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POWERED WIND TUNNEL TESTING WITH HYDRAULIC MOTORS

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Abstract

The integration of propulsion systems in aircraft design is complex and often needs to be investigated in wind tunnel tests. A number of hurdles must be overcome with powered testing. The provision of power into the model and across the balance may interfere with the measurements due to unwanted forces, thermal effects, or electromagnetic interference. The direct thrust generated by the propulsors needs to be known and subtracted from the main balance measurements to come up with the pure aerodynamic effects. The power system and its associated instrumentation needs to be incorporated into a usually already crowded model.

Electric, pneumatic, or hydraulic motor solutions are used for powered wind tunnel models. This article gives an overview on the potential of using hydraulic motor technology for model and full scale powered wind tunnel testing. Not only the motors but also the associated systems and the required infrastructure are described.

Keywords: Wind tunnel testing, powered wind tunnel model, hydraulic motor technology

1. Introduction

Driven by increasing pressure to reduce the carbon footprint and taking advantage of new possibilities offered by innovative thermodynamic, hybrid, electric, and hydrogen technology, established players in the aviation industry and startups are working on new architectures for commuters and airliners and novel solutions for urban air mobility. Many of these present unique aerodynamic challenges in relation to propulsion system integration. The Vertical Flight Society's eVTOL Aircraft Directory alone lists more than 550 electric and hybrid-electric vertical takeoff and landing concepts in various stages of development [1].

The evaluation of whether the interactions between the power system and the aerodynamics of the air vehicle are expected to be significant enough to warrant the added complexity and cost of a powered wind tunnel model is not always straight forward. But, when the propulsion system is contributing significantly to the generation of lift, either directly (powered lift) or indirectly (blown lift), it can usually not be omitted. The required power densities and high RPMs (revolutions per minute, of propellers or fans), as a result of the scaling laws, make it typically impossible to resort to standard industrial motors in wind tunnel models. Custom-designed pneumatic, hydraulic, or electric motors are commonly used for that reason.

Air turbines tend to provide the highest power density per given volume and run at very high RPM. The expanded air can pose problems due to the adiabatic cooling effect and the aerodynamic characteristics of the model may be altered when the used air must be ventilated into the test section. Electric motors are easy to control and their power density has increased significantly in recent times. Cooling is often a challenge and may limit run times in order to keep the electric motors within their thermal operating range. Hydraulic motors are based on a simple, easily adaptable technology. They

are thermally stable and do not have a significant effect on nearby sensors. Although they are easy to operate for long durations, they require special care to operate cleanly. Figure 1 gives an overview of specific power values (power per volume) for RUAG hydraulic motors in comparison to typical values for air turbines and electric motors.
The provision of power to the motors is another point where significant differences exist between the systems. Routing electric cables inside the model is probably the easiest way to bring power to the motors. Care must nevertheless be taken so that the high current does not affect sensitive instrumentation in the model. For hydraulics and pneumatics piping must be installed. The high pressures involved does not make this a straight forward task. For the incompressible hydraulic oil, the return lines can be of the same diameter as the input lines. Compressed air which is expanded in the turbine needs large return lines. Alternatively, the air can be directly exhausted into the wind tunnel, a solution often chosen for turbine simulators where the core jet is thus simulated. This is obviously not possible with hydraulics.
Often, wind tunnel facilities can only provide one or two power options, as the hardware and infrastructure for each of these technologies is expensive. At RUAG, hydraulic or electric motors, up to a total maximum power of 700kW can be used in the wind tunnel.

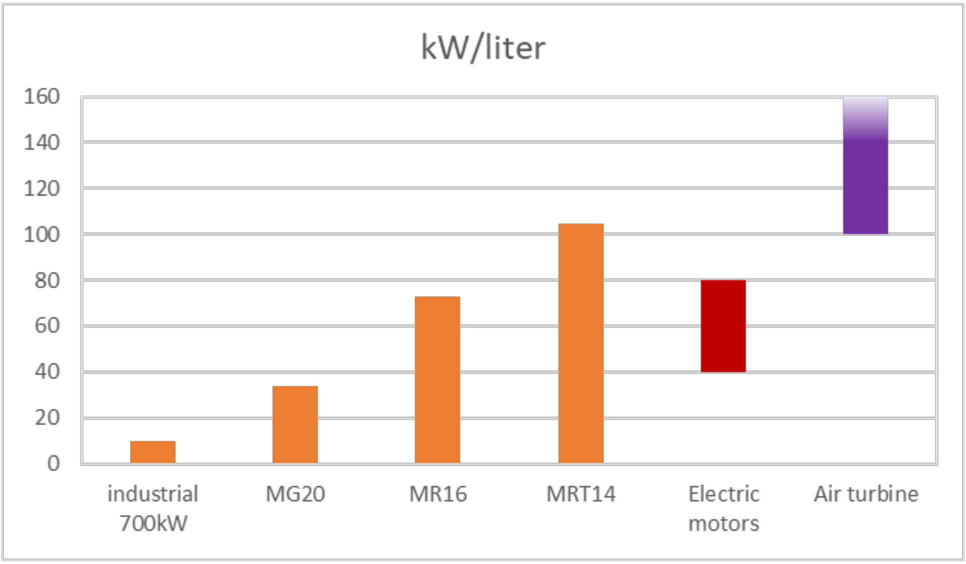

Figure 1 – Comparison of maximum power per volume of RUAG hydraulic motors (orange) in comparison to pneumatic (purple) and electrical power (red) solutions. Electric motors may be runtime limited.

The present paper starts with a historical overview on the use of hydraulics in the RUAG wind tunnels. It is followed by a general description of requirements for powered wind tunnel testing before the specific components of a hydraulically powered model and its associated systems are discussed in detail. The paper finishes with results from a few typical tests with hydraulically powered wind tunnel models.

2. Evolution of hydraulic motor technology for wind tunnel tests

From the very start of the RUAG facility's operation in 1946, powered testing was part of the portfolio. Electric motors provided (limited) power to drive propellers or fans for jet engine simulators. In order to avoid the huge investments required on the infrastructure side for supporting the operations of air turbines, F+W, the predecessor of RUAG, looked into the possibility to use hydraulic motors to overcome the power and runtime limitations of the then used electric motors. First successful wind tunnel tests were performed in the early 1980s using off-the-shelf industrial hydraulic motors. The necessary pumps and oil distribution system were installed at that time and allowed testing single- and twin-engine airplane models.

