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AERODYNAMIC APPROACH OF A VARIABLE STATOR CONTROLLABILITY FOR A SMALL RADIAL TURBINE

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ABSTRACT

A measurement campaign focused on volute outlet conditions and its effects on the variable stator controllability has been conducted on a radial turbine. Indeed, the use of a variable geometry system implies the continuous control of the stator opening to best match the throat section to engine operating conditions. The control of this section highly depends on the mechanic system clearances and the aerodynamic moment transmitted to the actuator. Those two parameters are related to the aerodynamic moment generated on the blades. A previous campaign has allowed simultaneous measurements of the moment on 3 blades thanks to strain gauges. The study described in this paper developed an integrated device for the simultaneous measurements of the 13 blades. This new system integrated to the central housing of the turbocharger reduces the manipulation on the instrumentation. The first part of results concerns the influence of the volute outlet conditions and its effects on the aerodynamic moment of all the blades. The second part deals with the influence of the moments on the controllability along the engine line.

INTRODUCTION

A radial flow turbine is employed in almost all turbocharging applications for its compactness, robustness, economic production and relatively low specific speed. The radial turbine comprises two main elements; a stationary component that produces the swirl by accelerating a high pressure fluid and a rotating component that extracts work from fluid. The stationery component, referred as stator, can be either a series of angled blades or alternatively a vaneless housing where the flow accelerates through a throat in the tangential inlet section of the housing. The benefits of the stator have been shown in the literature [1] [2]. A vaned stator stage has higher peak efficiency than a vaneless stator one but is more sensible to off design conditions. Therefore, to provide high efficiency and wide operating range, the variable stator geometry has been developed.

A variable geometry turbine uses pivoting inlet guide vanes to modify the throat area and provide a better match between the turbocharger and the engine. Through changes in inlet guide vanes positions, the power transferred to the turbine and, hence, to the compressor can be modified. Thus the airflow to the intake manifold can be controlled. Several references have discussed on the control of the system which is primordial to take benefits [2] [3]. The control method includes a simple increase of the turbine area with engine speed [4] and transient strategies have been developed from steady state data. Despite demonstrated benefits in term of transient response, production applications have been limited due to the increased cost of the new technology and the fact that the continuous progress of the conventional turbochargers made the potential gains less tangible. Recent paper deals with the advantage of the vaneless volute either in term of efficiency or operating range compared to vaned volute [5].

However, the VGT (variable geometry turbine) is receiving renewed attention as an enabling technology for application of EGR (exhaust gas recirculation), method for NOx reduction [6]. The second benefit is a reduction of the turbo lag [7] but it needs a multi variable control.

The development of control strategies implies the continuous control of the stator opening. The control of this section is submitted to clearances in the mechanic system and aerodynamic moment transmitted to the actuator. Both these problems are related to aerodynamic moment generated on blades. The sign of the moment is modified by the incidence flow on the blades. Homogeneous volute outlet conditions would provide similar moment on all the blades. The angular position would be correctly imposed. However, previous study [8] has shown inhomogeneous stator inlet conditions. This is mainly due to the spacers (cf. ***Figure 2***) which provoke an important drop of the moment. The influence of the volute is also a non negligible element particularly near the tongue where a recirculation zone perturbs the flow and so the moment on the first blades. However, the blades pivot freely because of mechanical clearances and the angular position cannot be precisely controlled. The integrated moment transferred to the actuator is likely to change sign in function of fluid incidence on blade. The two aims of the paper are first to evaluate the effort on the actuator and detect a probable inversion which can cause an instable turbocharger operating point. In this case, the ECU which pilots the system may not provide the good set points. Second, to determine the amplitude of the set point depending the operating point of the engine. Indeed, the effort applied by the actuator will not be the same if the system tends to open or close. This would avoid the over boost or under boost effects that makes the power delivered by the engine unstable.

NOMENCLATURE

Moment	N.m	Moment of the blades
Qrt	g/s	Corrected mass flow
Special characters		
α	[-]	Opening angle
Π_T	[-]	Pressure ratio
Subscripts		
max		Maximum

EXPERIMENTAL METHOD

Variable geometry system

The variable geometry system has been described by previous paper [2]. It is composed of crank arms that are all linked to a common ring which controls, thanks to the actuator, the angle of all the blades (cf. ***Figure 1***). The two extreme positions of the stator are:

- i Closed when the throat section is minimum (1/5)
- ii Opened when the throat section is maximal (5/5)

The design opening corresponds to 3/5 opening position.

