Generating Vibration with Artificial Muscles*

Petri KESKI-HONKOLA, Matti PIETOLA

Abstract: This paper presents a study on the applicability of pneumatically actuated McKibben type fluidic muscles for producing mechanical vibrations in heavy machinery. Although McKibben type artificial fluidic muscles have been commercially available for couple of years, they are for the time being not very commonly known and used only in very restricted and special applications.

Fluidic muscles can produce even ten times the force of pneumatic cylinder with the same pressure difference and diameter. They are also practically slip-stick free which enables them to generate smooth movements. Another feature of the muscle is that there is interdependence with force and degree of contraction. Force is reduced while the muscle contracts. This feature enables the muscles to automatically center the position of the load when mounted in reverse-coupled manner and pressurized at the same time.

The artificial muscle actuated vibrator presented in this paper was constructed to replace a pneumatic motor-camshaft vibrator used to produce the vibration movement in a test installation. The muscle vibrator was designed so that the frequency, waveform and amplitude of the vibration could be adjusted. The problems related to the camshaft vibrator, like fluctuation of vibration frequency, difficulty in positioning the vibrated load and realizing an automated system were solved with the new vibrator.

Keywords: Pneumatic artificial muscle (PAM), artificial pneumatic muscles (APM), Fluidic muscle, McKibben type muscles, Generating vibration,

1 Introduction

McKibben type artificial fluidic muscles have been commercially available from 1980's (Bridgestone Rubber Company of Japan), 1990's (Shadow Robot Group of England) and 2000's (FESTO Company) [1] [2]. However they are not very commonly known actuators and they are typically used only in special applications. Yet these lightweight, easy to assemble and relatively inexpensive pneumatic actuators could replace many conventional actuators in many applications. In this paper the use of this type of artificial muscle is examined in an application where a specific vibration (waveform, amplitude, frequency, duration) has to be produced.

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There are many ways to produce vibration. Commonly used actuators are solenoids (as used in acoustic systems), motor-camshafts and hydraulic or pneumatic cylinders. A test installation at TKK/Department of Machine Design was originally equipped with a pneumatic motor-camshaft for producing the vibration needed. However this application had a number of problems. When ending the vibration sequence the camshaft most probably stopped in a wrong position and the load was left displaced. Camshaft could be manually positioned, but that would make automating the test sequence impossible. After a short period of testing there also occurred some wearing in the bearings, which caused more error in the load position.

Another difficulty was the speed control of the pneumatic motor. Motor speed was controlled only by manually adjusting the air pressure of the system. Pneumatic motor was also meant for higher nominal speed so the torque was too low to maintain constant speed in this application. Also when the bearings of the motor heated up and the load varied it influenced the speed of the motor considerably and changed the vibration frequency.

A new vibrator was designed in order to meet the needs of the test installation. After considering different options McKibben type pneumatic artificial muscles (PAMs [2]) were selected as actuators. Other names used of PAM are artificial pneumatic muscles (APM [3]) and fluidic muscle [4]. PAM is relatively cheap, clean and easy to install when pressured air

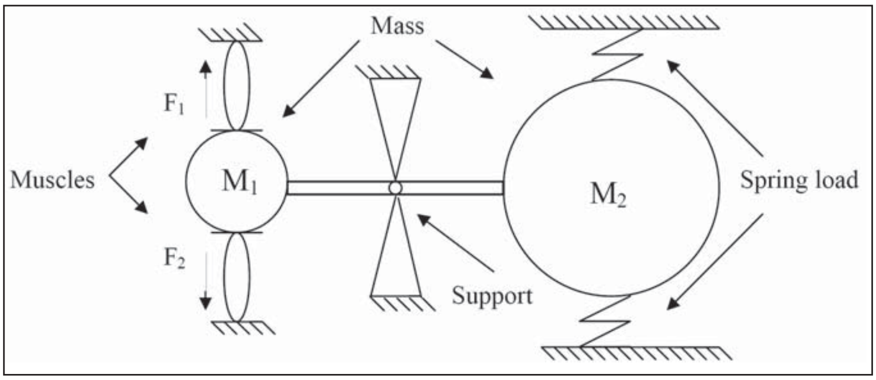

Figure 1. *Vibrating mechanism*

is available. They are also lightweight and service free. These muscles are very application specific and they should be selected very carefully.

