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Control solutions for processes with large load variations

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Abstract: *The paper presents some aspects about the control of processes with important load variations during their operation and discusses adequate control solutions for this problem. The first one is based on a multiple model structure and the second one on a feedback - feedforward structure. Their applicability is analyzed by means of a real-time structure implementation using a RST control algorithm. Based on the software implementation, an analysis of the advantages and disadvantages of the proposed solutions is made. Based on the observations a third solution is proposed. –This is a combination between multiple model and feedforward structure, with better results.*

Keywords: *multiple models, robustness, switching, load variation, pneumatic, software application.*

1. INTRODUCTION

Industrial and transportation areas can provide examples of many processes which exhibit important "load" variation during their operation. Elevators, pneumatic positioning systems, cranes, robots arms, convoy ships, military jets and railway trains are examples of processes that can be subject to large load variations. Various practical and theoretical control solutions provide valuable answers for these [1-4].

The present paper compares two classical solutions: the first one is based on a multiple model (MM) or multiple controller structure, while the second one is based on a feedback – feedforward structure (FF-FB) [5-6].

The implementation of the multiple model solution is quite natural – a model / controller pair could be associated to each functioning load or regime. Each corresponding control algorithm could "drive" the process to its functioning interval; preserving the tracking performances of the control system in spite of changes in the dynamic of the process. It is known that in multiple model structures two specific problems have to be addressed: the selection of the best model/controller and the switching strategy. For the processes included in this class the most important is the second one – switching between algorithms.

The second solution is equally expected – because the load variation (assimilated to a disturbance) can be measured or known a priori, a feedforward controller can be used to add an anticipative control element to the feedback command [11], pre-empting, thus, the disturbance affecting the process.

By studying the advantages and disadvantages of the MM and FF-FB solutions, we propose a hybrid control algorithm which leads to better results.

The rest of the paper is organized as follows: the second section presents the phenomena exhibited in the targeted processes. The third section arguments the proposed control strategy and the fourth refines the control law design procedure. The fifth section presents simulation results that validate the proposed control solution. Finally, conclusions are drawn in the sixth section.

2. TARGETED PROCESSES PRESENTATIONS

As presented in the introduction, transport and industrial areas offer a lot of processes examples where large load variations occur during continuous functioning regime [7].

Some of them are positioning systems with pneumatic actuators [7]. In this case, load variations can be treated as important disturbances and the regulation problem can be solved using robust control algorithms. But, a general robust control algorithm is usually too

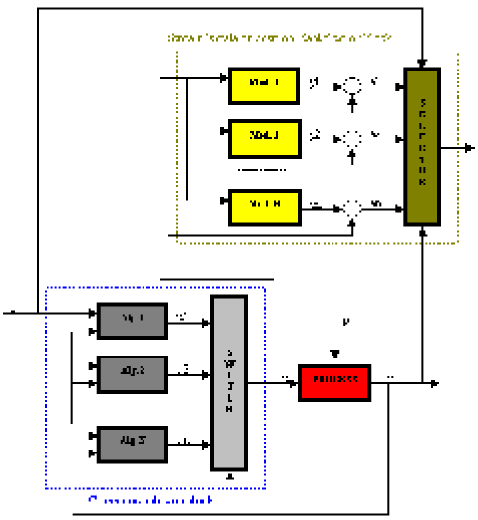

Fig. 1. General multiple model control structure

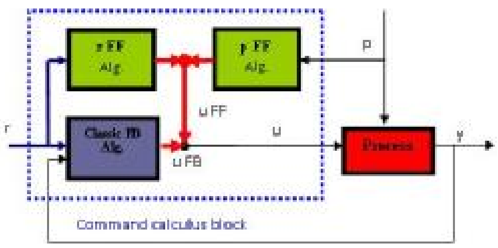

Fig. 2. General control system with both feedback and feedforward control

complex or difficult to implement as real time control strategy. On the other hand, classic control algorithms as PID, and one degree of freedom control architectures in general, can only address one single problem: either disturbance rejection or reference tracking. So, after a major load variation, even if the control system manages to effectively reject the "disturbances", usually the tracking performances might be affected.

These are part of the arguments for a negative recommendation in using of a single control algorithm or a classic feedback control structure for this type of problems.