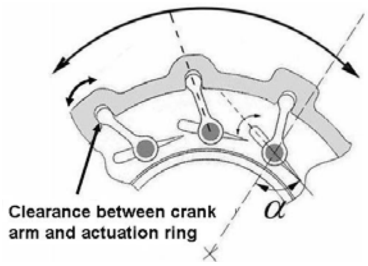

Figure 1: Variable geometry stator

Clearances have been introduced to allow the movement between all the pieces.

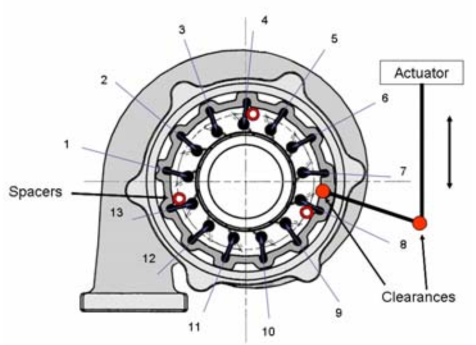

Figure 2: Clearances

The three different types of clearances are listed:

- i The clearances between the actuation ring and the crank arm (cf. ***Figure 1***). Depending the blade aerodynamic moment, the angular position of the blade is free to fluctuate around its mean position spoiling the knowledge of throat section;
- ii The clearances between the actuation ring and the control arm which have an influence upon the control of the opening (cf. ***Figure 2***);
- iii The clearances between the blades and the turbine housing ensured by spacers. These clearances allow the blades pivoting movement but generate secondary flow in the stator channel. Moreover spacers have intrusive influence in the main flow at stator inlet.

Measurement method

To study the flow distribution at the inlet of the stator, the aerodynamic moment of all the 13 blades has been measured simultaneously with a specific instrumentation based on a dedicated miniaturized multi gauges device. Two micro-gauges were stuck on the crank arm of each blade (cf. ***Figure 3***).

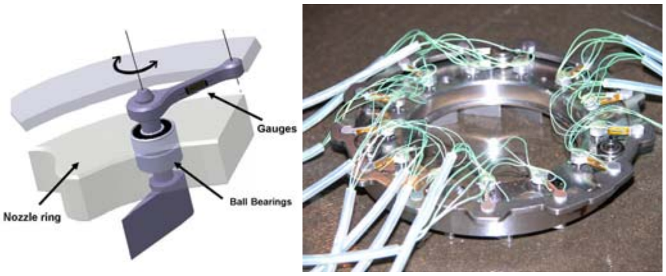

Figure 3: Measurement of the moment

The position of each vane and the position of the spacers are given on ***Figure 2***.

The measurement of aerodynamic moment with strain gauges has been discussed previously [8]. This allows determining the flow distortion. Indeed, the aerodynamic moment of the vanes is related to both the incidence and the magnitude of the incoming velocity. Therefore, all the blades have the same opening angle which means that the difference is only due to the flow. The aerodynamic moment is transferred through the axis to the arm. To reduce friction between the axis and the nozzle ring, micro ball-bearing were used. Because of the fixing crank arm’s head on the actuation ring, this moment is converted in flexion inducing deformation, measured by the gauges. The extension or compression of the strain gauges on each side of the arm produces an antagonist modification of electric resistance. A Wheastone bridge converts this modification in electric signal transferred simultaneous to acquisition modules (*National Instruments* FieldPoint).

The stator system is no longer fixed to the volute but to the central housing to avoid manipulation damages. To transit the wires (cf. ***Figure 4***), the central housing has been machined and an accommodation piece has been added.

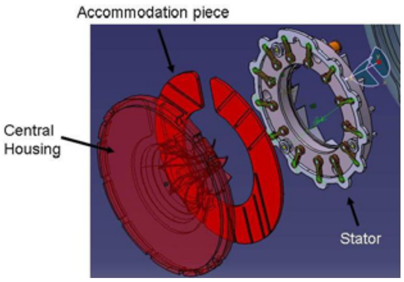

Figure 4: Stator accommodation

The pneumatic actuator controlled by a pressure regulator ensures the opening of the stator. A specific sensor measures its displacement. A first calibration of the stator was made without air. Then, a correlation with previous results for fixed stators allows validating the system. At last, an ENTRAN traction/compression sensor measures the global effort transferred to the actuator.