In the laboratory test installation a vibration with maximum frequency of 5–20 Hz and maximum amplitude of 2 mm was needed. The vibration actuator was required to produce fifteen seconds long bursts of vibration every second hour.

PAM is an actuator that can only produce pulling force and the amount of force is reduced when the muscle contracts. This means that to produce bi-directional motion in vibrator, muscles have to be organized in reverse-coupled manner. On the other hand, due to the interdependence of force and contraction, when muscles are pulling from both sides they can center the load. This was one of the main reasons why muscles were used in the first place.

2 PAM-Vibrator

As described above the vibration was needed in a laboratory test installation. Original motor-camshaft vibrator wasn't sufficient and a new vibrator was needed. To solve the problems McKibben type muscles were selected to be used as new actuators.

Vibrating system couldn't be modeled and simulated in detail at the time because of tight schedule. There were also some variables that couldn't be determined at the time. This meant that some assumptions had to be made and all components were selected to be sufficient in performance.

Vibrating mass is over a hundred kilograms, but it is supported by an axel, so that the vibrator doesn't have to support the whole mass. However the mass is not fully balanced, so there is a static load of some 300 N to the vibrator. Additionally to the mass, different kind of spring loads are also applied to the system, depending what kind of test is being made, *Figure 1*.

2.1 McKibben type artificial muscle actuator

J. L. McKibben invented McKibben type pneumatic artificial muscles (PAMs [2] or APMs [3]) in 1950's as an actuator to be used in prostates. The principle of the muscle is the fact that a network of non-expandable fibers has been inserted around an inflatable rubber tube. Under pressure this tube expands in diameter and shortens in length, *Figure 2*. Fluidic muscle can contract even 25% at the maximum pressure of 600 kPa. [3].

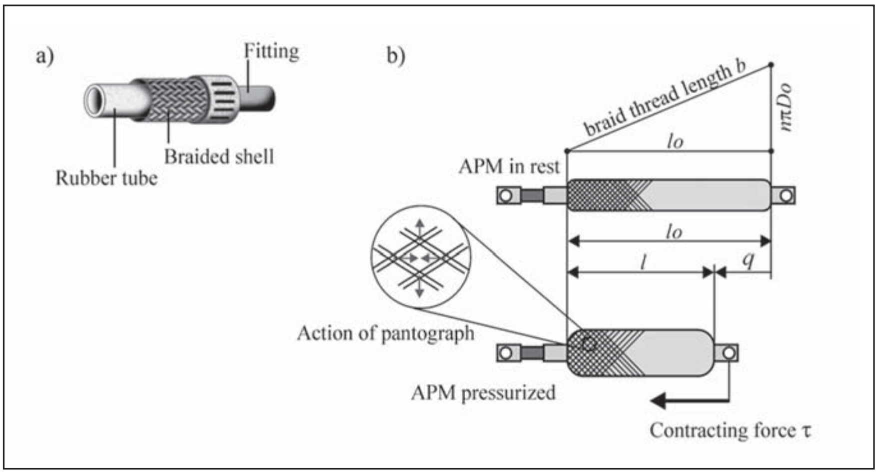

Figure 2. *Working principle of McKibben type fluidic muscle actuator [3]*

Artificial muscles are commonly operated with pressured air but they can also be operated with hydraulic medium like water. This is the reason why pneumatic muscles are also called as fluidic muscles [4].

While expanding, the muscle can only produce pulling force ten times stronger than same size conventional pneumatic cylinder. However the amount of force is reduced when the muscle contracts as shown in *Figure 3*. This means that to produce bi-directional motion, muscles had to be organized in reverse-coupled manner. Gravity or a spring can also be used to pull the muscle back to its nominal length. Due to the interdependence of force and contraction, when muscles are pulling from both sides at the same pressure they move to the position where forces are equal at the both sides. This means that if no outside forces applied, muscles move to center position. If there is a constant load force involved, muscles can be pretensioned so that when the muscles are pressurized at the same time the load is centered to certain position. This was one of the main reasons why muscles were selected as actuators in the new vibrator [4].

