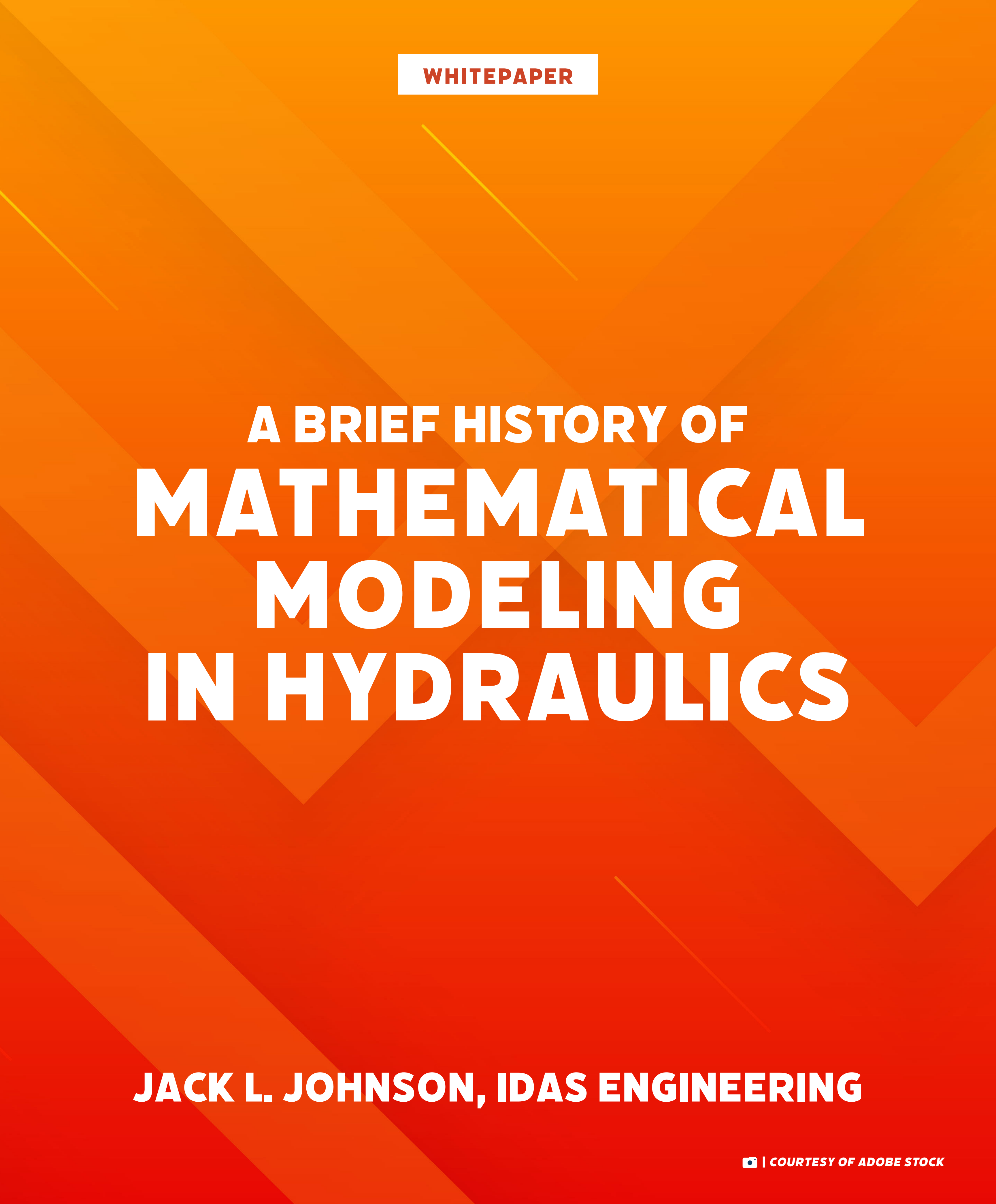
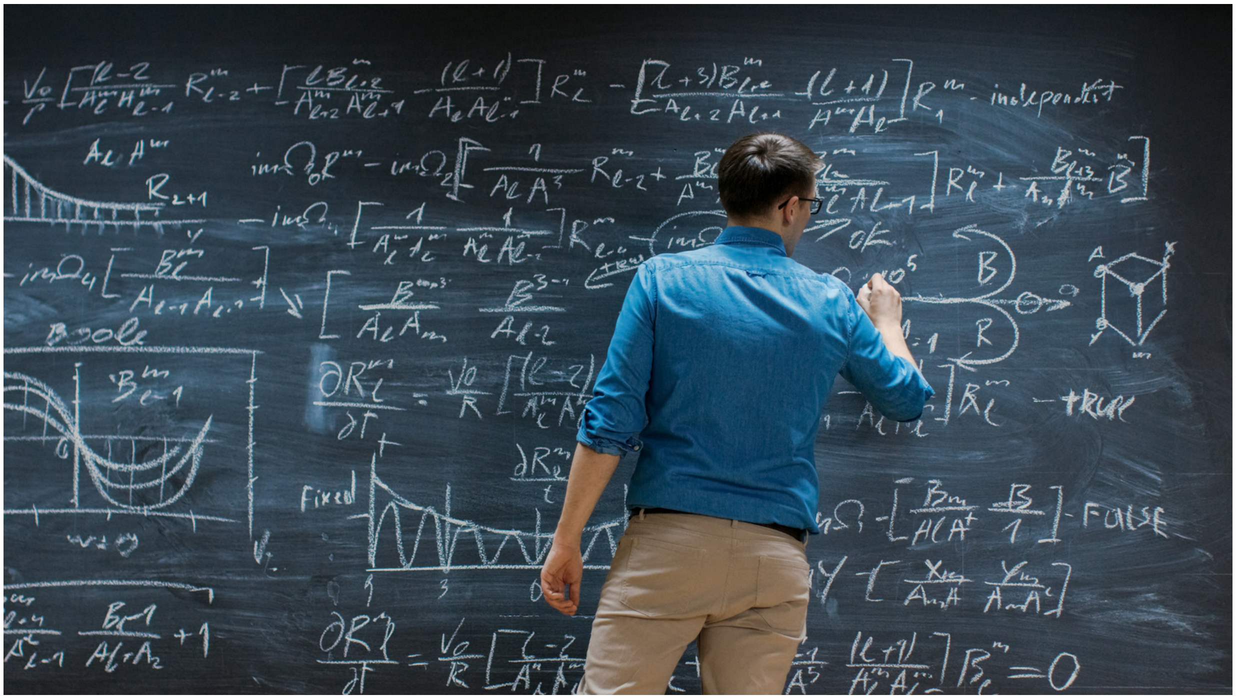