Wind tunnel testing of the A400M military transport aircraft in the RUAG facility resulted in new requirements [2]. The four-engine wind tunnel model needed more compact engines. The solution consisted of an industrial piston-type hydraulic motor. A new housing was manufactured to comply with the outer shape of the nacelles and a number of tuning measures allowed the motors to reliably run at the required higher RPMs and power levels. Two mass flow dividers and bypass valves allowed the individual control of the four motors driven by the two existing hydraulic supply pumps.

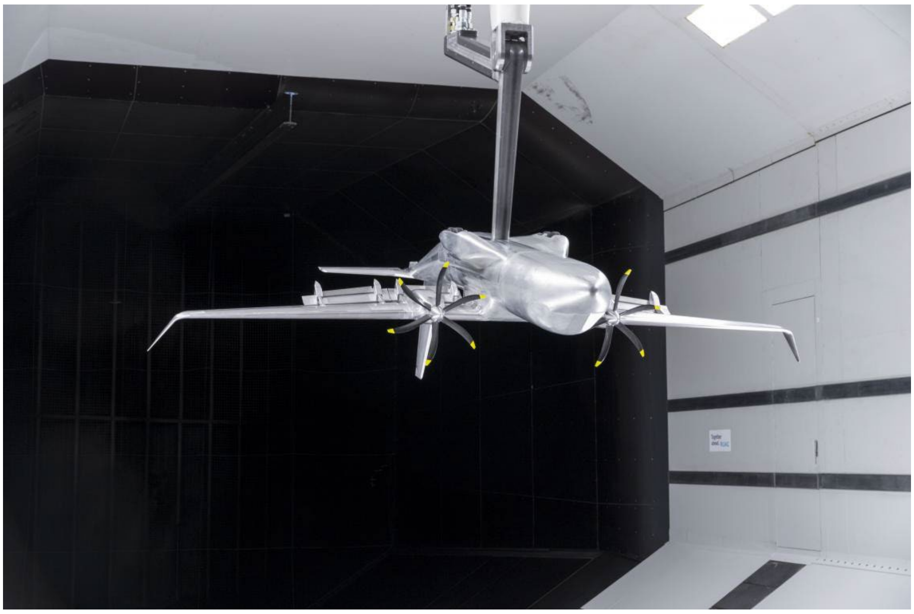

Figure 2 – Clean Sky POLITE model in RUAG LWTE wind tunnel

Around 2008 RUAG was approached by Boeing and Rolls-Royce for the performance of wind tunnel tests on an airframe powered by two counter-rotating open fans [3]. With the need for individual RPM control, the counter-rotating topology did not allow the use of piston type motors and no off-the-shelf motor did offer sufficient power density. Therefore, RUAG started developing a gear type motor of its own. In less than half a year, during which several design iterations were tested to failure, a motor emerged which was found to be robust and would fulfill all requirements. At the same time, the existing hydraulic power supplies were replaced by four individually controllable 250 kW hydraulic pumps to cover the increased power needs.

These motors were highly successful and their derivatives were and are still used in many other applications, for example the Clean Sky projects ESICAPIA with a pair of turbofan simulators and the propeller powered LOSITA [4]. But they were found to occasionally be too large for the size of models typically tested in the RUAG facility. This led to new requirements for smaller and more powerful motors. A single-disk motor based on the gerotor concept allowed to shrink the size of the motors substantially, to under 90mm in diameter, while maintaining similar power levels (Figure 7). This motor today forms the basis of several derivatives among which the two-disk tandem motor is the latest development. It is used to run a turbofan simulator at up to 30'000 rpm and 100 kW [5].

But hydraulic motors are not only used to drive scaled models in our test facility. A setup based on an industrial piston motor allows full-scale propeller tests up to a maximum power of 600 kW at 1800 rpm (Figure 3).

Figure 3 – Isolated full- and model-scale propeller test for Textron McCauley

3. Powered model wind tunnel testing

3.1 General requirements

The requirements for the power system of a wind tunnel model are very diverse and depend to a large extent on the goal of the test and the acceptable level of complexity. Ideally, the power system simulates the flow conditions representative of the full-scale object in an exact way. This means that the motor power and the rotation speed have to fulfill the requirements dictated by the scaling laws. This leads to high power densities and RPM since both increase linearly with the model scale. In addition, the following points need to be considered:

- The RPM must be controlled to very tight tolerances in spite of the changing loads during an angular sweep of the model. In the RUAG wind tunnel, we are looking for values better than ±1 rpm/1000 rpm.
- Instrumentation such as strain gauge balances may be sensitive to temperature gradients and electromagnetic interference. While the latter can be excluded for hydraulic motors, temperature variations can be reduced by controlling the temperature of the hydraulic oil feeding the motors.
- Insulation or even active temperature control help to stabilize the readings of nearby strain gauge balances.
- Except for some special setups, the power supply lines need to bridge from the non-metric to the metric side of the balance. This must be achieved in a way which minimizes mechanical interferences or keeps them correctable. These corrections depend on the topology of the balance crossing system and may further be functions of oil temperature, volume flow and pressure. A very stiff balance will intrinsically reduce the relative effect of the crossing system.
- Industrial, off-the-shelf motors often do not achieve the power density and/or the speed required in wind tunnel tests. Thus, custom solutions are usually needed.
- The ability for the model to accept different support options, at RUAG ventral and dorsal struts, pose special design challenges to distribute the power in both cases to the motors in the model.

– Especially for multi-engine aircraft, the feed and return lines in the wing section compete with instrumentation cabling and pressure tubing for scarce space.

