Keeping up with dynamics of next generation missiles

Michael A. Warden*[a], Robin Hauser[a], Peter Hofstetter[a], Martin Kägi[a], Matthias Meier[a], Walter Rindlisbacher[a], Anastasios Stomas[a], Peter Wälti[a]
[a]Acutronic Switzerland AG, Techcenter Schwarz, CH-8608 Bubikon, Switzerland;

ABSTRACT

In an effort to comply with the increasing quest for higher dynamics and increased inertia of test units modern HWIL-systems are employing increasingly larger hydraulic actuators. A new 3-axis flight motion simulator with increased performance is reviewed. Also future trends of the HWIL-systems are discussed both for hydraulic and electric actuators. Some drawbacks of hydraulic systems, including increased acoustic noise levels and extensive service and maintenance requirements from the hydraulic power unit, limited stroke of the actuators for large systems and poor small signal performance are discussed and compared to the performance of electric actuators. Can the electric actuators advantages make up for the power density performance gap?

Keywords: hydraulic actuators, electric actuators, power density, performance gap

1. INTRODUCTION

Increased dynamical specifications for advanced hardware in the loop (HWIL) systems are being requested. Furthermore a call to obtain such systems in an all electric configuration is noticeable. Both of these developments are discussed. In section 2 the broadening of demands on the HWIL systems is demonstrated by contrasting an earlier system with 2 late machines. Then in section 3 a brief overview of the development of torque density is presented, including electric and hydraulic motors used in our systems. the next section presents an advanced FMS which uses a combination of hydraulic and electric drives. It is discussed with respect to the outcome of substituting the hydraulic actuators with electric ones.

2. DEVELOPMENT OF DYNAMICS AND INERTIAS

2.1 Example systems

Over the years the torques required to reach requested accelerations has continued to increase due to a combination of moment of inertia of the unit under test (UUT), the specified acceleration, rate, bandwidth (BW), and field of view requirements. In order to give an impression of this development a comparison of three typical systems is presented below. Two of these systems are from a more recent period and the third system has been on the market for some time. In Table 1, the maximum values of torque required to accelerate only the UUT itself is given together with the rate and BW specifications for three selected flight motion simulators (FMS). CARCO S-458R-3 was chosen by scanning all CARCO systems built before the year 2000 and selecting the one with the maximum required torque on the outer pitch axis. The next two systems, Amstar production and HD7736 are typical representatives of more recent systems with increased performance requirements. The Amstar systems has been described previously [1][2] and will not be further detailed in this document.

Comparing the three systems in table 1 shows how the required torque in terms of accelerating the UUT only (the supporting structure is not included here) has increased over the years. In addition the increased torque comes in combination with an increase in rate and bandwidth. As shown below both increases finally equate to an increased demand for torque. At higher rates the servo valve pressure drop will increase and this will need to be compensated by either higher initial pressure or a larger initial torque. Likewise the higher BW requires stiffer structures which will also add inertia to the structure requiring more torque.

*mwarden@acutronic.ch; phone +41 55 253 23 18; fax +41 55 253 23 33

Table 1. Three systems are compared. The first system, CARCO S-458R-3 was the system with the highest requirement for torque on all three axis. The next two systems are examples of more recent deliveries.

	Roll			Yaw			Pitch		
	Torque (kNm)	Rate (°/s)	BW (Hz)	Torque (kNm)	Rate (°/s)	BW (Hz)	Torque (kNm)	Rate (°/s)	BW (Hz)
CARCO S-458R-3	1.4	400	35	3.1	200	14	3.1	200	14
AMSTAR (Production)	0.032	600	15	8.5	450	15	8.5	450	15
HD7736	0.87	600	25	4.2	300	20	4.2	300	20

3. HYDRAULIC VERSES ELECTRIC

3.1 Torque density

The torque density gap between hydraulic and electric actuators has decreased in time but still remains significant enough to be a dominant factor in the choice of actuators for HWIL-systems. The closing of the torque density gap was driven by different developments.