Maximum force produced in respect to nominal diameter is represented in *Table 1*. Muscles with nominal diameter of 20 and 40 mm can theoretically produce more force, but it might damage the muscle and is not recommended by vendor.

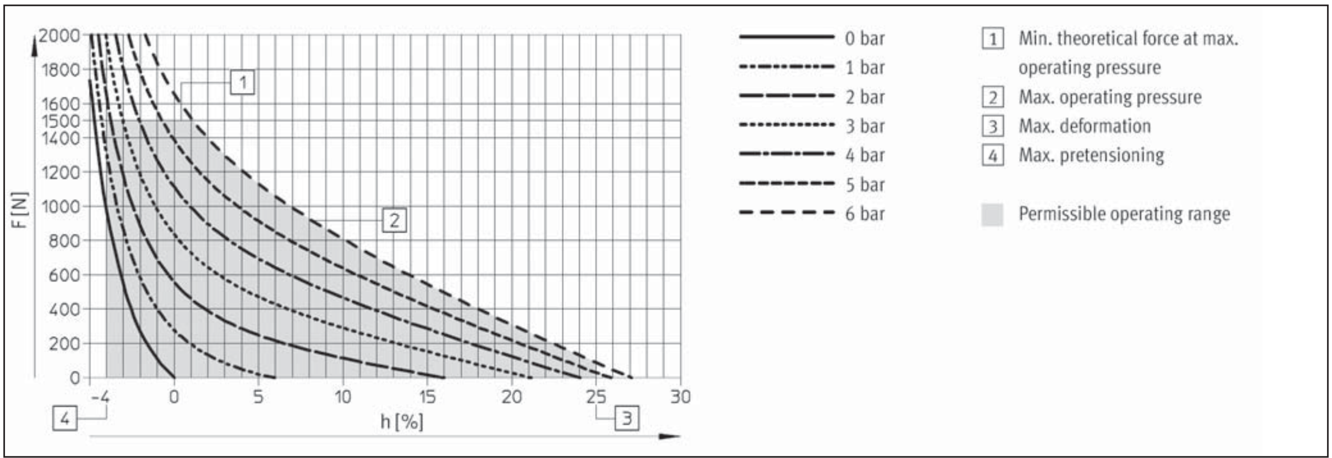

Figure 3. *Festo DMSP with diameter of 20 mm. h is the percentage of contraction [5].*

Table 1. *Maximum force of FESTO-DMSP fluidic muscles [5]*

Nominal diameter	Maximum Force
10 mm	630 N
20 mm	1500 N
40 mm	6000 N

2.2 Mechanical Design of Vibrator

Controlled vibration of 5-20 Hz with maximum amplitude of 2 mm was needed in a laboratory testing installation. In machinery, suddenly applying or releasing large loads often causes such vibrations as described. In the tested application the actuator had to produce a fifteen seconds short bursts of vibrations every second hour. Final settings used were 12 Hz and 0.7 mm

These muscles can contract 25 % from its nominal length but only a fraction (0.9 %) of this was used to obtain more force, Figure 3. It was calculated that the load mass could be vibrated fast enough with 1200 N of force. Because there was also the extra load caused by the system of springs a construction of two parallel muscles on both sides of the actuator was selected to produce enough force. Muscles were installed in reverse-coupled manner and as pairs, *Figure 4*. Load is attached between the muscle pairs so it can be pulled up and down. These medium sized muscles have a radius of 20 mm and nominal length of 80 mm and they can produce a maximum force of 1200 N each. This means 2400 N of maximum force to one direction. In this application maximum amplitude is limited to 0.7 mm but it could be easily changed and made larger since it was realized with simple adjustable mechanical end-stoppers. If the amplitude is increased then the maximum frequency will naturally be reduced.

2.3 Pneumatics

Two Festo 3/2 (MHE4-MS1H-3/20-1/4) fast switching on/off-valves were selected to control the airflow to the muscles, *Table 2*. They are capable of producing ten times the frequency that is needed. Current consumption of the valves is shown in *Figure 5*. These valves ensure adequate airflow and response time. One valve feeds air to one side of the vibrator and another to the other side. This means that two muscles are connected to one valve. By applying pressure to one side at a time the mechanism is made to vibrate, *Figure 6* [4].