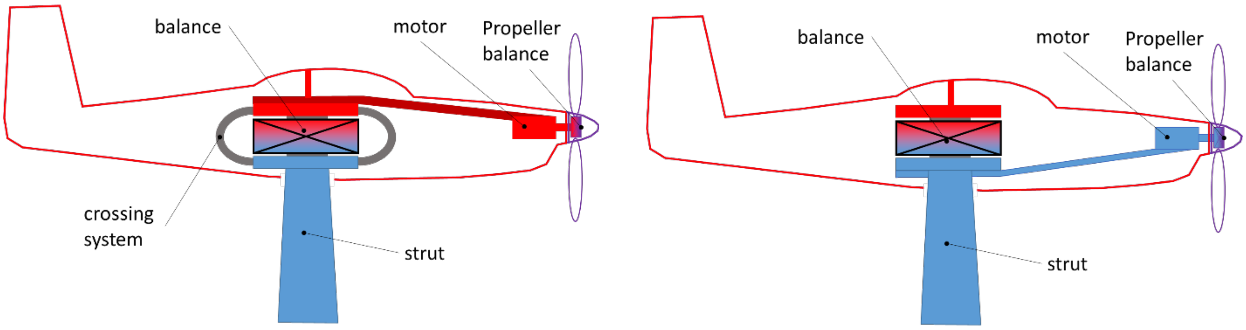

Figure 4 – Powered model concepts for a ventral strut model support. Motor on metric (left) and non-metric side of the model

3.2 Model concepts

The goals of powered wind tunnel testing are diverse. A propeller manufacturer is interested to determine the performance of its product with the least possible interference from any mounting structure. The focus of an aircraft developer is more on the interaction between the power plant and the airframe, so called installation effects, and on overall performance data. This results in different wind tunnel model and test setups. Often elaborate bookkeeping methodologies will have to be used to extract the various effects of interest.

From a test setup point of view, required data can be obtained with just two basic configurations: the motor is on the non-metric or the metric side of the model's main balance (Figure 4).

The former is normally used for isolated propulsor setups and often also for single engine aircraft. It has the advantage that the power supply to the motor does not need to cross the main balance, allowing for a much simpler setup. Propeller forces are measured directly with a rotating shaft balance. The main balance does not measure any direct thrust effect, only the slipstream effects on the airframe. Installation effects can thus easily be determined by comparing power-on to power-off cases.

Especially for multi-engine aircraft this simple solution is generally not possible. The motors must be mounted on the metric side of the model. A balance crossing system for the power supply lines, causing minimal and correctable interference on the measurements, must be put in place in the often constrained space of the central fuselage.

To obtain installation effects, the direct thrust of the propulsor must first be measured and subtracted from the main balance readings. A typical bookkeeping methodology for a test setup with a turbofan simulator is shown in Figure 5. The full model (wing/body/nacelles) is measured at a given power setting (wbn_X). F_N' is the direct thrust generated by the propulsor(s). It is either obtained by a direct measurement, for propellers a rotary shaft balance is normally used for this purpose, or by an a-priori calibration (isolated setup). wbn_TFN denotes the full model measurement with a flow-through nacelle (power-off case). From these three baseline measurements, the propulsor interference effects are determined.

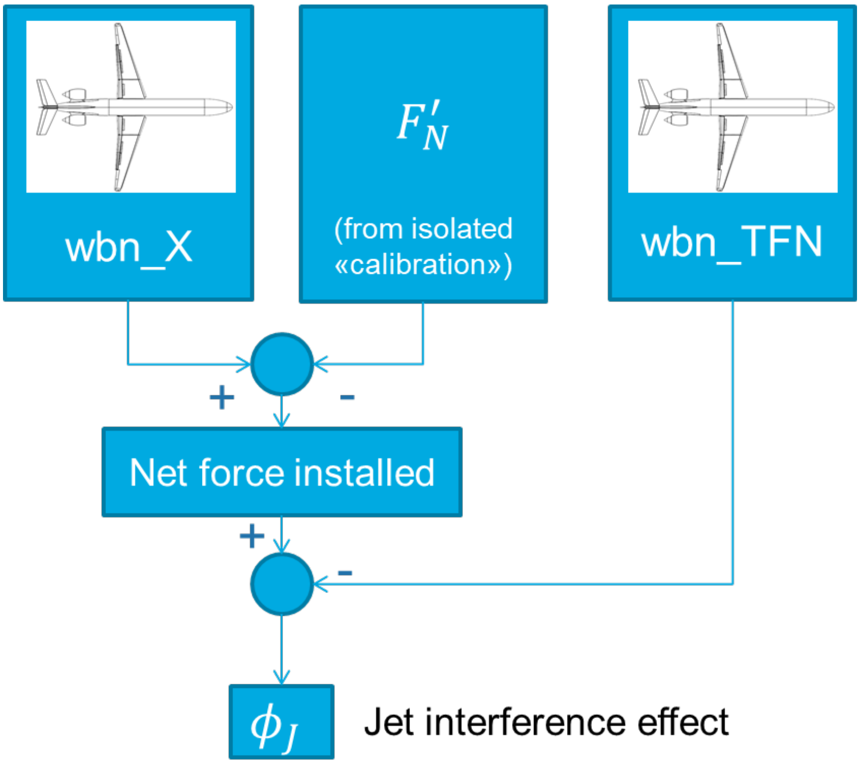

Figure 5 – Example of bookkeeping methodology to obtain the jet interference effects for a turbofan powered model.

4. Hydraulic power system

4.1 Overview

The hydraulic system consists of (Figure 6):

- Pumps to provide conditioned oil to power up to four motors.
- The control system to individually control each motor.
- Particle filters to protect the motors from crashes induced by impurities in the oil.
- Valves near the pumps to close the lines going to and returning from the test section.
- A valve block near the test section to inhibit flow into the test section when oil lines in the model need to be opened (e.g. during installation). The valve block also allows to combine the oil flow from multiple pumps to feed for example one large motor or to short-cut the test section for initial oil conditioning.
- The bypass valve to protect the motor(s) when the return line pressure exceeds a certain value. The diaphragm allows to dissipate the negative power generated during windmilling cases.
- The strut to integrate all the needed feed, return and drain lines. Its main purpose is to mount the model in the test section.
- The balance with its crossing system which is normally a fixed assembly, calibrated as a unit and integral to the strut assembly.
- The fuselage box which represents the interface between the balance and the model. It is usually designed so that the oil can be routed to the propulsors independently of whether the model is installed in a dorsal or ventral strut configuration.

- The motor which provides the mechanical power to the propeller or fan. It also contains instrumentation to control the RPM and to monitor its operation with accelerometers and temperature sensors.
- The user interface on a PC which allows the test engineer to set the RPM and monitor the operation of the system. Different safety features for controlled emergency shut downs are implemented in the operator console.