WHITEPAPER

A BRIEF HISTORY OF MATHEMATICAL MODELING IN HYDRAULICS

JACK L. JOHNSON, IDAS ENGINEERING

| COURTESY OF ADOBE STOCK



THIS BRIEF HISTORY OF mathematical modeling of hydraulic machines is written in first person in large part because it has five different themes, or threads, running through it. It is about the significant advances in electronics that have influenced the progression of hydraulic modeling and, more specifically, the required simultaneous advancements in computer hardware, and third, computer software. The fourth thread is the development of the hydraulic models from a more mathematical, or theoretical point of view. The fifth thread, in the nearby sidebar "A personal witness to a fabulous journey," contains first-person observations and anecdotes of a less-technical nature.

I decided to focus on energy conversion models for rotating machines, both pumps and motors, rather than expand it to all components in a complete system in the interest of brevity, but still give a bit of insight. There are suggestions of other components, and specialists in those areas will likely catch them. Pumps and motors are in the limelight because of the most recent work I have been involved in, namely evaluation of ISO 8426 (2008) method, the international standard dealing with the empirical determination of pump and motor displacement. We have no way to determine displacement directly. Some mathematical models and assumptions are required.

EARLY DAYS

Necessity, they say, is the mother of invention, to which I hastily add that war is the mother of necessity. WWII was certainly a calling for great need, sucking up all the new technology. Save for the inconclusive slaughter in WWI ("The war to end all wars," which never really ended), we entered WWII's horrible conflict after a half century of expanding, and modest, technological progress in automobiles, industrial production lines, airplanes, electrical appliances of countless types, and a burgeoning radio industry, among many more.

We emerged from WWII with commercially viable television, jet aircraft, rudimentary digital computers, atomic energy, and we were little more than a generation from putting men on the moon and bringing them home safely. From that backdrop, the most massive technological revolution in history was well under way. Readers who are interested in a detailed history of fluid power in its entirety are urged to obtain a copy of John Pippenger's grand tome, *Fluid Power - The Hidden Giant* [4].

POST WWII ELECTRONIC PIONEERS

The most notable postwar invention was the transistor, credited to Nobelists Shockley, Brattain and Bardeen, the disagreeing and competing intellectual giants of Bell Labs. The information processing age lie ahead by a mere couple of decades. We continue to feel and reap the benefits of their accomplishments and will for many more years to come. Progress in speeding the processing, transmission and exchange of information has been explosive in the 80+ years since the end of WWII. Electronics is the means and science of information processing and transmission. Hydraulics is the means and science of power transmission. It seems that there is less inertia in the millions of tiny silicon gadgets than in the tons needed by hydraulic machines. Power transmitters are large and heavy. Electronic information transmitters are small, almost microscopic.

It was in this same post-WWII time period that hydraulic engineering had its first enlightenment, led by our own cadre of original thinkers. Seminal work helped take hydraulic machine design and manufacturing out of the tinkerer's shop and introduced it to the engineering department. Visionary pioneers chose to emphasize the mathematical methods for predicting behavior of hydraulic machinery, and explain how they can work to achieve better methods of component design and system/applications design. They were the earliest of math modelers of hydraulic machines.

FLUID POWER PIONEERS AND THE FIRST ENLIGHTENMENT

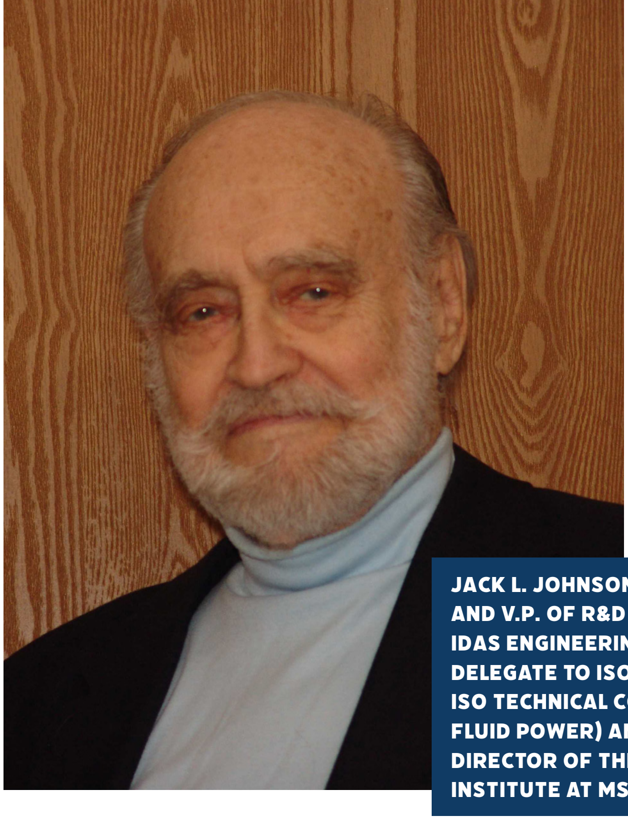
Computers were not widely available, and useful software had not yet been developed, otherwise the pioneering work might have been embraced much earlier by a much broader audience. First, a visionary with pioneering spirit was embodied in Warren Wilson [5] (1950) who was an advocate of hydrostatic transmissions as controllable and efficient means of transmitting rotational power. We are still interpreting his method for determining displacement, since it was brief, but he saw the need. And we are still waiting to adopt variable-displacement pumps as replacements for the inherently energy-hungry, but widely used, directional valves to control hydraulic machines. Wilson proposed pump and motor models consisting of an ideal flow generating/absorbing element along with internal leakage elements, losses, that diminished the efficiency.

