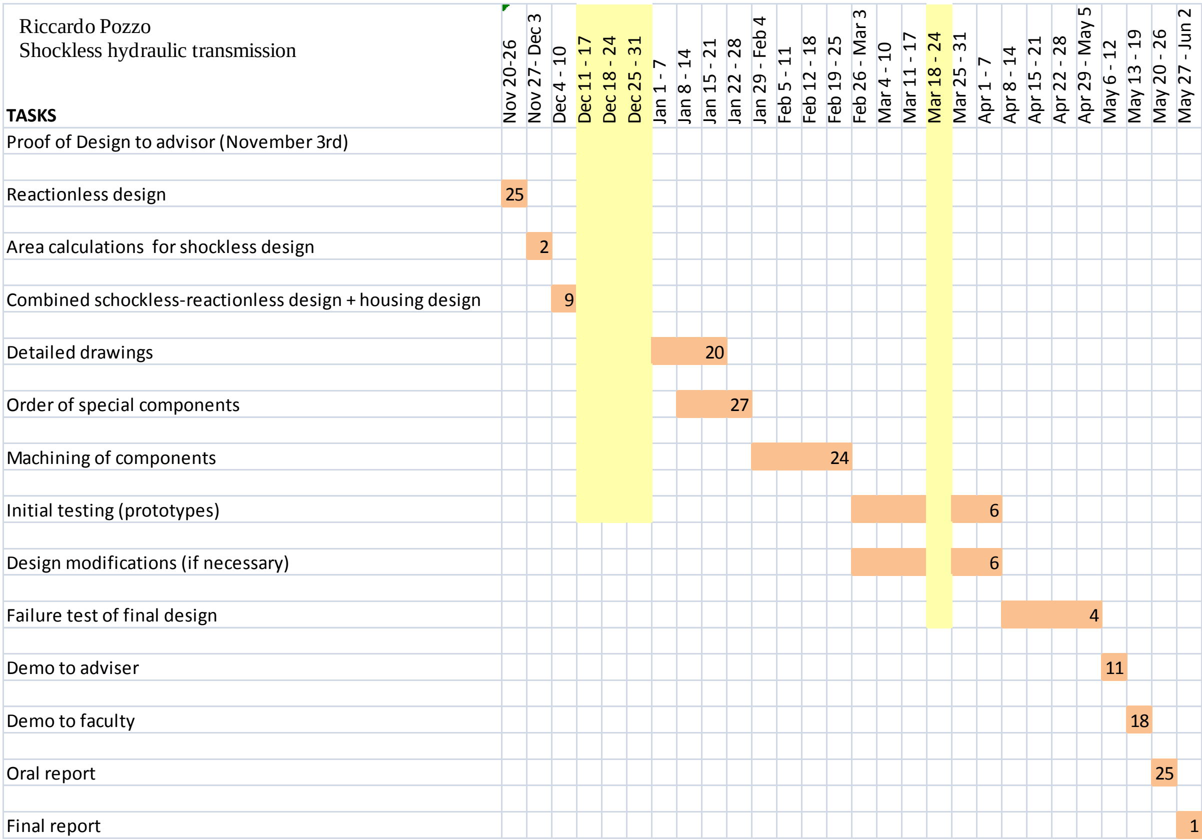
							Avg
Safety	1	2	3	4(7)	5(15)	N/A	4.68
Adjustability	1	2(1)	3(2)	4(4)	5(11)	N/A(4)	4.39
Precision	1	2	3	4(6)	5(16)	N/A	4.73
Size	1	2	3(18)	4(4)	5	N/A	3.18
Reliability	1	2	3(1)	4(16)	5(2)	N/A(3)	4.05
Ease of assembly	1(1)	2	3(4)	4(3)	5(5)	N/A(9)	3.85
Ease of replacing	1	2(9)	3(1)	4(4)	5	N/A(8)	2.64
Innovation	1	2	3(4)	4(16)	5(1)	N/A(1)	3.86
Low cost	1	2(2)	3(17)	4(3)	5	N/A	3.05

Thank you for your time.

APPENDIX C – QFD

Riccardo Pozzo Shockless hydraulic transmission 9 = Strong 3 = Moderate 1 = Weak	Size (cm^3)	Number of components	Weight (kg)	Material	Screwing torque (Nm)	Roughness of components (µm)	Spring constant (N/mm)	Assembly time (s)	Cost (€)	Product is new (yes/no)	life expectancy (hours)	Spring preload (N)	Customer importance	Designer's Multiplier	Current Satisfaction	Planned Satisfaction	Improvement ratio	Modified Importance	Relative weight	Relative weight %
Safety	3			9	9						1		4,23	1	4,68	5,00	1,1	4,5	0,08	8%
Adjustability		3										9	4,27	1	4,39	4,40	1,0	4,3	0,08	8%
Precision				3		9	9				3	9	4,64	1	4,73	4,75	1,0	4,7	0,09	9%
Size	9	9	3	1			1		3				3,86	1,5	3,18	4,50	1,4	8,2	0,15	15%
Reliability				3		1					9		4,82	1	4,05	4,80	1,2	5,7	0,11	11%
Ease of assembly	3	3	1		3			9				1	4,14	1	3,85	4,50	1,2	4,8	0,09	9%
Ease of replacing	1				9								3,05	1	2,64	3,00	1,1	3,5	0,07	7%
Innovation									1	9			4,59	1,0	3,86	4,80	1,2	5,7	0,11	11%
Low cost	3	3	1	3		1		1	9				4,91	1,5	3,05	4,90	1,6	11,8	0,22	22%
Abs. importance	2,65	2,57	0,78	2,17	1,62	1,12	0,94	1,04	2,57	0,97	1,31	1,60	19,3					53,2	1,0	
Rel. importance	0,14	0,13	0,04	0,11	0,08	0,06	0,05	0,05	0,13	0,05	0,07	0,08								

APPENDIX D – SCHEDULE, BUDGET



BUDGET

FORECASTED	
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Machined components	$100
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