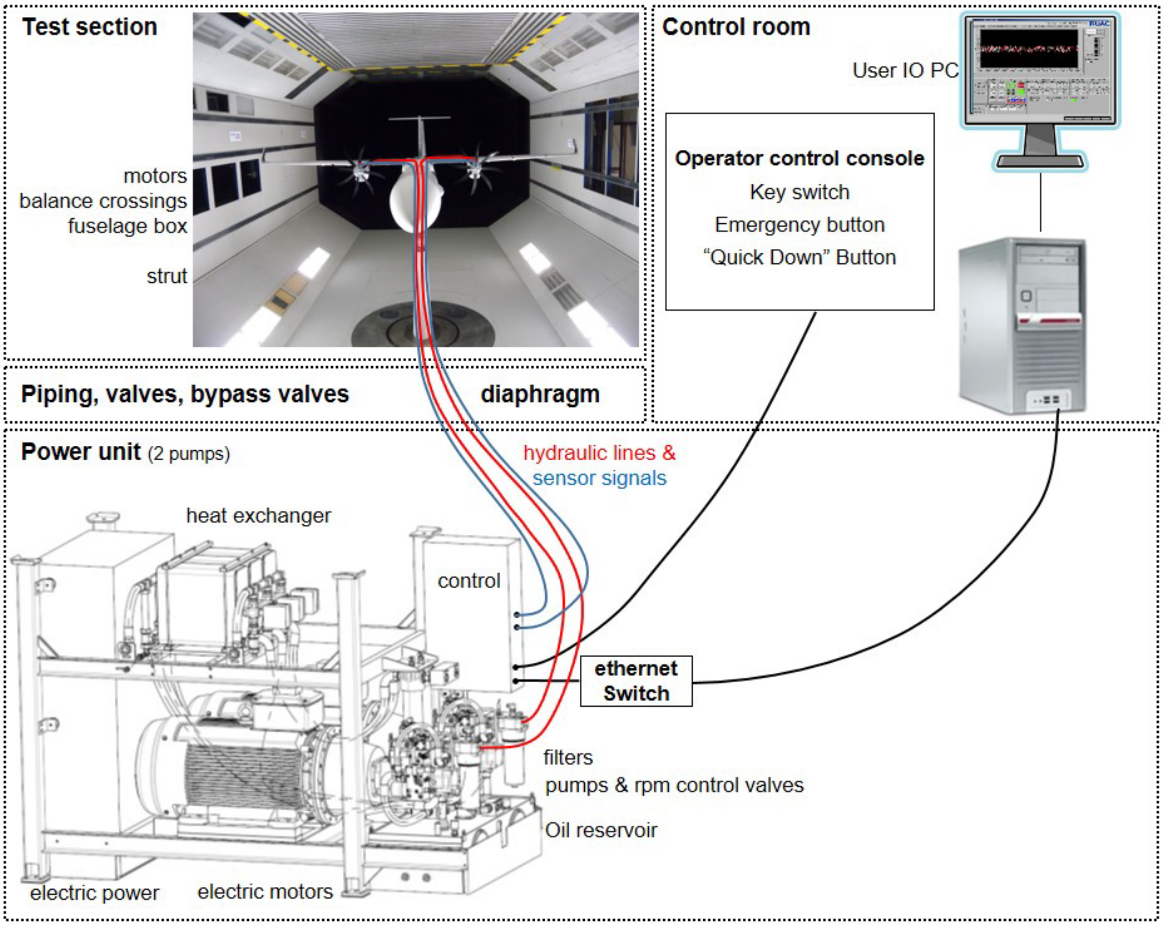

Figure 6 – Overview off hydraulic system (two pump system only).

4.2 Motors

All the latest RUAG motors are using the gerotor architecture (Figure 7). This type of motor gives the smallest diameters and is easily tailored to the specific requirement of a given wind tunnel model, both from a performance and an integration point of view. Axial and torque pulsations are comparatively low, which is an advantage especially in combination with propeller balances. Further, the topology allows the implementation of a hollow shaft. This may be of use to route instrumentation cabling or when a counter-rotating propulsor configuration shall be built.
Industrial hydraulic motors are normally optimized for efficiency and longevity. For wind tunnel tests, efficiency is not a major concern and run times between inspections are measured in the low hundreds rather than in the high thousands of hours. The challenge is to achieve the required high power levels within the often small volume of the scaled engine nacelle. Motors for turbofan simulators normally need to run at high RPM values while motors for propellers run at more moderate speeds but higher torque levels. These differing requirements influence the design of a specific motor.

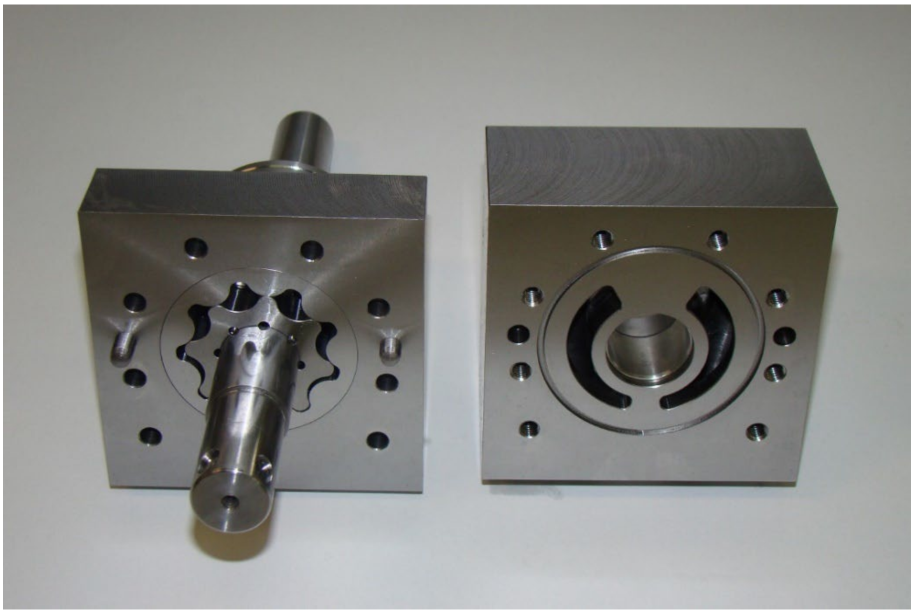

Figure 7 – Internals of a gerotor motor. Prototype with square engine case.

The engineer has a number of design parameters which allow him to optimize the motor to the particular needs. But there are also limitations:

- The power supply and losses in the piping limit the available maximum pressure at the motor.
- The maximum oil volume flow is given, although this can be increased by using pumps in parallel.
- The shaft diameter is a function of the required torque and the bending resulting from the lateral loads caused by the oil pressure acting on the inner gear.
- Geometrical constraints and running smoothness influence the minimal number of teeth.
- The maximum size of the gear is limited by bearing speed considerations.