First, both for safety and cost reasons the increase in pressure for hydraulic actuators has slowed and so the torque densities, which are mainly dependent on pressure, have reached a plateau. Second, torque densities of electric motors have increased over the same time period because of advances made in magnetic material, design, manufacturing techniques and electronics. For example after the introduction of rare earth magnets (SmCo in the 1970's and NdFeB in the 1980's) modern electric torquers employ permanent magnets which have increased remanent magnetic inductions B_R, which directly increases the torque for constant current. In addition the coercitive field strength H_C of modern rare earth magnets is increased resulting in a reduced sensitivity to demagnetization effects of high driving currents allowing the air gap to be closed further and also to use higher currents resulting again in more torque.

The torque density gap between hydraulic and electric torquers is demonstrated in Fig. 1. Recent advances in electric torquers themselves are also evidenced in Fig. 1. The goal is to demonstrate the density gap and show its approximate size and not to present a comprehensive compilation of motors. Also motors were chosen only from three different suppliers and depending on the design these values can be different for other suppliers. Fig. 1 shows peak torque density values as a function of effective surface area. This is defined as the area given by the rotor circumference times rotor length and is a measure for the magnetically active region of the torquer where the torque is produced.

First, consider the green squares. These are values from AlNiCo DC-motors with brush commutation. Although AlNiCo can have very high remanence (B_R=1.35T) the coercive force is rather low (H_C=0.5MA/m) resulting in the peak torque densities shown in the figure. Note that the values presented here are only typical ones, due to the huge variation of magnetic alloys and their magnetic properties, which depend strongly on composition and manufacturing. As with all other actuators the values increase with effective surface. Increase in length is nearly torque density neutral because both torque and mass increase in a linear way with length. On the other hand torque increases with rotor radius due to the proportionality of torque and the increase in number of poles with radius. The net effect is depicted in the figure.

Second, the brown triangles show values for DC-motors with brush commutation and rare earth SmCo (B_R=1.1T, H_C=1.8 MA/m) magnets, with increased torque densities in comparison with the AlNiCo types.

Third, the blue hashes are values of state of the art electric brushless torquers, which have higher values due to their design and usage of rare earth NdFeB, which has the maximum combination of B_R=1.1T and H_C=2.8 MA/m. Unfortunately these very high torque densities are obtained by sacrificing ultra smooth operation and accepting increased cogging torque. Albeit cogging can be corrected for by adjusting the commanded current as a function of rotor position this technique becomes more demanding as rotation speeds increase and higher current loop bandwidths are required.

Finally, the three double vane hydraulic actuators shown as red dots have identical diameters and variable lengths. Their torque densities are significantly higher than for the electric ones. Also, all densities were calculated from the masses of the frameless motors parts only (rotor, stator). Including the additional masses required for mounting will increase the mass of electric motors by about 100% whereas for hydraulic actuators the increase is about 25% thus increasing the torque density ratio of hydraulic versus electric by a factor of 1.6. Naturally these numbers are only very rough estimates, because they depend significantly on the specific design of the compared actuators. Furthermore using electric actuators with larger effective surfaces than hydraulic ones will mean an increased moment of inertia of the rotor requiring more torque.