Second, Blackburn, Reethof and Shearer [6] (1960), also pioneers in technology, produced their compendium of mathematical methods for predicting performance of servovalves, pumps and motors, building upon Wilson's work. In their Introduction the authors state:

". . . many current hydraulic devices are being designed but not engineered."

These three researchers at MIT supported the basic pump/motor models of Wilson, but offered broader subject matter, most notably, servovalve advances made during the war years. They summarized and condensed the works of others and consolidated it with works of their own, showing original thinking as well. Their efforts would add engineering to the designs.

Third was Herb Merritt [7] (1967), whose textbook carries timeless information for devising and using mathematical models. It remains, arguably, one of the most widely cited books in the world because it is a book written by an engineer, for engineers, and contains many of the accepted first principles of hydromechanical physics. And his book, too, supports the basic Wilson pump and motor models. But Merritt added that trending higher pressures warrant including effects of compressibility. All of these pioneers recognized the need for models.



JACK L. JOHNSON IS CEO AND V.P. OF R&D WITH IDAS ENGINEERING, A U.S. DELEGATE TO ISO TC 131 (THE ISO TECHNICAL COMMITTEE ON FLUID POWER) AND RETIRED DIRECTOR OF THE FLUID POWER INSTITUTE AT MSOE UNIVERSITY.

The basic models were developed and understood, the differential equations had been around for a few centuries, but the computational capabilities were woefully behind. In 1957 I was earning my Electrical Engineering degree by doing calculations on a slide rule. It's a precious possession to this day: A Post Cat. No. 1460 Versalog from The Frederick Post Company, made of bamboo by Hemmi in Japan [8]. The origins of our calculators, it still seems, lie in the Orient with abaci from antiquity and now, silicon chips.

At the time of this, the first enlightenment, industrial hydraulic pressures were at levels that today, would seem to be appropriate only for pilot sources. That's an overstatement, but 10 MPa was a high pressure at the time. Today, it is commonplace for operating pressures to have trebled or quadrupled from those of the 1950s and 1960s. Higher pressure operation necessitates models that include the loss in flow caused by the compressibility of the liquid fluid of hydraulics.

During this first enlightenment, SAE produced its own test methods for pumps [9] and motors [10]. Included was a method for determining displacement. The test was conducted at a low pressure drop across the test specimen while turning at a standardized shaft speed. The measured flow at that set of conditions was, by definition, the ideal flow. Dividing ideal flow by the standard test speed produced the displacement. The problem with this method is that the point of maximum flow-to-speed-ratio did not always occur at the standardized test conditions, and pumps and motors sometimes produce operating points with volumetric efficiencies that exceed 100%. The SAE method was not a part of this study because the sources were donated legacy data and SAE requires that the specific procedure be followed. No compatible data was donated.

Volumetric efficiency above 100% is too often interpreted as a product of faulty data, which is not necessarily the case. It is caused more by a faulty definition. Volumetric efficiency is an artificial construct. It is the product of mortals who desire knowledge and performance insights, and a metric for the ability of a pump to convert speed to output flow and for a motor to convert input flow into output speed. This goal is worthy, to be sure, because that is exactly what pumps and motors are supposed to do. And it provides vital data for the user of the pump or motor, however, its utility is not as great nor as precise as we might wish as a figure of merit for the machine, because it is, after all, artificial. It is, like all engineering calculations, only an estimate of what we want to know.

ORIGINS OF U.S. FLUID POWER ORGANIZATIONS

NFPA: John Pippenger has been an indispensable source for details of the key organizations that were formed in the U.S. in the decades of the 1950s and 1960s. Forty-one men attended the first meeting of the National Fluid Power Association, at Bedford Springs Hotel, Pa., 19 May 1953. The first president of the NFPA was John Hanna, Benjamin Ashton was the vice president and Barrett Rogers was the executive secretary.

FPS: The Fluid Power Society, Chapter One, was formed on 20 May 1960 out of the Industrial Hydraulics Training Association (IHTA) in the V8 Engine Plant of Chevrolet, Flint, MI, with George Tinetti as president. Without a specific date, Pippenger records that FPS Chapter Two in Milwaukee followed quickly, presumably also in 1960, with Russell Henke as its president and also its National President. Through the ensuing years FPS has been conjoined with NFPA and MSOE. It is now headquartered in Cherry Hill, N.J. Their name has been changed to International Fluid Power Society (IFPS).

FPEF: Pippenger cites the ascension of Frank B. Wilkinson as President of NFPA in 1967 as being instrumental in the formation of the Fluid Power Education Foundation. FPEF has been instrumental in receiving donations and distributing them to worthy students as grants and scholarships. It currently shares its headquarters with NFPA in Milwaukee, Wis.