From these boundary conditions, a theoretical maximum performance envelope for gerotor hydraulic motors can be derived. The corresponding graph in Figure 8 shows the maximum power achievable as a function of RPM for a given motor diameter. Actual performance data of some of the manufactured motors is shown for comparison.
Beside reliable operation at nominal power and RPM, the motors must also be able to run at very low

speeds, e.g. 200 rpm. This capability is needed to zero various sensors in the absence of significant aerodynamic and inertia loads before a wind-on run is performed. This poses challenges for the hydraulic bearings and on stable RPM control.
All motors include a sensor for speed control. Angular position is normally only needed for processing the in-plane loads (1P) of a rotating shaft balance (RSB). Thus, for all motors built to date, phase measurements are performed by the telemetry (or slipring) system and not on the motor. Temperature sensors in the vicinity of the bearings and accelerometers provide data for health monitoring.
Additional motor features include:

- A locking mechanism for the shaft to allow the propeller or fan nut to be torqued. This feature is further of use when static loads need to be applied on a rotating shaft balance for checks.
- In some applications a mechanical fuse is integrated to protect the fan or propeller from overload conditions generated by a sudden stoppage of the motor.
- The sense of rotation of most motors can easily be changed.
- Interfaces for fan, propeller, rotating shaft balance and telemetry system mounting

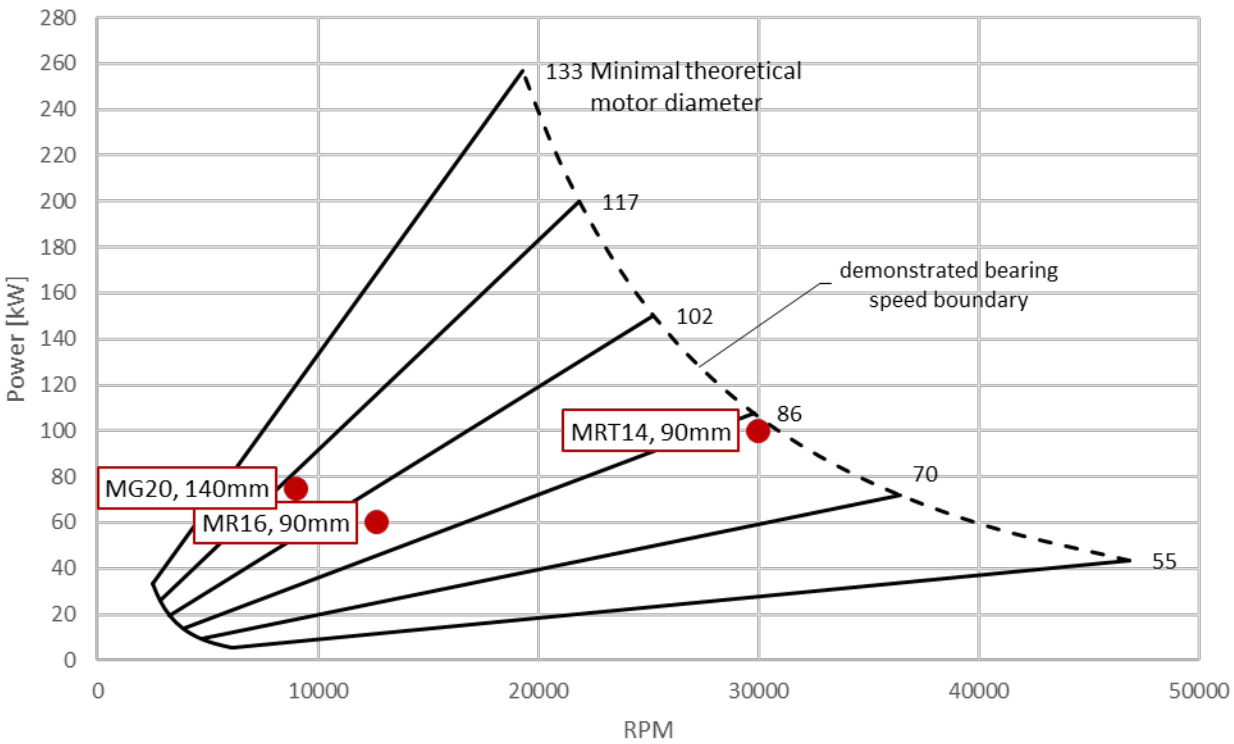

Figure 8 – Speed and power range of RUAG gerotor hydraulic motors compared to their diameter in millimeter. The theoretical lines are given for single rotor configurations.

The motor case can be designed for different supply and return line interface positions: side in-line, side across, or axial, as shown in Figure 9 for a motor of the type MR07. For turbofan simulators, the pylon is often an integral part of the case so that obstruction from a relatively voluminous hydraulic interface in an aerodynamically critical area can be avoided. Figure 10 shows an example of a turbofan with a metal 3D printed motor case.

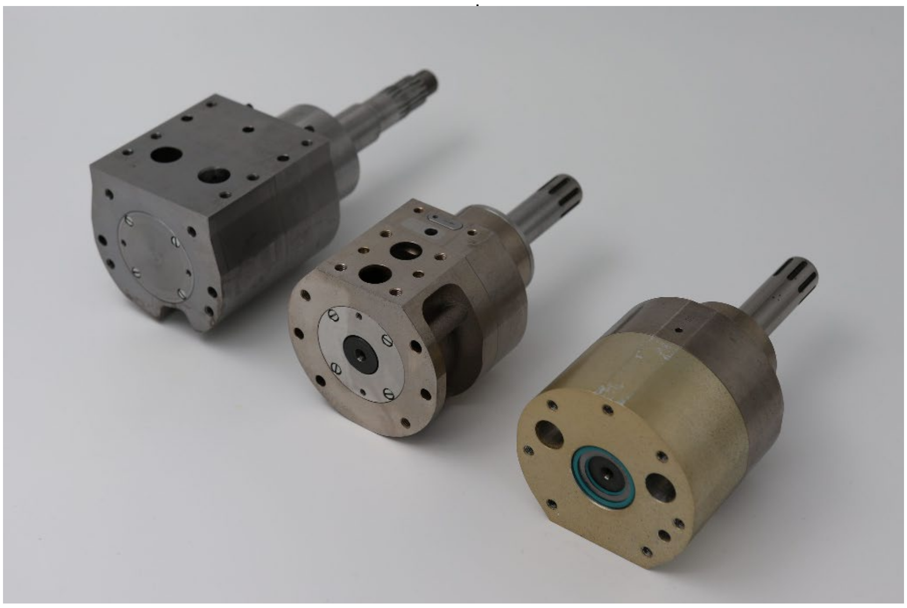

Figure 9 – Three hydraulic motors of the same type with different case and inlet/outlet interfaces

Figure 10 – Mini-turbofan simulator (left) with pylon integrated in the motor case (based on MR09). On the right: Turbofan simulator for ESICAPIA, based on an MG20 motor.