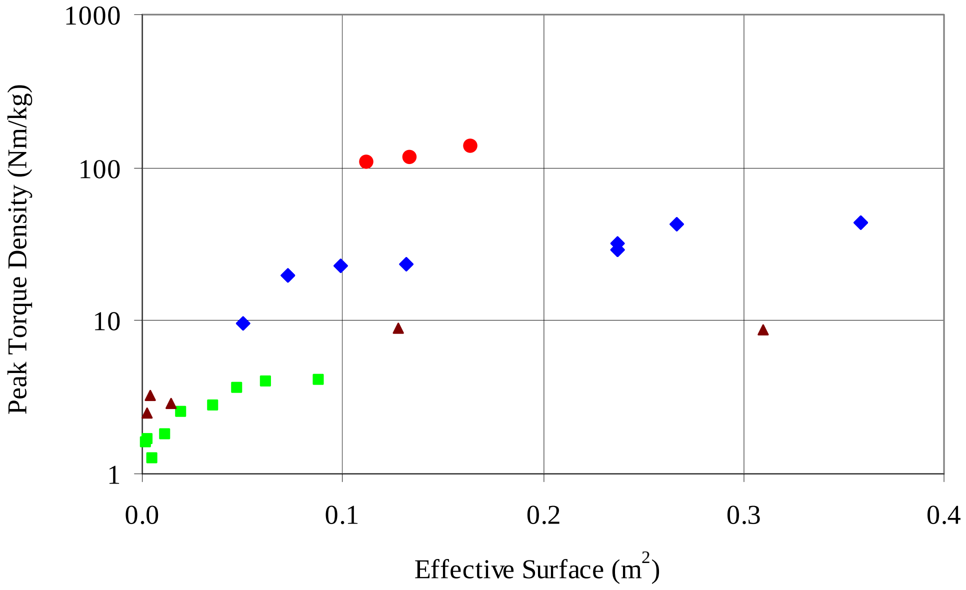

Fig. 1. Peak torque densities as a function of effective surface area (see text for definition) for various actuators. Red dots are double vane hydraulic actuators of identical diameter and variable length, operating at an initial pressure of 160bar. They have higher torque densities than the modern direct drive frameless electric torquers of similar effective surface areas. The blue hashes show brushless torquers designed with rare earth NdFeB magnets. For comparison the brown triangles represent direct drive, electric, brush commutated torquers using rare earth SmCo magnetic materials, and the green squares are similar to the brown triangles only with AlNiCo magnets. Note how torque increases with effective surface area for small actuators and saturates for larger motors. Also note the development of electric torquers towards higher torque densities due to the employment of advanced magnetic materials.

3.2 Further distinctions between electric and hydraulic systems

For operational systems the inherent drawbacks of hydraulic actuators are well known. Acoustic noise from the hydraulic power unit (HPU) can be significant and even when this inconvenience is often eliminated by placing the system in a separate room this does add to the cost of the overall system. In addition, hydraulic systems need to be serviced more often due to oil contamination and seal wear. This also places high demand on fluid filters. Also servicing is in general awkward work due to oil leakage.

For system installation further disadvantages of hydraulic actuators are evident. System tuning becomes more demanding due to various effects including non ideal medium, such as temperature dependent viscosity of the oil occurring at high fluid velocities and corresponding heat generation. Position dependent hydraulic pressure- and displacement oscillations requiring a high BW pressure control loop as discussed in [3]. Slip-stick effects of seals cause additional non linear effects. Unfortunately our hydraulic actuators use small diameter shafts resulting in low frequency mechanical resonances which limit the BW. With respect to safety special care has to be taken in order for example to ensure that the valve controls are not shorted, which could result in unwanted actuator movement. Also after an emergency stop the system remains pressurized until the actuators relieve their pressure.

Although many of these drawbacks are compensated by some very favorable properties of hydraulic systems we do notice a strong inclination of customers to obtain fully electrical systems.

One obvious advantage of the hydraulic systems are their ability to hold a position with very little power loss. This is given by the fact that static torque is produced by pressure and not flow. Even with a large unbalance the power loss is minimal and allows to use an unbalanced gimbal design with reduced moment of inertia, as shown below. Because in electric systems torque is generated by current they have high losses at low rates.

Drawbacks of electrical actuators include high losses at low rates, due to the fact that torque is generated by current. Also the price to torque ratio is high. This economical aspect is shown in Fig. 2. Actuator purchasing prices for small piece numbers are shown as a function of peak torque. A positive aspect is the saturation of price with peak torque for electric actuators, but the hydraulic actuators remain extremely price competitive as evidenced by the huge price gap, which is even larger when including the generation of hydraulic power with the HPU and the electric power with the amplifiers and cabinets.