ISO\TC131\SC8: In essentially this same time period the National Fluid Power Association accepted the Secretariat of the newly formed TC131 (ISO Technical Committee on Fluid Power) from ANSI (American National Standards Institute, the official ISO Member Body), naming James I. Morgan as its first Secretary. According to Pippenger, TC131 held its first plenary meeting in London in September of 1970. Nine Subcommittees were formed, with SC8 being identified as the Testing Subcommittee. As the U.S. Delegation Leader, I attended the first meeting of SC8 (James Hamilton, National Engineering Laboratory, Glasgow, Scotland, SC8 Chairman) which was held at The British Standards Institute, London, in January, 1971. I met Gijsbert Toet at that meeting. The first technical review dealt with the testing of pumps, motors and integral transmissions, the forerunner to the current ISO 4409. The current Secretary of ISO\TC131 is Denise Husenica, following Karen Boehme (ret). TC131 International chairman in 1971 was Z. J. Lansky, Technical Director, Parker Hannifin Corp.

TOET AND HIS TWO-STEP METHOD

In 1970, Prof. Gijsbert Toet, Eindhoven Technological University, Eindhoven, The Netherlands, produced his seminal paper [12], and its later English translation and updating [13], regarding determination of the derived capacity of hydraulic pumps and motors. It is described and implemented as a two-step, semi-graphical procedure. In it he points out the one shortcoming of the Wilson Method which doesn't take into account the Couette effect. Couette effect is the supplying of fluid that is caused by the action of, for example, a piston that drags viscous fluid into or out of the outlet chamber of a pump or motor. Toet's method takes Couette effect into account. More recently, a review of Huhtala [14] along with the

THE ADVENT OF PERSONAL COMPUTERS MEANT AFFORDABLE AND UBIQUITOUS COMPUTATION WITH HYDRAULIC MATHEMATICAL MODELS NOW BECAME POSSIBLE.

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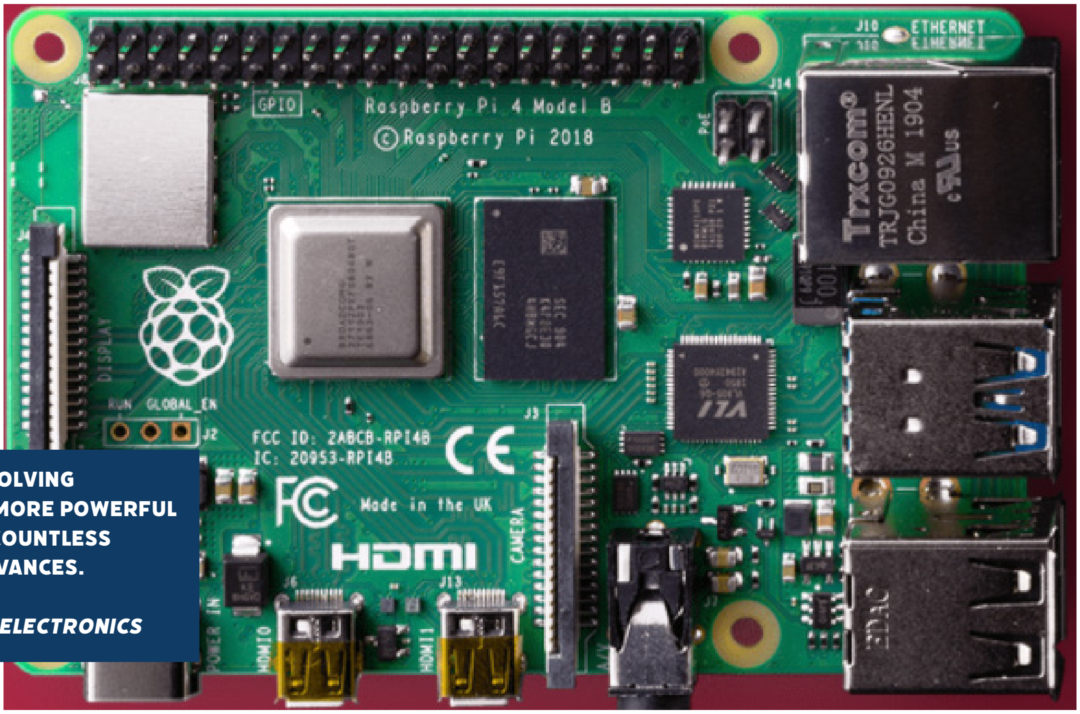


DECADES OF PROGRESS INVOLVING INTEGRATED CIRCUITS AND MORE POWERFUL PROCESSORS HAVE LED TO COUNTLESS ELECTRONIC-HYDRAULIC ADVANCES.

| *COURTESY OF NEWARK ELECTRONICS*

procedures outlined by Toet, the regressor for Couette effect is the same as that which Huhtala identifies as the compressibility effect when viscosity is constant.

In 2001, the husband and wife team of Jaroslav Ivantysyn and Monika Ivantysynova [11] published their very detailed book on the design and analysis of all types of positive displacement pumps and motors. They also took modeling to a new plateau in two ways. First, the extensive design details are valuable in creating so-called “white box models.” These models require details regarding internal dimensions to produce. Such models are valuable to the designers of pumps and motors, and they are often proprietary and closely held trade secrets of their manufacturers. They are eminently useful, but not a goal of any model standardization. Second, the authors introduce a generalized kind of empirical modeling, that is, “generic black box modeling” based on using regressors. These are simple polynomials of the normal independent variables governing machine performance, namely pressure, speed, viscosity and displacement setting, each raised to a variety of exponential powers and in combinations of their products. Such models do not rely upon the first principles of physics, and therefore have an attraction to those users who lack knowledge of either internal dimensions or an understanding of the internally operative physics of the machine(s). These generic polynomial modeling methods have found champions in industry and academia because of ease of use and flexibility.