Both control valves have an adjustable choke in their release channel, Figure 6. This means that the release speed of the air from the muscles can be adjusted. When release channel is choked, the idle muscles are not emptied immediately and they keep producing force for a while. This allows adjusting the form of the vibration.

System pressure levels were set to 400 KPa. This pressure produces the

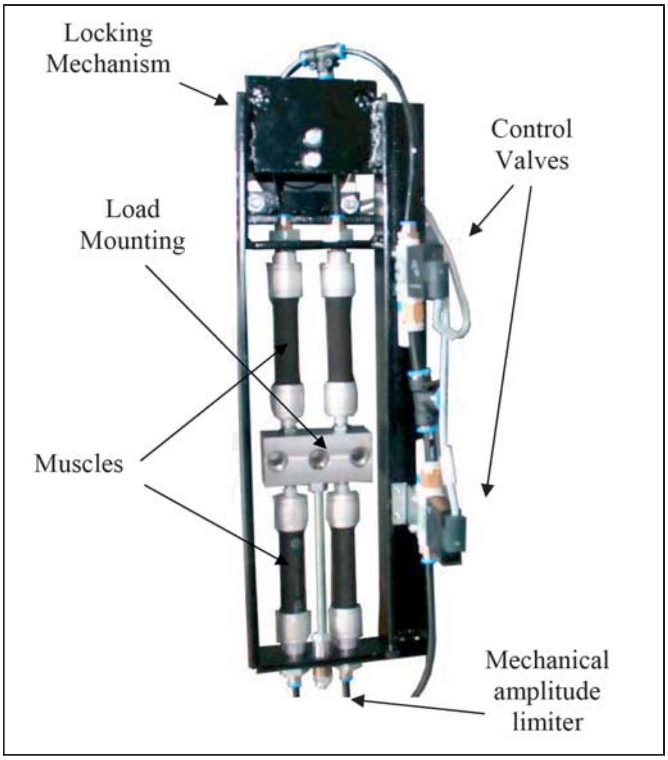

Figure 4. *Artificial muscle vibrator*

Table 2. *MHE4 fast switching valves [6]*

Opening and closing times	3.5 ms
Maximum switching frequency	230 Hz
Nominal airflow	400 l/min
Operating voltage	24 V

maximum force that the muscles can endure at this setup.

There is also a third valve (Lock Release Valve) which uses a pneumatic cylinder. This cylinder locks the vibrating mass and ensures that the load stays in a right position while the vibrator is off. Cylinder is spring actuated and the lock opens when pressure is applied trough the Lock Release Valve, *Figure 6*.

Command to produce vibration is generated in a PC-based measurement computer by a LabView program and delivered to Siemens LOGO! PLC. After receiving command signal, PLC directs power to an oscillator circuit for fifteen seconds. PLC also controls the locking cylinder and releases it while system is vibrating.

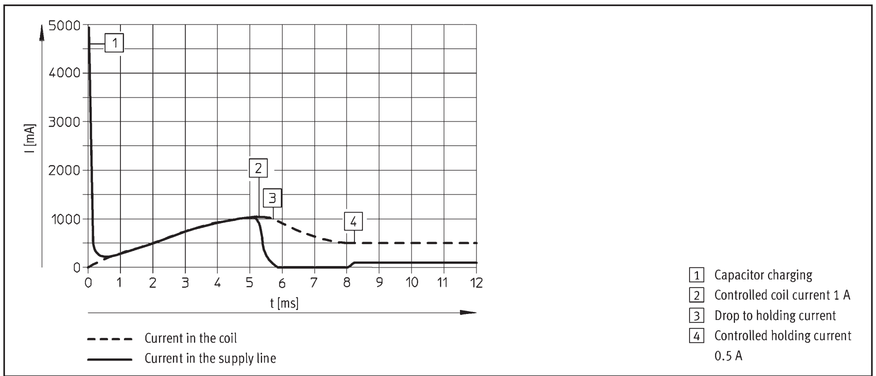

Figure 5. *Supply current curve of the control valve [6]*

Pneumatic connections of the system is made so the air doesn't change in the muscle and therefore they could heat up, but while using small amplitude of 0.7 mm heating does not happen. Only with faster vibrations and larger amplitudes, e.g., 20 Hz and 2 mm, the thermal load would be a problem.