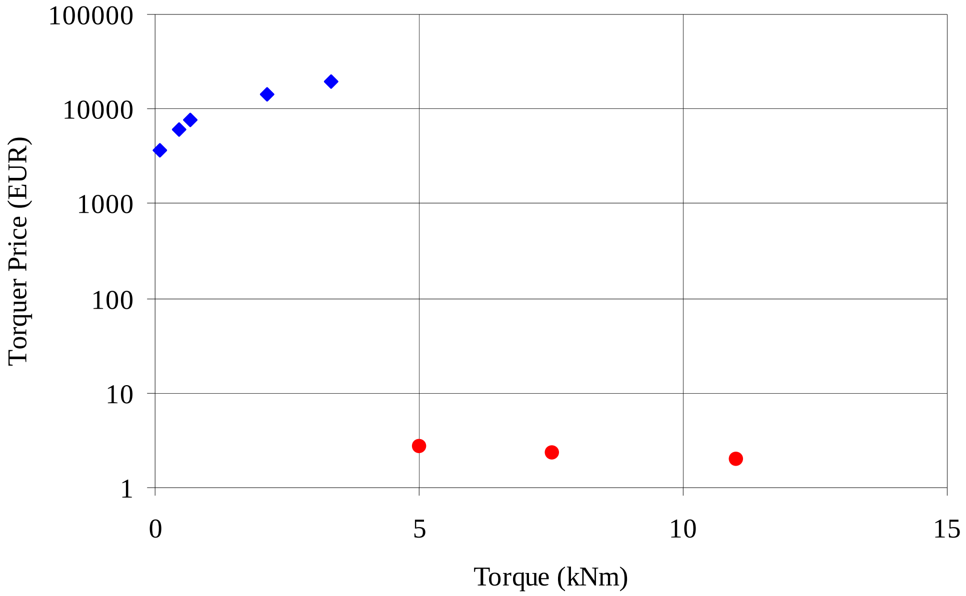

Fig. 2. Price gap between hydraulic and electric actuators. Blue hashes are price of electric actuators as a function of peak torque and red dots are values for hydraulic actuators. Note that the gap is significantly larger than the peak torque gap described in Fig.1.

4. THE SERIES HD7736 FLIGHT MOTION SIMULATOR

The Series HD7736 FMS is a precision 3-Axis Missile Flight Motion Simulator together with a 2-Axis Target Motion Simulator (TMS). The system is a recent design for high dynamic missile tests. The HD7736 provides a comprehensive platform for HWIL simulation of guided missiles, munitions and other inertial systems.

The 3-Axis FMS is configured with a horizontal outer (pitch) axis mounted on a closed gimbal for maximum stiffness, a middle (yaw) axis, which is orthogonal to the outer axis and is supported by an open gimbal structure. Finally the inner (roll) axis, supported by the middle axis gimbal supports the payload mounting area.

The inner axis has continuous angular freedom and is driven by a high torque brushless AC motor. The middle axis has limited angular freedom of ±55° and is driven by a double vane hydraulic actuator whereas the outer axis has an angular freedom of +100°/-140° and is driven by a single vane hydraulic actuator. A hard-anodized aluminum tabletop on the roll axis serves as the payload mounting surface.

The system is shown in Figure 1. The optimum compromise between minimum inertia and maximum required stiffness, in order to obtain a structure where the first structural mode was at least a factor 2 higher than the specified frequency response was performed using FEM analysis.

For this model, where the required offset was 1m the roll axis was driven by a barrel role drive. With this construction it is possible to place a direct electric torquer very close to the yaw axis. The distance from the yaw axis to the mass center of the electric drive is only 0.1m resulting in minimal inertia on the yaw axis. In contrast if a hydraulic drive had been used for the roll axis, the large offset of 1m would have placed it at least 1m from the yaw-axis. In this case the hydraulic actuator would need to have a huge advantage in torque density in order to compensate for the large offset. Specifically, in order to arrive at the same inertia as with the electric drive the torque density would need to be $(1/0.1)^2=100$ times the electric one thus demonstrating the advantage of an electric actuator for the roll axis.