But, to say that Toet’s method languished in obscurity over the ensuing 50 years would be incorrect. It found its own advocates and supporters; however, it was never accorded any official recognition as would be given, for instance, in an international standard. Meanwhile, in 1988, an ISO standard, led and championed by Jim Bolinger (ret, Sauer-Sundstrand), was adopted at the ISO level that presented an empirical method for determining displacement. That version was withdrawn in 2007 and replaced by the ISO 8426 (2008) Method [15]. However, it took an overly simplistic approach. It is a quick method that this author has used from time to time with reasonably useful results, although they are somewhat erroneous. The method requires that the straight line of flow (Toet reports that the Couette effect results in a curved line for flow vs pressure), as a function of pressure at a constant speed, be extrapolated to the flow axis. The flow value at the intercept is harvested as the ideal flow. The ideal flow is divided by the constant speed and the result is taken as the displacement, also called the derived capacity. This method has been widely criticized, anecdotally, as well as in writing, for example by Garcia and Nicholson [16] as producing unreliable results.

Post [17] (1996), a colleague and contemporary of Toet, did a follow-up on displacement, writing a paper that compared ISO 8426 (2008), Wilson and Toet Methods. It involved testing of several different pumps, plus analyses of different methods in all combinations of pumps and methods.

THE SECOND ENLIGHTENMENT

The second enlightenment was primed to start in the late 1970s or early 1980s, but got delayed a decade or more. This was the period when the personal computer was born as a machine that would eventually find its modern progeny resting on nearly every desk in the world.

Computational power was destined for consumer and business use, dedicated to unfettered personal access to any and all who wanted it. The personal computer was a reality, even though its seriously limited DOS operating system delayed its technological advancement for at least a decade. It’s my opinion that Bill Gates, Microsoft, was not a business genius. He was a clever negotiator who played into the vanities of IBM and assured them that they were invincible, and therefore IBM did not need a patented/protected design for the PC, and all PCs were to use DOS. In the 1970s and 1980s there were literally thousands of PC manufacturers operating from basements and garages who were making “IBM compatible” computers. Each one had a copyrighted, and mandated, copy of DOS installed, a situation arranged by Mr. Gates, the negotiating wizard. I saw one advertisement that claimed its machine was “more compatible with IBM than IBM.” That is an interesting assertion, indeed. IBM is no longer in the personal computer business, but Bill Gates is currently the second wealthiest person in the United States of America. But lamenting aside, the most important issue was that millions owned computers and millions would program them, making both machine and software available almost without limit, and growing at a warp speed pace. Affordable and ubiquitous computation had caught up with the hydraulic models, but the timing was off.

In the late 1970s and early 1980s, NFPA meetings were rife with talk of the need for math models and simulation software. The personal computer was an emerging reality, giving engineers unlimited access to computational capabilities. This was also to have been the time when agriculture, construction, logging and other forms of off-road machinery would adopt electronic controls, making electronics a factor before, during and after OEM production. Alas, a recession struck in 1982 at the wrong time, delaying the upgrades. Anecdotal reports at mid-recession time told of a reluctance on the part of OEMs to put electronic controls on their machines when the dealer repair technicians were not yet properly trained. Additionally, the economic recovery was impeded in the user markets, delaying adoption of electronic controls (autos were well on their way) by a decade or more. Eventually, electronic controls were adopted, but perhaps the real change took place around the turn of the 20th to 21st Century and at a more leisurely pace than might otherwise be expected.

Math modeling and simulation were picked up by progressive hydraulic manufacturers and placed under coveted private wraps rather than into the sunshine of public domains via international standards. The second enlightenment was only partially realized. Now, we have a manufacturing industry that rejects the standardization of math modeling and simulation. It's my belief that hydraulic manufacturers would make more money if they emulated the electronics manufacturers and sold to a well-educated marketplace rather than have to send an engineer along with every pump or valve stack that is shipped.

A PERSONAL WITNESS TO A FABULOUS JOURNEY

IN ADDITION TO ELECTRONICS and computers and software and hydraulic models, I would also like to share my insights as a personal witness to a fabulous journey through the most fascinating period in the history of the world. I was proudly born from peasant stock to a homemaker and an itinerant, unemployed cheese maker and erstwhile gandy dancer in the deepest, darkest part of the Great Depression, the second child of what would become three before WWII started. My Dad would tell how he would walk down the railroad tracks in the winter to pick up coal that had fallen from the tenders of the steam locomotives of the day. It kept the house warm for a young family. He had few regular jobs, that I can recall, before 1942. We all felt the depression, but clung tenaciously to hope.

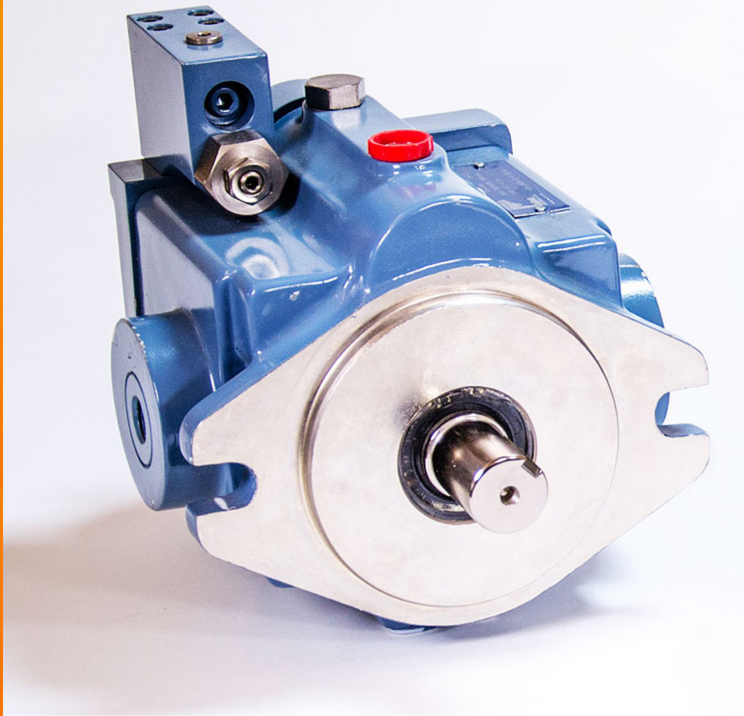
That my parents coped and cared for their family, in spite of the challenges in a constant survival mode, is attested to by the fact that my two sisters and I are still here after more than eight unique decades. My solid, supportive family was the launching pad for a full and rewarding career in engineering. I experienced first-hand the depression and was a lad growing up during WWII, but too young to participate. I recall one memorable day for this impressionable youngster, when a massive, all-day military convoy drove through our little farming town in North Central Wisconsin in 1943. Miss Placzynski, our 4th Grade teacher, let us press our noses against the windows for hours and watch this marvelous parade. No circus could compare. I knew not the convoy's origins, nor its cargoes nor their destinations. But it was clear that their reason was to protect me, so willingly, and all the others who didn't have to go.