Using the connection described in *Figure* **7** reduces thermal load. Pressured air is directed through one-way valve in to the muscle. Releasing pressure from the control valve opens the quick exhaust valve and releases pressure from the muscle. This kind of setup allows air to flow through the muscle and carry the excess heat out with it.

2.4 PLC (Programmable Logic Control)

Vibration is produced at a certain intervals and it lasts for fifteen seconds.

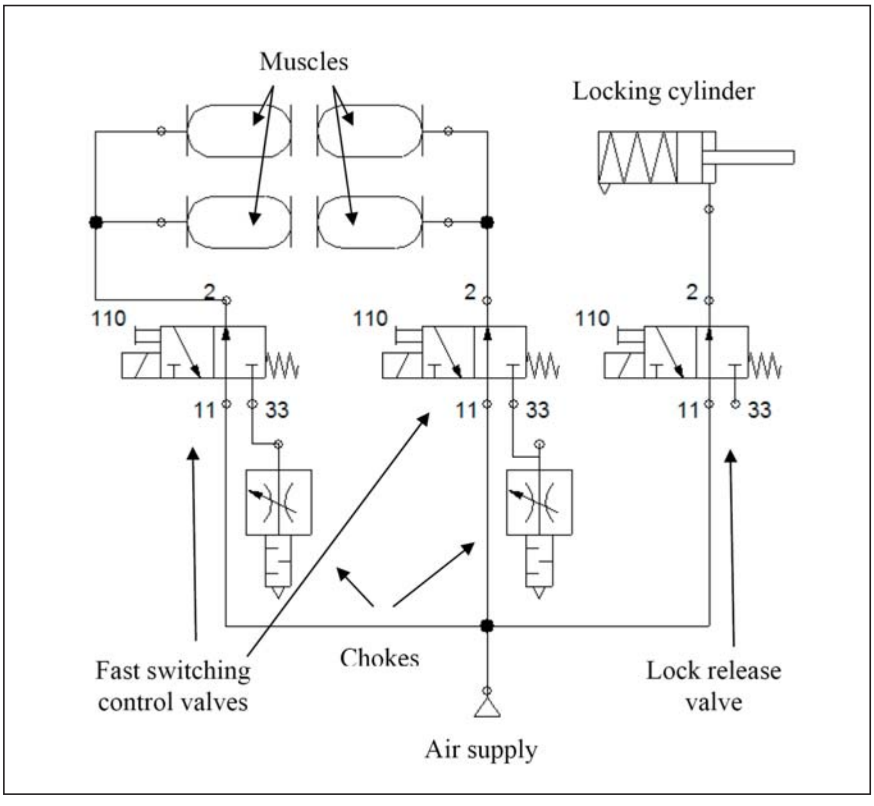

Figure 6. *Pneumatic chart of the muscle vibrator*

2.5 Oscillator

LOGO! PLC relay has a maximum switching time of 0.1 s. This means that it can't be used it to produce over 10 Hz vibrations. For these reason a separate oscillating circuit was made. It can produce square wave signal from 8 to 25 Hz. On and off time of the signal can be adjusted separately. PLC feeds oscillator circuit with 24 volts when vibration is needed, thus controlling the time and duration of vibration. Oscillator circuit feeds current to the two fast-switching valves in turns. This again makes the muscles contract one side at a time and load starts to vibrate.

3 Measurement system

In this section the measurement arrangement and sensors will be described in detail.

3.1 Data acquisition system

Measurement system and control system are partly the same. Same PC-based data acquisition system (National Instruments NI PCI-6229 and LabVIEW 7.1) was used to control the intervals of vibration and collect the