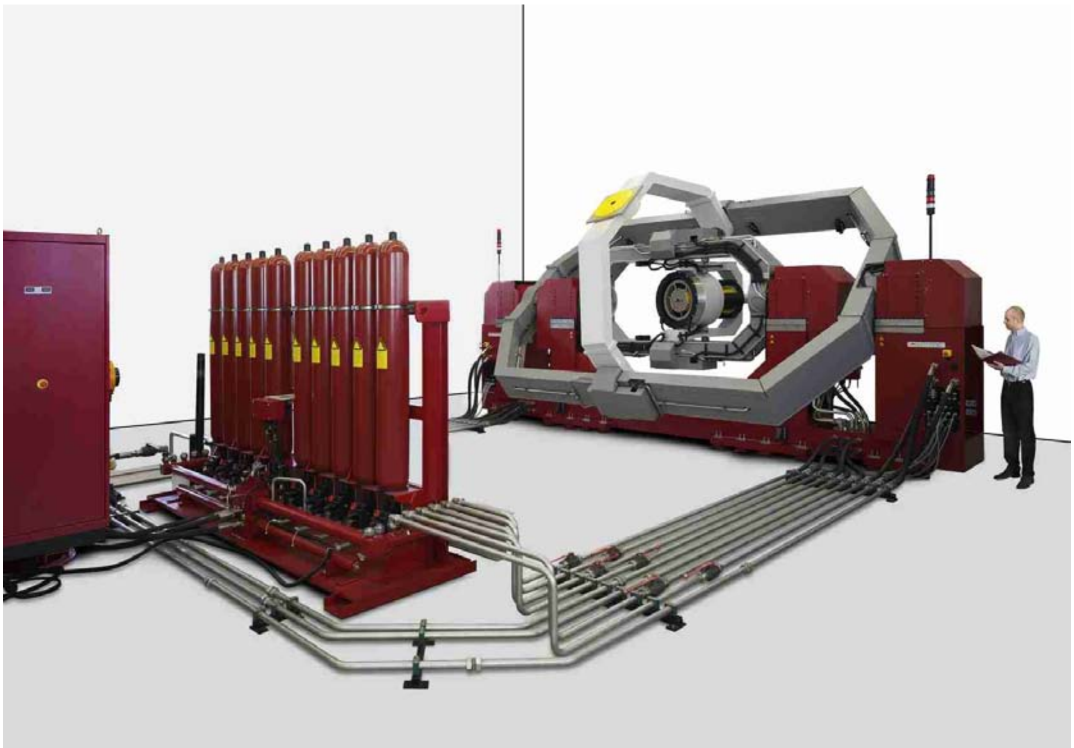

Fig. 3. The series HD7736 FMS including the two axis HD7727-T TMS. In addition to the parameter shown in Table 1 the system required a large UUT of 1m length, 176kg mass and up to 0.5m diameter. The roll/yaw and pitch axis are continuous/±60° and +100/-140 respectively. Note the accumulators and the piping to the simulator which require considerable installation time.

The choice of actuator for the yaw axis is determined mainly by the resulting torque on the pitch axis, as shown below. The system shown in Fig. 3 uses two double vane hydraulic actuators for the yaw axis. In this hydraulic configuration the inertia of the two yaw axis actuators for the pitch axis amount to only 34% of total yaw axis inertia. Replacing the actuators with electric ones of similar torque would increase this percentage to 120%. In this case the hydraulic torquers would be the most dominant part of total inertia of the yaw-axis. Even if the structure could be made completely weightless, the yaw-axis inertia of the all electric system would be larger than the hydraulic one.

For the pitch axis, which required an angular freedom of +100/-140 two single vane actuators were employed providing a total of 60 kNm of torque. Since on the outer pitch axis the weight is of no further concern with respect to machine performance an electric actuator could have been employed. Also because for the single vane actuators the torque density gap shown in Fig. 1 is halved. On the other hand because the yaw-axis used a hydraulic actuator anyhow the infrastructure (HPU) was available and only had to be dimensioned to incorporate the pitch drives.

5. FUTURE TRENDS FOR ACUTRONIC

5.1 Customer requirements

At Acutronic we are currently faced with a variety of often opposing requirements. In addition to the technical advances such as higher torque and BW, customers are asking for reduced delivery times and also reduced costs. We are able to meet these demands as shown by the electro-hydraulic HWIL system described here, though a trend towards all electric systems is evident.

5.2 Conclusions

In conclusion we have shown how dynamic requirements for HWIL-systems have increased. On the other hand the torque density gap has closed over the years allowing us to keep up with customer requirements using hybrid electro-hydraulic designs. All electric systems are preferred due to the many drawbacks of hydraulic ones. They may be realized but will still require significantly more torque on the outer axis than the hybrid systems.

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