4.3 Hydraulic power station, oil distribution and motor control system

The hydraulic power station is built with off-the-shelf components (Figure 11). Compared to standard industrial applications, a much finer control of the volume flow is needed so that the speed of the motors in the model can be accurately maintained to within ±1 rpm/1000 rpm, independently of the changing load conditions encountered during a polar. A swash plate on the pumps sets the nominal oil flow volume and a bypass valve is used to fine-tune the motor RPM by comparison against the target value. No control valves are needed inside the model. Heat exchangers allow the oil temperature to be maintained within tight tolerances. This provides a thermally stable environment for the model's instrumentation which may be in close vicinity of the motors and the oil distribution

system. Each of the four 250 kW pumps can deliver up to 360 liters/minute of oil at a maximum pressure of 400 bars. The units are arranged in two transportable groups and are operated through a single user interface.
Permanently installed pipes route the feed, return and drain lines to a distribution point located above the wind tunnel test section. There, valves allow the distribution of the oil flow and/or the isolation of the pumps from the test section.
The motors are operated through an intuitive graphical user interface. New set points can be registered while the motors are running. The push of a single button will then adjust all motors to the new values. RPM can also be coupled to the wind speed or vice-versa. This will keep the advance ratio of a propeller constant and ensures that it remains in a safe range, avoiding overload situations during a change of wind speed. In addition, a "safe RPM" condition can be defined for each motor which the operator can command by the push of a single button. RPM, temperatures and accelerations are continuously monitored and will trigger alarms if they leave their safe range. Moreover, two emergency stop modes are implemented. The "soft emergency stop" executes a quick, safe and coordinated shut down of the hydraulic pumps and the wind tunnel. The "hard emergency stop" shuts off the pumps immediately. This may lead to overload situations and damage the blades and the propulsor. All activities and messages of the control system are logged to allow error analysis in case problems are encountered.

Figure 11 – Hydraulic power station with four independent pumps delivering up to 250 kW each.

4.4 Balance crossing and central fuselage box

For crossing the balance by the hydraulic lines, a well-defined routing is necessary, so that interferences on the measurements due to hydraulic pressures and temperature gradients are kept at a minimum. A calibration process further allows residual interference forces to be compensated. This is even more challenging when the crossing needs to be housed within the confined space of a fuselage.
Several standard balance crossing systems are available at RUAG (Figure 12). They are used for a number of different models. Depending on the number of motors on the models, the allocation of the supply and return lines may change. While each motor does need a dedicated supply line (in order

to individually control it), the return lines of multiple motors can often be combined. If there are less motors than supply lines, two or more supply lines will be joined. This reduces piping losses and maximizes the symmetry of the oil flow across the balance and thus minimizes interference effects. Figure 13 shows the middle balance crossing system of Figure 12 installed for a turbofan simulator isolated test. Four input lines feed the single motor and two lines are used for the return flow.

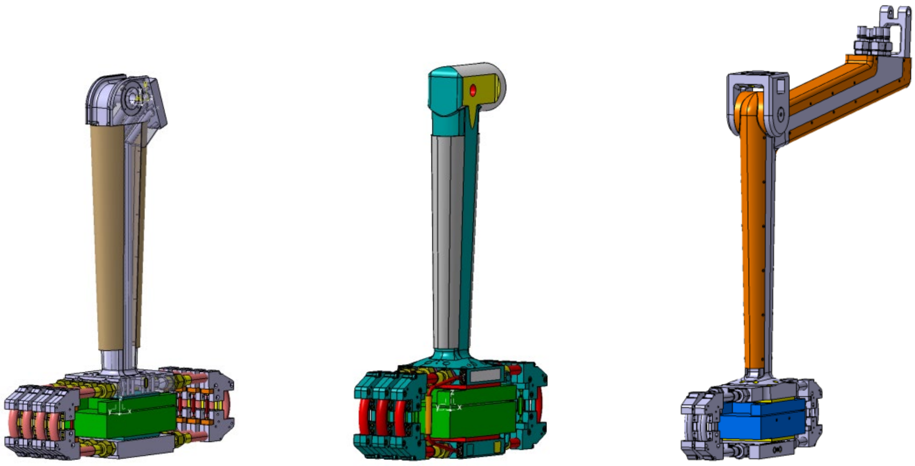

Figure 12 – Balance crossing systems with strut for a maximum of 4 fully independent motors (left), 1-4 motors with common return lines (middle), and two motors.

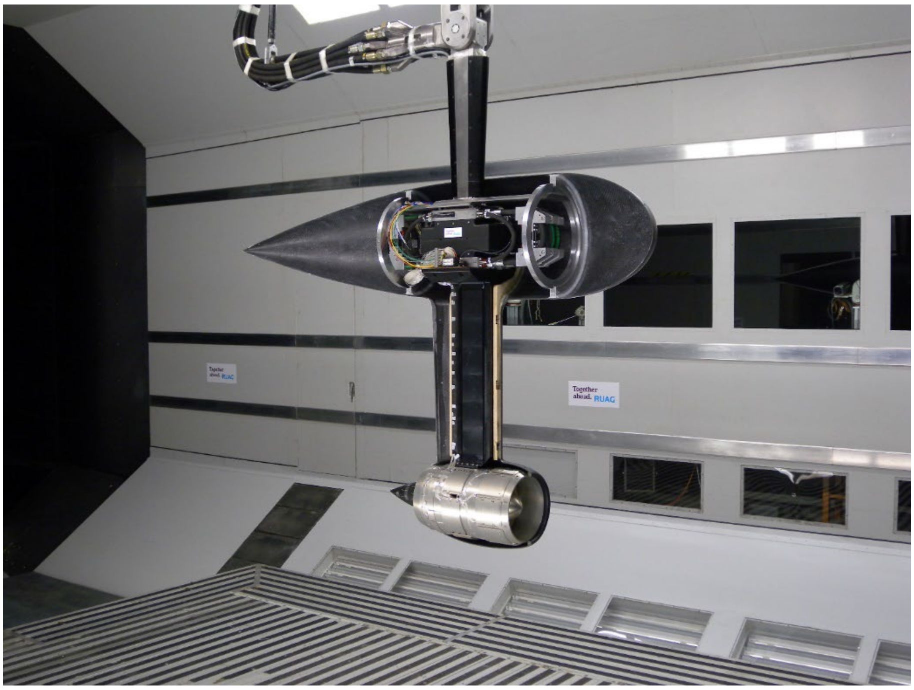

Figure 13 – Isolated test setup with removed covers showing the balance crossing in the drop shaped bulb and a turbofan simulator attached by a metric sting shielded by a non-metric fairing (ESICAPIA).