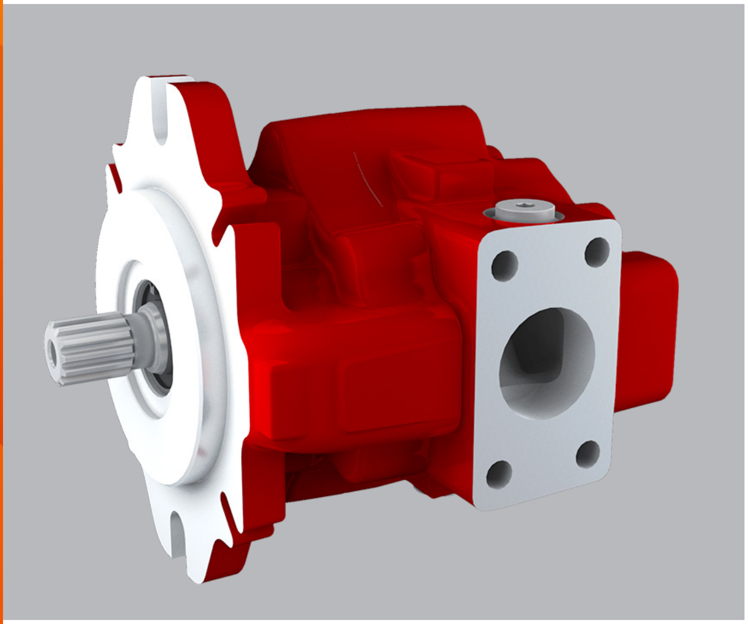
That was so typical of Miss Placzynski. She taught us such real life things and fun things, too, that interested 10 and 11 year olds and piqued our boundless curiosity. She taught us popular songs. My favorites were "Mairzy Doats and Dozy Doats and Liddle Lamzy Divey" [1], a novelty song to help cope with war's insanity. And there was the Army Air Corps (now the US Air Force) song, "Off We Go" [3]. I knew then that someday, somehow, some way, I would earn a pilot's license. There is this personal side as background because the history I summarize is the contemporaneous period of my own life. I lived it and watched it as the explosions of the war filled the newsreels, followed by the explosions in technology meant to satisfy our hunger for convenience. The technological revolution continues today, without always being recognizable as it unfolds.

More importantly, I had the very special pleasure of meeting many of the pioneers and great thinkers of my day, and so many of the "Greatest Generation" [3], too many of whom never returned. It is both history and memory, and dear as well. I think I am not alone, being in a very fortunate cadre of contemporaries who have observed the scenes that I have. It has been a fulfilling journey, indeed. The trip includes, but is not limited to, the five threads in this brief and focused history: electronics, computers, software, hydraulic systems and their math models, and exceptional personal experiences, all of which converge in the hunt for useful mathematical models for pumps and motors.

Pre-dating me were the ashes and carnage of WWI which begot Versailles, which begot the vengeful rape and plunder of Germany's wealth, assuring that fascist dictators would arise and resume the war. And those political errors begot the much greater ashes and carnage of WWII, and in turn begot the same universal, renewed chorus from the victors for harsher reparations than those following WWI. Fortunately, political leaders with cooler heads and understanding of history prevailed. Instead, the Marshall Plan was implemented and former enemies' homelands were rebuilt and democratized and remain our allies to this day. They are economic competitors, to be sure, but political allies.

From WWII has come 75 years of no WWIII, and a more welcoming environment for the genius of great minds and visionaries to apply their creativity to helping mankind instead of destroying it. Therein lay the origins of this great age of technology, born into the detritus of war's death and destruction. Merely surviving a depression, and then a war, were formidable challenges for the world. But enlightenment lay ahead.





ELECTRONIC ADVANCEMENTS

In the ensuing decades integrated circuits advanced at a rapid pace, leading to ever-tinier, more powerful and faster processors operating at higher and higher speeds. Cooling problems caused computer clock speeds to stop increasing beyond a few gigahertz, so multi-processor chips were invented to make use of parallel processing rather than serial processing. The internet was invented and access was turned over to the public. Electronic innovations are too numerous to mention beyond the most notable few. The millions of computer users assured that the explosion in computer hardware would be accompanied by an attendant explosion in useful software. Sixteen-core CPU chips, meaning a single integrated circuit contains 16 separate computers, are being produced at this moment.

But, it will be terawatts of power, more than gigahertz of speed and tens of computing cores, that will be needed to sow, cultivate, harvest and deliver the food from millions of point source farms to the distributed and hungry billions around the world. Hydraulic fluid power can be there to assist in this massive job. But we do not yet have any idea about the consequences of changing from millions and millions of distributed single point polluters spread across our roads and streets to a few multi-terawatt point sources for our electrical power as vehicles become more electrified. A viable power generation and distribution system has not yet been thought through.