3. PROPOSED CONTROL STRATEGY

The first impression can be that an adaptive controller might be a solution for these processes, but, due to almost instantaneous load variations, the necessary adaptation time (process model identification, model validation etc.) prevents the classic adaptation control algorithm from being a valid solution.

The goal of the control algorithm concerns mainly the reference tracking performances. These must be maintained in spite of major and instantaneous load variations.

As mentioned, one of the adequate solutions is the use of a multiple model control structure. This is an adaptive control scheme too, but here all controllers are pre-calculated. For the control algorithm a two degree of freedom RST structure can be chosen [5]

Load variations determine the selection of the corresponding control algorithm – the one that can track the set point with best performances. Model/load type selection can be determined using a load sensor - as illustrated in Fig. 3.

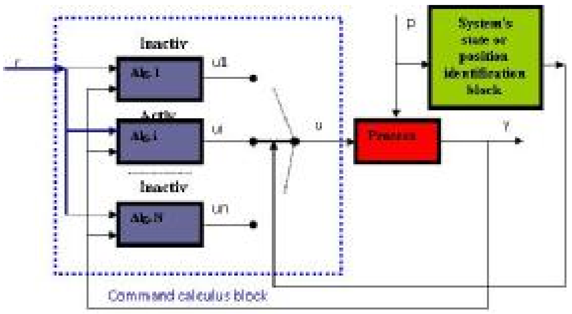

Fig. 3. Particular multiple model control structure

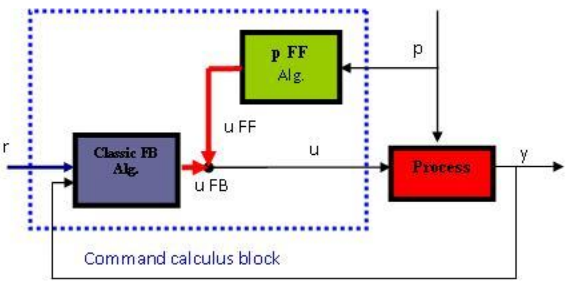

Fig. 4. Particular control system with both feedback and feedforward control

The switching problem can be partially solved through robust design of each control algorithm. Then, all inactive algorithms are maintained in "hot" state – each calculates an appropriated control value, but only after switching this value is applied to the process.

This is a different approach towards the switching strategy; for most applications the multiple model structure must not generate control shocks at the time of the switching. The shocks will be present because major disturbances affect the system. The most important objective is to preserve the set point tracking performances and, of course, system stability. The stability problem was studied in [9]

Another difference in comparison to the usual approach is that, for stability reasons, each control algorithm must have enough robustness to control "neighboring" regions [10].

The second solution uses the feedback - feedforward control structure presented in figure 4 [11]. The feedforward block compensates the load variation measured as disturbance ***p***. Only the feedforward block corresponding to the disturbance is used here, without the part that feeds forward the set point. The global command $u(k)$ generated by the "Command calculus block" is then:

$$u(k) = u_{FB}(k) + u_{FF}(k)$$

where: - $u_{FB}(k)$ and $u_{FF}(k)$ represent the outputs of the feedback and feedforward blocks respectively.

The output of the feedforward block can take either continuous or discrete values. In the first case, an accurate model of the way the disturbance acts on the process has to be available, which is not always possible. In the second case, a set of compensatory discrete values could be determined through experiments.

For the feedback algorithm, the same RST controller structure is chosen, allowing robust design for disturbances rejection and set point tracking.

There are a lot of advantages and disadvantages for both solutions. As far as the multiple model (feedback) control is concerned, the main advantages are:

- The corrective action is taken whenever the output deviates from the set point under the action of disturbances (major "load" or others).
- An appropriate control algorithm based on an identified mathematical model of the process is applied on each functioning regime.
- The same closed loop performances are maintained over the entire functioning domain.

On the other hand, the disadvantages of the multiple model (feedback) control are:

- Even if the appropriate controller is selected through switching, the compensation of the output error may still need a fairly large interval of time.
- The closed loop evolution may not provide satisfactory tracking performances in the wake of a large load variation.

The main advantage of feedforward control is that the corrective action is taken before the output deviate from the set point.

The disadvantages of feedforward control are:

- The disturbance(s) must be measured on-line.
- An exact mathematical model of the process is usually required for controller design.