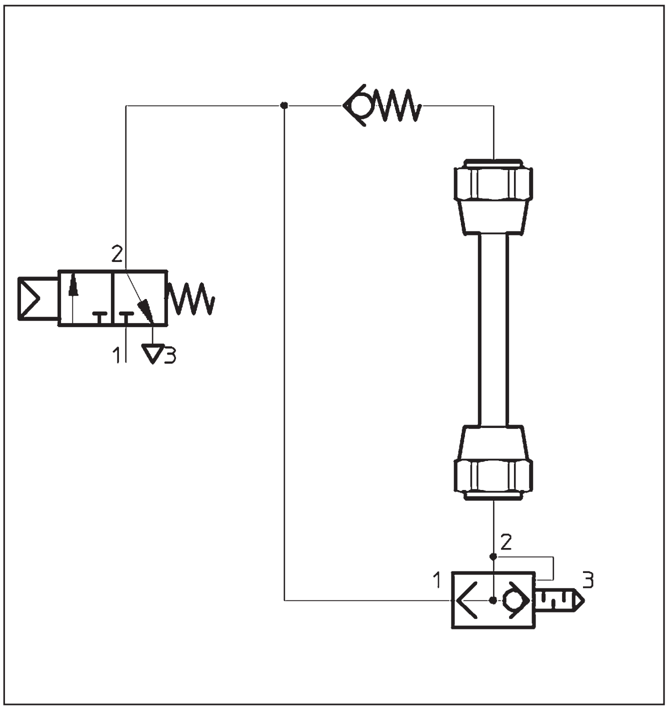

Figure 7. *Reducing the thermal load [5]*

data. Data was stored at the frequency of 2 kHz, which means that the interval of samples is 0.5 ms.

3.2 Position Sensor

Vibration form was measured near the connection point of the vibrator. A linear potentiometer was used,

Figure 8. Static values were certified with a manual displacement sensor. When amplitude of the vibration is low (under 1 mm) and maximum frequency is less than 30 Hz, the performance limits of the sensor are not exceeded, *Table 3.*

3.3 Measu-rement arrangement

In all measurements there is a spring related force additio-nal to the inertia of the system. Measurement sensor, electronics, mechanism of the vibrated system and the data acquisition system are same while measuring both vibrators.

Table 3. *Datasheet of POT-100-LWG [7]*

Maximum Stroke	100 mm
Resolution	0,01 mm
Maximum speed	5 m/s
Maximum acceleration	200 m/s²

4 Results

Measurement results are shown in **Figure 9.** They represent the position of load in mm as a function of time. All signals are filtered with same filter and while some phase shift occurs the amplitude and waveform are not affected at a significant level.

There are four different charts titled Fast, Middle, Medium and Original Motor.

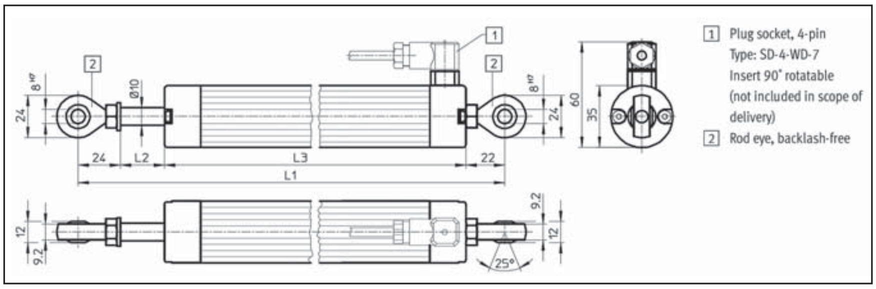

Figure 8. *Potentiometer MLO-POT-100-LWG [7]*

First three represent the new muscle actuated vibrator at different vibrating frequencies. Original Motor is measured with the original camshaft mechanism which is rotated with pneumatic motor.

5 Discussion

The vibration produced by the original pneumatic motor-camshaft mechanism is presented in **Figure 9**, lower right graph. Vibration has amplitude of 0.4 mm and frequency of 17 Hz in this specific measurement, but during the tests it was noticed that the frequency could vary by itself significantly and go even up to 50 Hz. The waveform is not the sine that it should be. This is probably caused by the wear of bearings and that there is unnecessary play in the mechanism. This would also explain that the amplitude is smaller than it should be.

First test with PAM actuated vibrator was made with the lowest frequency that the oscillator circuit would allow. The result of this measurement is shown in **Figure 9** lower left graph, labeled as Normal. Waveform is near square wave because the valve chokes are fully open and the movement is stopped by the mechanical stopper which limits the amplitude to 0.6 mm. Little bounce caused by the end stopper is also visible.