THE FIRST STANDARD ON DISPLACEMENT

The U.S. Technical Advisory Group to ISO\TC131\SC8\WG13 is the Working Group that is responsible for hydraulic pumps, motors and integral transmissions. Their purview includes the revisions to ISO 8426 (2008) Method. Anecdotally, several members of WG13 expressed poor results when using the ISO 8426 (2008) document for the same reasons. Instead, their verbal reports praised the Toet method in preference over the ISO 8426 (2008) Method. The U.S. took the position that the five-year review of 8426 (2008) should result in replacing the existing standard and, furthermore, the U.S. agreed to lead that effort. Prof. Jose Garcia PhD, Purdue University, accepted the leadership responsibility of the review and revision project.

But this discussion is getting ahead of itself. In 2016 the U.S. Delegation to WG13 put together a proposal for a new official ISO project to prepare mathematical models of hydraulic pumps and motors. I volunteered to be the project leader and expanded on the integer-only Invatysyn-Invantysynova [11] polynomial modeling by allowing for non-integer exponents on the polynomial terms and more flexibility in the regressors. However, this proposal was narrowly rejected in a vote just prior to the scheduled meeting of WG13 in San Antonio, Tex. in May of 2016. After a detailed technical presentation to the gathered WG13 members, the group remained unswayed and continued its opposition to a project for mathematical modeling. A standardized math modeling project was dead.

BREAKTHROUGHS IN MATHEMATICAL MODELING OF HYDRAULICS HAVE LED TO HIGHLY ENGINEERED COMPONENTS AND SYSTEMS, SUCH AS THESE STATE-OF-THE-ART PISTON PUMPS.

📷 | *COURTESY CONTINENTAL HYDRAULICS (TOP), BUCHER HYDRAULICS AND LIEBHERR COMPONENTS.*

ORIGINS OF PSR ANALYSIS

Instead, the German and French delegates informally requested of the assembled U.S. delegates, Paul Michael, Sam Hall, and this author, that they undertake a personal effort to find a way to reduce the number of data samples needed to create useful mathematical models of pumps and motors. The U.S. delegates accepted that challenge, with me taking the leadership role. I was an unlikely candidate for the role, given my lack of interest, knowledge and experience in statistics because this, indeed, was perceived as a role that required a thorough review of the statistics of sampling. Regardless, this was the plan as the group adjourned its San Antonio discussions and returned to their respective homes.

In due time, the U.S. members searched hopefully for some obscure formula that would say, for example, "If you want a model with a standard deviation of x% at a confidence level of y%, then use this formula to arrive a sufficient sample count." No such formula was found. With no clear path to delivering on the promise of San Antonio, I started with a new postulate in [18], but paraphrased here:

If the concept is valid that a small, finite number of samples can be sufficient so as to represent an unlimited population of possibilities (first part), then there must come some finite number of samples beyond which the regression model undergoes no improvement (second part).

This is an interesting postulate because there were decades, if not centuries, of experience using small samples to sufficiently represent much larger populations. There is unlimited empirical evidence to support the validity of sampling theory. It is the reason that fairly accurate forecasts can be made by political pollsters who conduct only about 1,000 polling calls to find out what the other 230,000,000 U.S. voters will decide. If the first part of the postulate is irrefutable, then the second part of the postulate must be true as well. The postulate is not profound. It is simple common sense and the second part is but a simple and logical consequence of the first part. The direction for the ensuing and validating research effort became clear.

To find the data sample count at which the model no longer improves, these straightforward PSR analysis steps, which are built around any conventional, linear, multiple regression computer program, will be helpful:

1. Collect test data from a worthy test specimen in a quantity that far exceeds the number of samples needed to create a useful and accurate model. Call this array the "Genesis File" or the "Genesis Matrix."

2. Select a "catalyst regression function" that is representative of the first principles of the pump/motor, which gives the regression program something to regress on.

3. Populate a new matrix, the "Regression Matrix" with the first few samples from the genesis matrix, starting with the fewest number of samples needed to satisfy the needs of regression (one more data sample than the number of independent regressors). Then perform regression on it, saving all the critical calculated data:

   a. All calculated regression coefficients.
   b. RMS value of residuals.
   c. Other desired figures of merit arising from regression.

4. Taking, again, from the Genesis File, add one more sample to the Regression Matrix, do regression again, and continue this iteration process until all data samples in the Genesis File are consumed (regressed) through the Regression Matrix.
5. Scan the RMS value of the residuals to determine where the residuals stop changing.

6. If the stopping count requires too many data samples, rearrange the order of the data so as to reduce the point of little or no change.

7. Repeat rearrangement of the Genesis File until the sample count occurs at an acceptable value.
The above procedure was named Progressively Sequenced Regression Analysis (PSRA). Other supporting terms that have been coined in the process are:

1. Catalyst regression function.
2. Learning zone.
3. Information saturation.*
4. Convergence zone.*

(*Through it all, it was discovered that the statistics industry has no term for that condition where the sample size is sufficient to create a useful and sufficiently accurate model. Information saturation is the term that we use for just that condition in PSR analysis. In the progress reports to WG13, convergence zone was also used. The statistics industry should adopt "information saturation" as a useful term.)