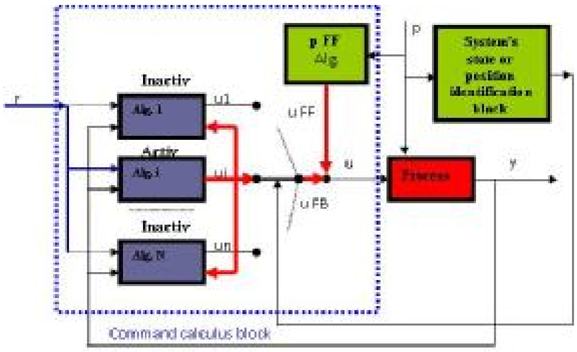

Fig. 5. Proposed control system with multiple model and feedforward control

Based on these observations a combined control structure (figure 5) can be designed: a multiple model structure for the feedback loop with a supplementary feedforward block. The role of the multiple model structure is to maintain the same tracking performances over the entire functioning domain. The feedforward block compensates for the need of leaps / jumps in the command due to load variations.

The measured load variation *p* determines, simultaneous, the switching between algorithms and the feedforward block command value.

The switching strategy is designed to prevent discontinuities in the command [10]; the main discontinuities in the command are determined by the feedforward block.

4. CONTROL LAW DESIGN

As specified before, for this study it was decided to use a RST algorithm for all proposed solutions. The design is based on the pole placement procedure [12] and Fig. 6 presents its structure.

The R, S, T polynomials are:

$$R\left(q^{-1}\right)=r_0+r_1q^{-1}+...+r_{nr}q^{-nr}$$
$$S\left(q^{-1}\right)=s_0+s_1q^{-1}+...+s_{ns}q^{-ns}$$
$$T\left(q^{-1}\right)=t_0+t_1q^{-1}+...+t_{nt}q^{-nt} \qquad (1)$$

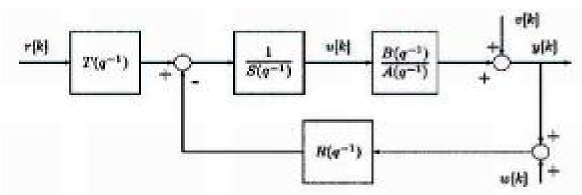

Fig. 6. The RST classical control algorithm structure

The pole placement design procedure is based on an identified model of the process:

$$y(k)=\frac{q^{-d}B(q^{-1})}{A(q^{-1})}u(k) \qquad (2)$$

where:

$$B\left(q^{-1}\right)=b_1q^{-1}+b_2q^{-2}+...+b_{nb}q^{-nb}$$
$$A\left(q^{-1}\right)=1+a_1q^{-1}+...+a_{na}q^{-na} \qquad (3)$$

This approach allows the users to verify, and if is necessary, to calibrate algorithm's robustness [12]. The next expression and Fig. 7. present the "disturbance-output" sensibility function:

$$S_{vy}(e^{jw})\overset{def}{=}H_{vy}(e^{jw})=$$
$$=\frac{A(e^{jw})S(e^{jw})}{A(e^{jw})S(e^{jw})+B(e^{jw})R(e^{jw})},\quad \forall w\in R \qquad (4)$$

At the same time, the negative maximum value of the sensibility function represents the module margin.

$$\Delta M\big|_{dB}=-\max_{w\in R}\left|S_{vy}(e^{jw})\right|\Big|_{dB} \qquad (5)$$

Based on this value, in an "input-output" representation, the process variation can be bounded inside of a "conic" sector, presented in Fig. 8, where a_1 and a_2 are calculated using the following expression:

$$\frac{1}{1-\Delta M}\geq a_1\geq a_2\geq\frac{1}{1+\Delta M} \qquad (6)$$

Note that a disadvantage of choosing this control algorithm is that, in order to identify a model of the process, one must select an appropriate operating point.