The measurement result labeled as Middle, **Figure 9** upper right graph, was measured at the frequency of 17 Hz. The amplitude is still at the maximum of 0.6 mm. Load is moving little faster upwards. This is because the load is off balanced to that direction and the muscles must work harder pulling the load down. This result shows that the goal set for the project was achieved.

Third measurement with PAM vibrator, **Figure 9** upper left graph, was to determine the limits of the system. It induced a lot of not wanted vibrations to the system and the results might not be very reliable. There was also a danger of breaking some parts of the larger system. Nevertheless a vibration over 30 Hz was achieved even if amplitude dropped to 0.3 mm.

The result of the study demonstrates that pneumatically powered fluidic muscles can be used to produce accurate vibrating motion of different waveforms in applications where pressurized air is preferred to oil and the required force is of moderate level. The advantage of pneumatic solutions is that they tend to be cheap and reliable compared to other alternatives. Choking the airflow, changing switching frequency of valves and changing pretension of the muscles

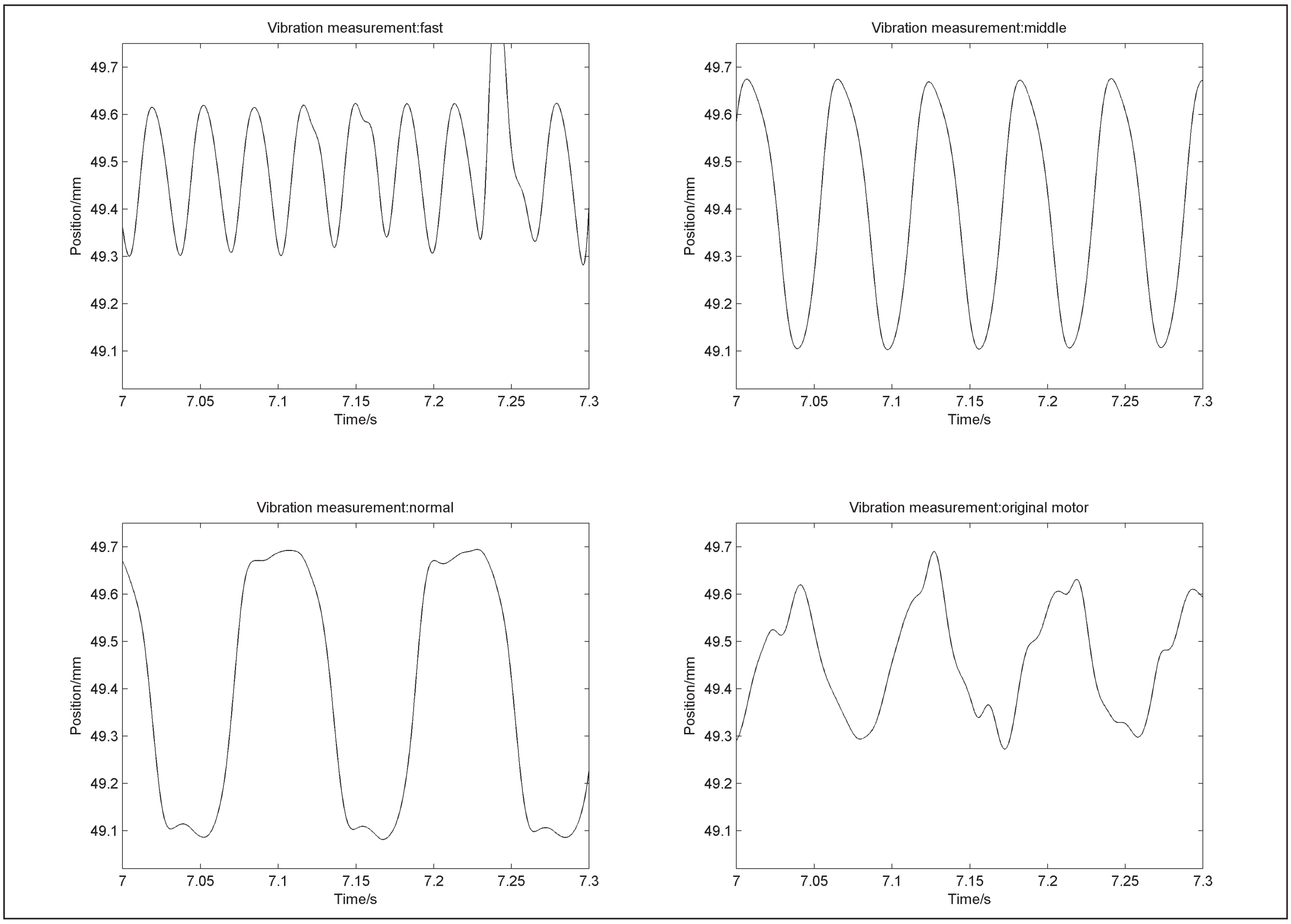

Figure 9. *Position of the load in respect to time. Fast, Middle and Normal represent the PAM generated vibrations. Chart titled Original Motor is generated by the camshaft mechanism.*

mechanically can be used to control dynamics of the movement waveform. With smaller load smaller muscles could use used (diameter of 20 mm and nominal length of 40 mm). This means that the volume of the muscles would be smaller and higher frequencies could be achieved with the same airflow.

6 Conclusions

Although the pneumatic motor in the original application was not optimal for this application a different motor would not have solved the problem of stopping the load to right position. Positioning the load in idle state was the main advantage of using pneumatic muscles. Also controlling the waveform by simply adjusting the chokes in control vale release channels was a great asset. Chokes were fully open while measuring the dynamics. In the final setup chokes were used to make vibration form more round.