A "fuselage box" forms the interface between the strut with the balance crossing and the model. It is usually designed so that both a ventral and a dorsal mounting of the model are possible. Accordingly, the fuselage box includes all required piping to route the oil to the correct locations in the model. Unused interfaces are capped with blind covers.

4.5 Test benches

Several test benches support the development of hydraulic engines at RUAG. An engine brake allows the testing of the motors or complete propulsor assemblies (Figure 14). The industrial brake is rated at 190 kW and 12'000 rpm. Higher speeds up to 47'000 rpm can be reached with the installation of a gearbox between the motor and the brake. In addition to other operating modes, the brake also offers the possibility to simulate a typical "characteristic propeller curve" (torque versus RPM). Other dedicated test stands are used to validate propulsor instrumentation. Further, a small open jet wind tunnel is available to test full propulsor assemblies under realistic flow conditions before they are used on a model in the large wind tunnel.
The test infrastructure is used to check motor performance and robustness over the full operating range, thus reducing the risks of costly down times during a wind tunnel test campaign.

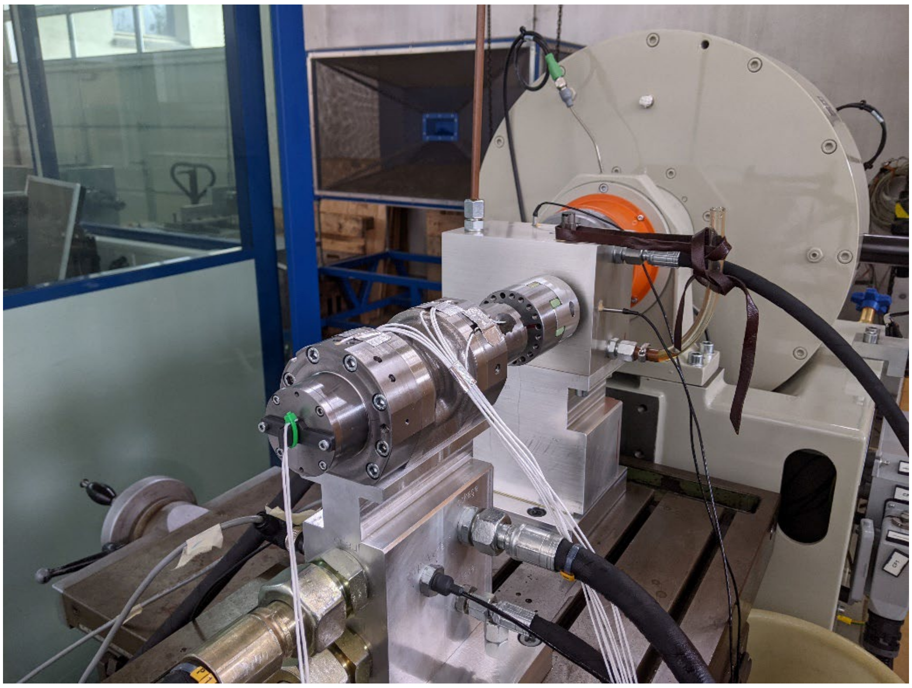

Figure 14 – Double disk motor MRT14, developed for the TRUflow project, on the test stand with a gear between the motor and the brake.

5. Wind tunnel tests

In RUAG's Large Wind Tunnel Emmen LWTE, hydraulic power systems have been used for commercial development projects such as the Saab 340/2000, the Airbus A400M, various Pilatus Aircraft designs and for a number of research projects, either EU-sponsored like ESICAPIA, LOSITA, POLITE/C-295 (Figure 2) and TRUflow, or privately funded by companies such as MT Propeller, Textron/McCauley (Figure 3). Often, model tests are combined with isolated tests to explore the performance of the uninstalled propulsor. For turbofan simulators an isolated test is mandatory in order to calibrate the propulsor.
Figure 15 gives a typical example of power effects on the lift and drag polars of a twin engine aircraft. The dashed lines show the gross data, i.e. the results obtained directly from the main balance, thus including direct power effects. The full lines are net results with the direct forces from the propellers subtracted from the overall measurement. Two aircraft configurations are shown, namely a clean cruise configuration and a high lift case (take-off). The power-off case, without installed propellers, is compared to a zero thrust case and a high thrust case. Higher power increases the lift. Two effects are contributing. The propellers generate a force component in the lift direction – the difference between the gross and the net curve. The slipstream effect is obtained from the difference between

the net curve and the power off baseline. The slipstream also increases the drag, an effect which is more pronounced for the take-off configuration than in cruise. Such data is obviously of importance to the airplane designer to estimate performance. But accurate knowledge of power effects may be even more significant when considering stability and control topics. The controllability of the aircraft in an engine out case, especially when high thrust is required during take-off is an issue of prime importance.