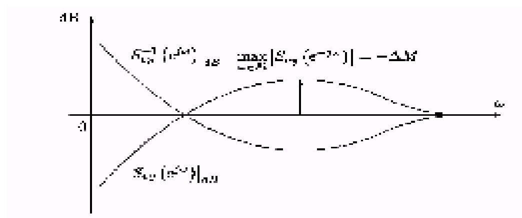

Fig. 7. Sensibility function representation

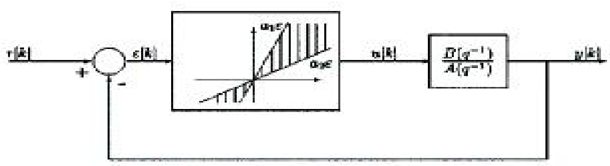

Fig. 8. Robust control design procedure

5. CASE STUDY

The performances of the proposed control structures (Fig. 3., 4. and 5. – with robust RST algorithms) were evaluated on using a software platform simulating a pneumatic vertical positioning system (pneumatic elevator) with variable load –

Fig. 9. The positioning system consists in a platform for various loads sustained by a vertical piston with compressible gas. The platform must elevate the load to a prescribed value which must be maintained during loading and unloading operations.

Three types of loads are considered: 1 – minimal (low) load, 2 - medium load and 3 - maximal (high) load. This imposes at least three models/controllers for the multiple model control structure.

This simulator can be connected to a control software application for maintaining the desired position of the elevator during load variation. The control software application (Fig. 10) has the following functionalities:

- connection with the software simulator;
- setting/applying the automatic command;

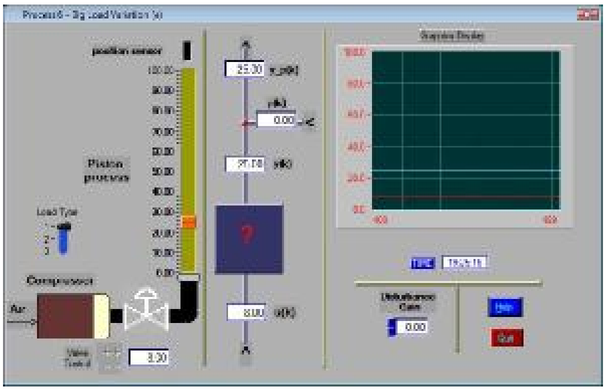

Fig. 9. Process simulator

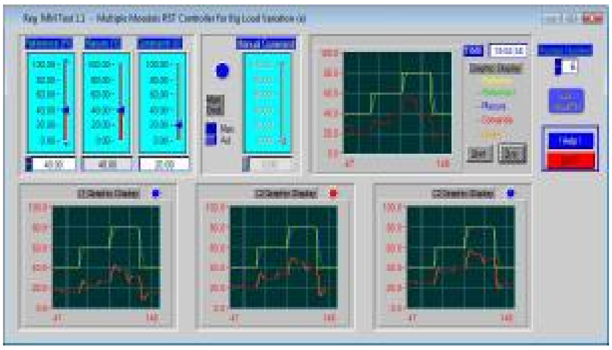

Fig. 10. Proposed control structure software implementation for the multiple model solution

- setting/applying the set point value,
- evaluation of RST algorithm output,
- setting the sampling period value,
- loading of process model and control algorithm parameters,
- loading of the variation of the load,
- displaying the real time evolution curves.

The simulator and the control applications were developed using National Instruments LabWindows/CVI an ANSI C base programming developing tool.

The approximated models for the positioning processes (identified for the lower, medium and high loads), obtained by using the recursive least square procedure [5] from WinPIM software are:

$M_1(q^{-1})=(0.6078+0.09312q^{-1})/(1-0.62q^{-1}-0.09881q^{-2})$

$M_2(q^{-1})=(0.5032+0.05767q^{-1})/(1-0.6221q^{-1}-0.0955q^{-2})$

$M_3(q^{-1})=(0.37047+0.075q^{-1})/(1-0.542q^{-1}-0.16207q^{-2})$

The corresponding RST controllers determined using poles placement procedure by employing the WinREG [5] software are:

$R_1(q\text{-}1) = 1.536917 -1.217656\ q^{-1} + 0.125103\ q^{-2}$

$S_1(q\text{-}1) = 1.000000 -1.117899\ q^{-1} + 0.117899\ q^{-2}$

$T_1(q^{-1}) = 1.4266960 -1.146866\ q^{-1} +0.164534\ q^{-2}$

$R_2(q\text{-}1) = 0.931829 + 0.201978\ q^{-1} -0.578523\ q^{-2}$

$S_2(q\text{-}1) = 1.000000 - 0.650645\ q^{-1} -0.349355\ q^{-2}$

$T_2(q^{-1}) = 1.782817 - 1.433137\ q^{-1}\ \ 0.205603\ q^{-2}$

$R_3(q\text{-}1) = -1.151901+4.367636\ q^{-1} -2.516586\ q^{-2}$

$S_3(q\text{-}1) = 1.000000 - 0.164894\ q^{-1} - 1.164894\ q^{-2}$

$T_3(q^{-1}) = 2.244719 - 1.804442\ q^{-1} + 0.258872\ q^{-2}$

The robustness performances for the sampling period T_e= 0.3 sec are: gain margin = 2.295 (7.22dB), phase margin = 56.2, delay margin = 0.30 sec, modulus margin = 0.564 (-4.97 dB). These assure good performance in disturbance rejection.