System has been running for two months and no problems have appeared. More PAM projects have been started inspired by this one. One area of interest is that the vibrator could be used to reduce vibration either by actually producing counter vibration or by changing its stiffness and thus changing the vibrating properties of the system.

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Povzročanje nihanja z umetnimi mišicami

Razširjeni povzetek

Prispevek predstavlja raziskavo o uporabnosti pnevmatično upravljanih mišic tipa Mc Kibben. Z njimi lahko povzročimo mehanska nihanja pri težjih strojih. Te umetne mišice s področja fluidne tehnike lahko povzročijo celo desetkrat večje sile kot pnevmatični valj z enako razliko tlakov in enakega premera. Praktično niso podvržene stick-slip efektu, zato lahko izvajajo enakomerne, neskokovite gibe.

S pomočjo umetnih mišic aktiviran vibrator, predstavljen v tem prispevku, je bil skonstruiran z namenom, da se zamenja vibrator, gnan s pomočjo pnevmatičnega motorja. Zasnovan je bil zato, da bo mogoče regulirati frekvenco, obliko nihajnih valov in amplitudo. Izhodiščne zahteve so bile ustvariti nihanja z najvišjimi frekvencami od 5 do celo 20 Hz in največjimi amplitudami 2 mm. Statična obremenitev vibratorja je znašala približno 300 N, čeprav je imela nihajoča masa preko sto kilogramov. Reduciranje je povzročilo vmesno podprtje (slika 1). Uporabljena je gumijasta cev, ki je z zunanje strani obdana z neelastičnimi vlakni (slika 2). Tlak v notranjosti cevi poveča njen premer in skrajša dolžino. Skrajšanje lahko znaša celo 25 % pri največjem tlaku 6 bar. Umetne mišice običajno delujejo s komprimiranim zrakom, lahko pa se uporabi tudi kapljevina, npr. voda.

Pri testiranjih so bile v veliki meri uporabljene frekvence nihanja 12 Hz in amplitude 0,7 mm ter sile do 1200 N. Načelno konstrukcijo vibratorja prikazuje slika 4, shematično pa slika 6. Uporabljeni so bili pnevmatični elektromagnetni ventili 3/2 izdelovalca Festo. Če se zrak v umetni mišici ne izmenjuje, nastopi problem segrevanja. Slika 7 prikazuje rešitev te problematike. S slike 9 je razvidna raznoličnost ustvarjenih nihanj tako po frekvenci kot tudi po amplitudi in obliki valov nihanja.

Trajanje preskusa in uporabnost vibratorja sta podani v zadnjem odstavku.

Ključne besede: pnevmatična umetna mišica (PAM), umetna pnevmatična mišica (APM), fluidična mišica, mišica tipa Mc Kibben, povzročanje nihanja,