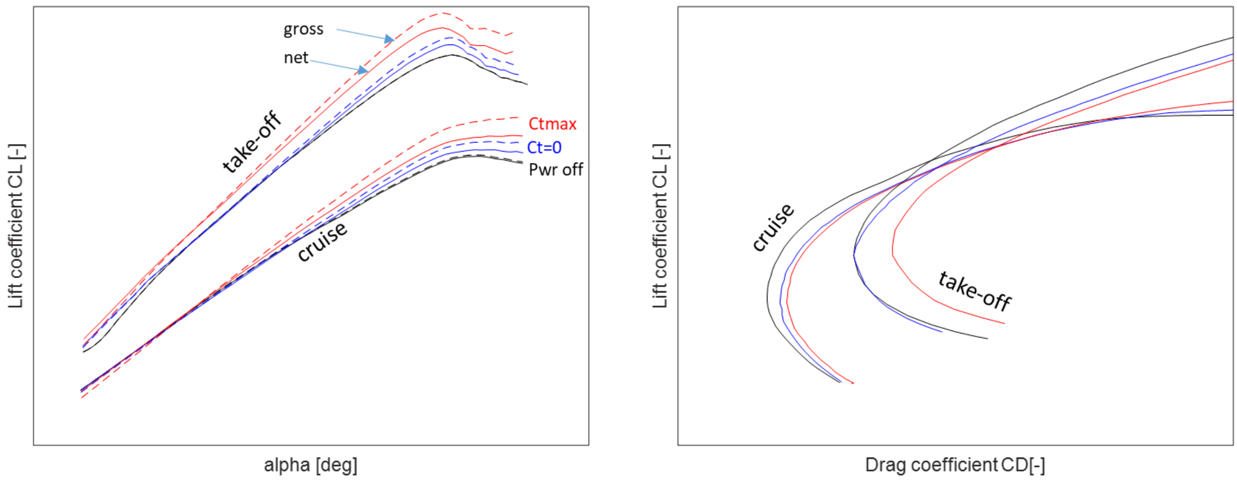

Figure 15 – Power effects for a twin engine aircraft. Red: high thrust; blue: zero thrust; black: power off (no propeller).

Figure 16 presents an example of results obtained from an isolated propeller test. The lateral force coefficients CNy and CNz are given as a function of the inflow angle (a pitch variation) at three thrust settings. Such data is of interest to determine propeller performance or, in combination with a full-model test, to evaluate installation effects on the propeller – how is the performance of the propeller affected by the presence of the airframe?

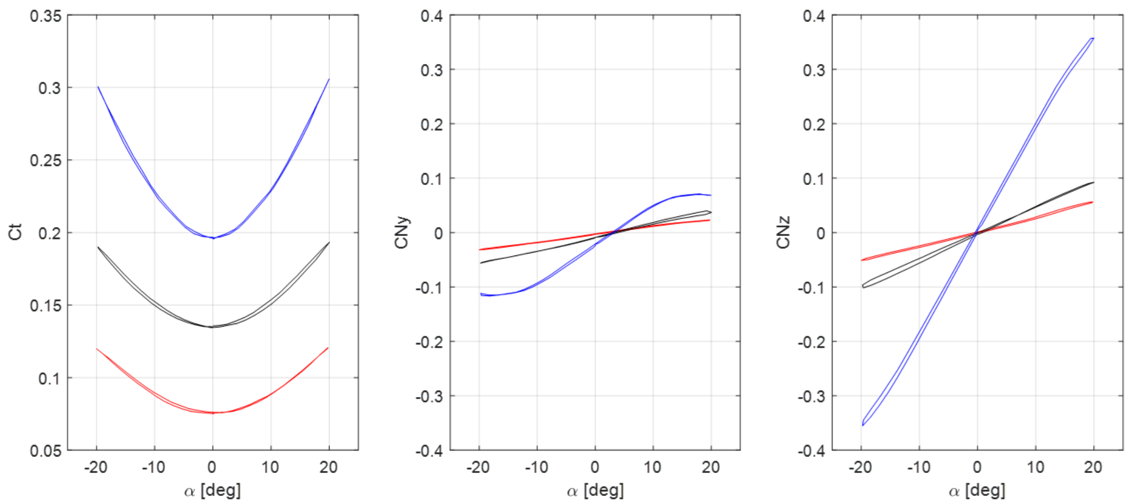

Figure 16 – Propeller forces in pitch from isolated test for three thrust settings.

The purpose of the Clean Sky Project TRUflow [5, 6] was to develop and demonstrate in the wind tunnel new measurement technologies suitable for investigating the flow in and around a nacelle of a turbofan with deployed thrust reverser (Figure 17). The setup uses the hydraulic motor MRT14 specifically developed to drive the single stage fan of the model. The motor uses a twin rotor tandem configuration and delivers in excess of 100 kW at more than 30'000 rpm. Achieved mass flow and fan pressure ratio for the unit are given in Figure 18.

Figure 17 – TRUflow wind tunnel model installed in the RUAG LWTE test section, with thrust reverser in the deployed configuration

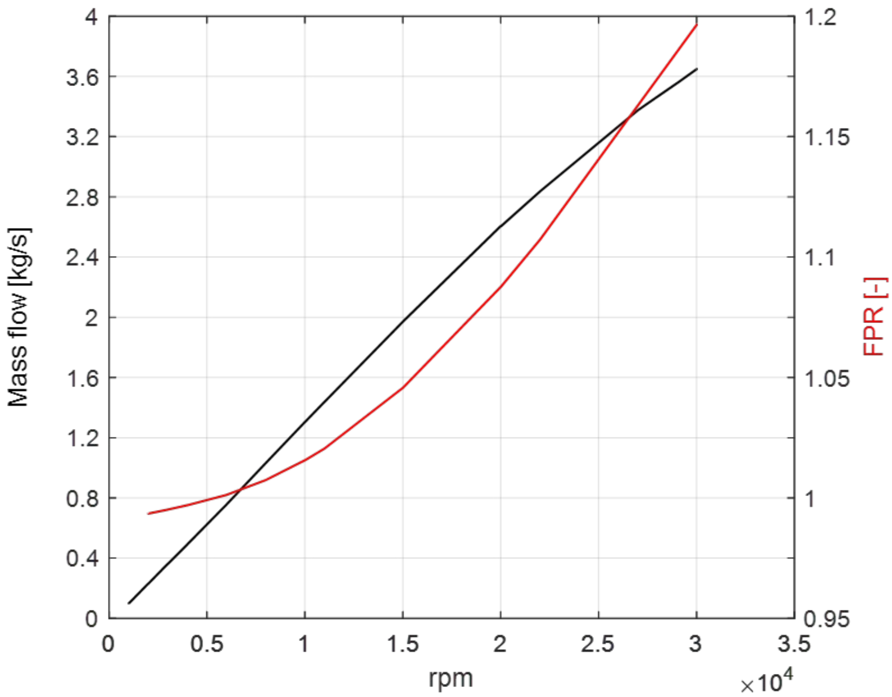

Figure 18 – TRUflow turbofan mass flow and fan pressure ratio FPR as a function of RPM [from 5]

6. Conclusions

Hydraulic propulsion is a viable, efficient and cost-effective solution for testing powered models from model to full-scale in the wind tunnel. Advantages of the technology are its robustness, scalability and ease of operation. Many propeller and turbofan powered aircraft models have successfully been tested using hydraulic motors at RUAG.

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