LATIN HYPERCUBE DESIGN AND DATA VERTEXING

Paul Michael and Pawan Panwar, MSOE, were instrumental in introducing me to Latin hypercube design of experiments. The number of samples in the hypercube's hyperspace predicts the minimum required sample count. In subsequent research, it was found that orthogonally sequenced data could be mined for its hyperspace vertexes, which produced information saturation similar to the Latin hypercube sequencing. That is, the number of vertexes predicted the number of samples for information saturation. The theory at this stage in the PSR development is that the minimum number of samples to recommend is equal parts of vertexes and Latin hypercube samples. That is, the recommended minimum sample count equals the number of vertexes in the hyperspace plus that same number of Latin hypercube tiers. So, if we have say, three independent variables in the pump/motor test plan, there will be nine ($2^3 + 1$) samples required. Additionally, the machine should be tested using eight tiers in the Latin hypercube test sequence, making the minimum data sample count of 17 samples. This theory requires testing on real data, which is in the planning stage now.

London Meeting: The latest international meeting was held in London in May, 2018. This author's presentation was at the end of the day and we were rushed by security to vacate the building. But the assembled group, which included Prof. Toet, managed to make these three requests, one of which was to continue the pursuit of the sample minimization method available with PSR analysis.

Analysis of donated legacy data: A three-member Study Team of volunteers had already been named at an earlier meeting, with Jose Garcia as leader of the team and John Montague and the writer as members. The popular Toet Two-Step Method was to be analyzed, along with a One-Step equivalent. Prof. Garcia asked me to include the Wilson Two-Step Method, having been motivated by the earlier-mentioned and interesting paper by Post [17]. The ultimate aim was to do a comprehensive comparison of these four competing methods.

The reported conclusions of the donated data study, under the leadership and guidance of Dr. Garcia, were:

1. The Wilson and Toet Two-Step Methods and the Toet One-Step Method all produce effectively the same results.

2. The ISO 8426 (2008) Method results diverge from the other three, confirming results of Garcia and Nicholson [16].

3. Pumps with pressure-balanced end plates produce different results at different viscosities. Evidence emerged, suggesting that all pumps exhibit viscosity-dependent displacement.

4. When all viscosities are regressed in one fell swoop, a third result arises, therefore leading to the urging that any new standards take viscosity into account.

THE THIRD ENLIGHTENMENT LIES AHEAD

Determination of derived capacity is a mathematical process because we do not have a direct measurement tool for displacement. Mathematical modeling methods are the only means for converting empirical data to a displacement value. With the proposed revisions to the derived capacity standard, we stand now at the threshold of the third enlightenment, aided and abetted by ever faster and more powerful information processing. New technologies include the hard-core modeling methods of digital twins, and there is also nanotechnology, and additive manufacturing, and the misnamed, but yet useful, artificial intelligence and machine learning. And other new technologies are on the horizon with more to come. Ours is but a small part of this broader technological advancement, but nonetheless important in order to keep fluid power in general, and hydraulic engineering in particular, viable and competitive. We need only step boldly and optimistically through the open door and adopt a new, internationally standardized mathematical model for empirically determining displacement of hydraulic pumps and motors. ■

REFERENCES

[1] "Mairzy Doats" is a novelty song written and composed in 1943 by Milton Drake, Al Hoffman, and Jerry Livingston, https://www.lyrics.com/lyric/2924050.

[2] Brokaw,T, 1998,The Greatest Generation, Random House

[3] Robert MacArthur Crawford, 1938, "Wild Blue Yonder" (The Air Force Song), http://wildblue.cc/song-lyrics/.

[4] Pippenger,John J; 1992, Fluid Power – The Hidden Giant, Amalgam Publishing Company, Jenks, OK, USA

[5] Wilson, W. E. (1950), Positive Displacement Pumps and Fluid Motors, Pitman Publishing, New York

[6] Blackburn, J F; Reethof, G; Shearer, J L; 1960, Fluid Power Control, The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, MA

[7] Merritt, H.E.; (1967), Hydraulic Control Systems, Wiley, New York.

[8] International Slide Rule Museum, https://www.sliderulemuseum.com/Post.htm

[9] SAE International, (December 2009) "SAE J745 - Hydraulic Pump Test Procedures, Recommended Practice," SAE World Headquarters, 400 Commonwealth Drive, Warrendale, PA

[10] SAE International, (December 1955) "SAE J746 - Hydraulic Motor Test Procedures, Recommended Practice," SAE World Headquarters, 400 Commonwealth Drive, Warrendale, PA

[11] Ivanysyn,J; Invantysynova, M; Hydrostatic Pumps and Motors, Akedemia Books International, New Delhi 110019, India

[12] Toet, G; Die Bestimmung des theoretischen Hubvolumens von hydrostatischen Verdrangerpumpen und Motoren aus volumetrischen Messungen, Olhydraulik und Pneumatik O+P, 14 (1070) No. 5 pp185-190

[13] Toet, Johnson, Montague, Garcia-Bravo, Torres, "The Determination of the Theoretical Stroke Volume of Hydrostatic Positive Displacement Pumps and Motors from Volumetric Measurements" has been published in Energies as part of the Special Issue Energy Efficiency and Controllability of Fluid Power Systems 2018 and is available online

[14] Huhtala, K; Modeling of Hydrostatic Transmission-Steady State, Linear and Non-Linear Models, Mechanical Engineering Series No. 123, Tampere, Finland 1996

[15] ISO 8426, Hydraulic fluid power – Positive displacement pumps and motors - Determination of derived capacity, ISO copyright office, Case postale 56, CH-1211 Geneva, 2008

[16] Garcia, J. M.; Nicholson, J; "Revisions to ISO 8624: A Standard for Determination of the Derived Capacity of Hydraulic Pumps and Motors," 2018 Manufacturers Directory, International Fluid Power Society, NJ

[17] Post, W.J.A.E.M.; "Models for steady-state performance of hydraulic pumps: determination of displacement," 9th International Workshop, University of Bath, 9-11 September 1996

[18] Johnson, J. L. (2018); :Design of experiments and progressively sequenced regression are combined to achieve minimum data sample size," Int. J. Hydromechatronics, Vol. 1, No. 3, pp.308–331.