For the considered closed loop system (process simulator and multiple model control structure – a set of tests was performed. The set point value was varied between 0% and 100% and the load was modified from low to high such that switching between controllers occurred.

Test 1 – sp=40%, load min -> medium, sp=60%, load medium -> min, load min -> medium sp=40% (load, elevate, unload, load, lowering)

Test 2 – sp=40%, load max -> medium, medium ->max, sp=60%, (load, unload, elevate)

Test 3 – sp=40%, sp=60% load medium, load medium -> min, load min -> medium (during elevation, drop, pick)

In the next figures the color code is: yellow – set point; green – filtered set point; blue – process output; red – control structure output RST algorithm. The lower region of the control application window presents the evolution the three control algorithms.

Fig.11. Test 1 - parameters evolution

Fig. 12. Test 2 - parameters evolution

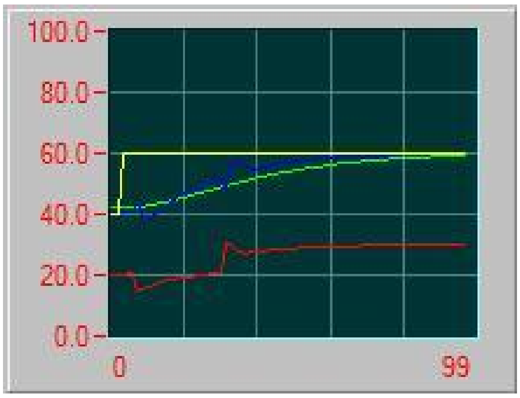

Fig. 13. Test 3 - parameters evolution

As expected, in case of test 1 and 2 there are no problems. The switching procedure is only “visible” through jumps in the commands. Set point tracking is quite precise.

In the third test, during the set point change from 40% to 60%, a controller switching occurs. The switch was determined by load variation (drop of a part of system’s load and pick of other supplementary load). Here, the tracking of set point in the neighborhood of the switching instants is not so precise but the system remains stable.

For the other two proposed control structures (fig. 4 and 5) control applications were developed with the same functionalities and connection abilities as above.

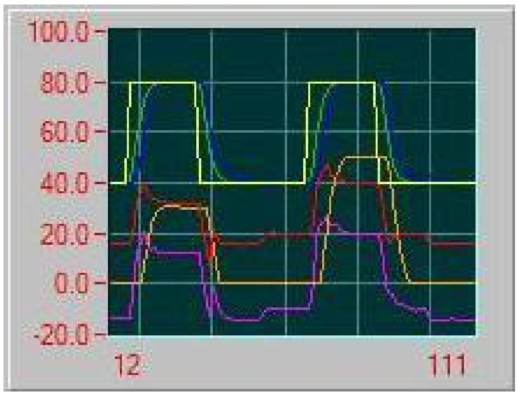

Fig. 14. (Simple) multiple model control structure tests

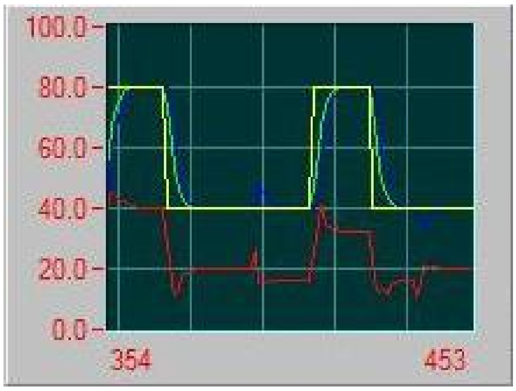

Fig. 15. Feedforward control structure tests

Fig. 16. (Combined) multiple model and feedforward control structure tests

We present three comparative tests where the process simulator switches between loads 1 (low) and 2 (medium). The switch is then followed by a change in the set point from 40% to 80%.

As expected, in the case of the (simple) multiple model control structure, the close loop system shows, except for the switching instant, good set point tracking (Fig.14).

The test corresponding to the feedforward control structure (Fig. 15) shows that the load switching generates a small output error, but the set point tracking performances are not very satisfactory.

The third control structure – combined multiple model and feedforward compensator (Fig. 16) provides the best performances toward set point tracking and improved performances during load switching.

6. CONCLUSIONS

The main contribution of this paper is to propose a hybrid MM-FF-FB control structure for processes with important load variations during continuous functioning and compare its results with the ones obtained by means of two classical control strategies: MM and FF-FB. The proposed control methodology showed improved results comparing to the classical structures.

These structures were tested by implementing them as real time control software.

The proposed solution uses a multiple model structure built around an RST control algorithm and a feedforward compensator block. The RST algorithm provides two degrees of freedom: different performances for set point tracking and disturbance rejection. The switching procedure relies on robust design towards disturbance rejection of each of the algorithms of the MM control structure.

The advantage of the proposed solutions is that it is numerically easy to implement. The main disadvantage consists in an increased computational resources necessity, especially for the multiple model structure, due to the parallel functioning of the individual control algorithms that it contains.

For limited computational resources the second control structure (Fig. 4) is recommended.

A balance between the number of control algorithms and their complexity was realized. An increased number of algorithms can determines a simpler structure for them. A smaller number implies a more robust structure for each one.

A limitation for the first solution (Fig. 3) is that switching is recommended to be made just between neighboring controllers. A “jump” is possible but it requires more robustness and can determine a longer settling time. However, these problems are eliminated by using the third solution (Fig. 5).

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REFERENCES

Boulter, T. B., - “Elevator Modeling And DC Drive Speed Controller Design”, *Applied Industrial Control Solutions LLC*, http://www.apicsllc.com/apics/sr_7/SR_7.Html, 2000

Fujimoto H., Y. Hori, and A. Kawamura, -“Perfect Tracking Control Based on Multirate Feedforward Control with Generalized Sampling Periods”, *IEEE Transactions on Industrial Electronics*, vol. 48, no. 3, 636-644, 2001

Goodwin, G. C., Graebe, S. F., and Salgado, M. E., - “Control System Design”, Prentice Hall, 2000

Kyoji, H., Masao, I., Hirofumi, O., Norihiro, M., Takeshi, K., - “Position Control of a Pneumatic Motor Driving System Using a Two-Degree-of-Freedom Controller”, *Nihon Yukuatsu Gakkai Ronbunshu Journal*, 31 (5); 145-150, 20009]

Landau, I. D., Lozano, R., M'Saad, M., “Adaptive Control”, Springer Verlag, London, 1997

Landau, I. D., Zito, G., - “Digital Control Systems”, Springer Verlag, London, 2006

Lupu C., A. Udrea, D. Popescu, C. Petrescu - Numerical Stability of Adaptive Control Algorithms- Buletinul Stiintific al UPB, seria C, apare in vol. 72, no.2, 2010, ISSN 1454-234x, pp. 61-72

Lupu C., Popescu D., Ciubotaru B., Petrescu C., Florea G., - “Switching solution for multiple-model control systems”, *14th Mediterranean Conf. on Control Autom.*, Ancona, Italy, June 28-30, 2006

Renn J.-C., Liao, C.-M., - “A study on the speed control performance of a servo-pneumatic motor and the application to pneumatic tools”, *The International Journal of Advanced Manufacturing Technology,* 23: 572–576, 2004

Stoianovici, D., Patriciu, Al., Petrisor, D., Mazilu, D., Kavoussi, L., - “A New Type of Motor: Pneumatic Step Motor”, *IEEE/ASME Transactions on Mechatronics*, vol. 12, 98-106, Feb. 2007

Tokhi, M. O., Al-Miskiry, M., Brisland, M., - “Real-time control of air motors using a pneumatic H-bridge”, *Control Engineering Practice,* 9(4), 449-457, 2001

Tsai, M. H. and Shih, M. C., - “A Study of the Pneumatic Counterweight of Machine Tools Conventional and Active Pressure Control Method”, *JSME International Journal Series C* 49(3), 890-896, 2006