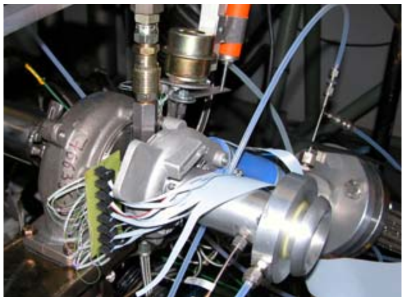

Figure 5: Instrumented turbocharger

The operating points of the stage are defined from a typical operating engine line, reproduced in steady air supply conditions (cf. ***Figure 6***).

The tests were made on test rig which ensures global functioning and instrumentation of a complete radial turbomachine (turbine fitted to a compressor). Due to strain gauges, the inlet temperature was limited to ambient temperature (290 K) and the operating points were adapted to obtain the same characteristic parameters (non-dimensional mass flow, pressure ratio) as those in real temperature conditions. The effect of the real operating temperature on clearances gaps are not discussed here.

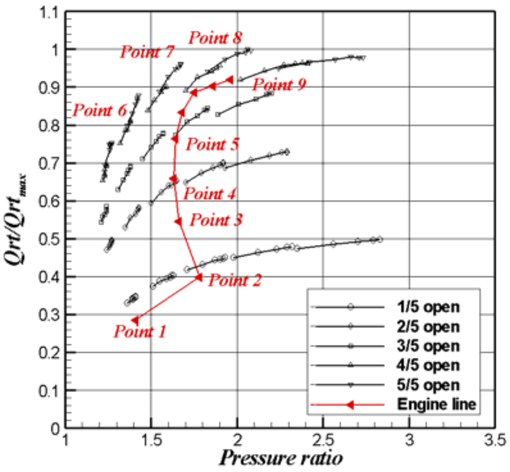

Figure 6: Engine line on turbine performance map

To reach those functioning points, the flow rate of the turbine is increased until the right value. Then the stator opening angle is adapted to obtain the good pressure ratio.

In ***Figure 6***, the engine line is presented on the turbine map. There are 3 zones for the engine line. The first zone (point 1 to point 2) corresponds to a minimal opening and a pressure ratio increase. The second one (point 3 to point 6) corresponds to a quasi constant pressure ratio evolution with an increasing stator opening. For the last one (from point 7 to point 9), the opening is maximal and the pressure ratio increase.

RESULTS

First, the influence of the volute outlet conditions on the aerodynamic moment of the stator blades is studied then its effects on controllability are discussed. Lastly, a dynamic approach is proposed.

Volute outlet conditions

The evolution of each blade moment for different operating points is first discussed. In ***Figure 7***, the aerodynamic moment for all the blades is plotted against the blade number for 3 points of the engine line.

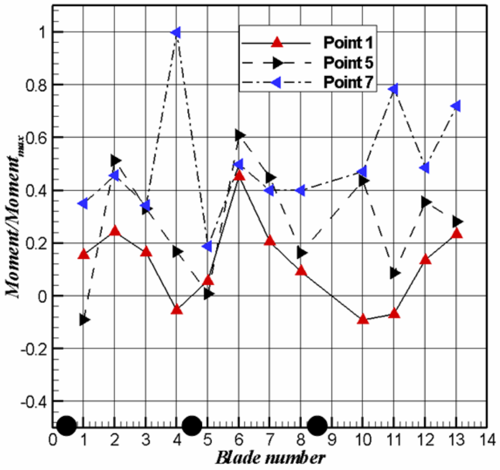

Figure 7: Evolution of the moment along the stator for three points

The black dots symbolize the position of the spacers on X-axis. A positive moment would open the stator. The flow is inhomogeneous all around the stator which confirms the results of the first campaign. Moreover, a severe drop on the moment is observed for the blades just downstream the spacers (blades n°1 and n°5), for all operating points. This perturbation of the flow is less perceptible for the curve associated to the point 7 (5/5 opening stator which corresponds to an opened stator) than for the point 5 (3/5 opening stator). Indeed, the diffusion of spacer wake is more important when the throat section is large.

For the operating point 7, the average moment is more important than the other point of engine line. Here, the opened stator is submitted to high incidence on large mass flow rate conditions. The next step is focused on one blade and the moment along the engine line is studied (cf. ***Figure 6***). The line evolution is splitted in 3 parts which correspond to the variation of two parameters (pressure ratio and opening angle):

i From point 1 to point 2, the increase of the pressure ratio induces a rise of the aerodynamic moment;
ii from point 3 to point 6, the opening of the stator blades at constant pressure ratio produces an evolution of the moment which passes through a minimum (near the design opening: 3/5);
iii from point 7 to point 9, the moment strongly increases.

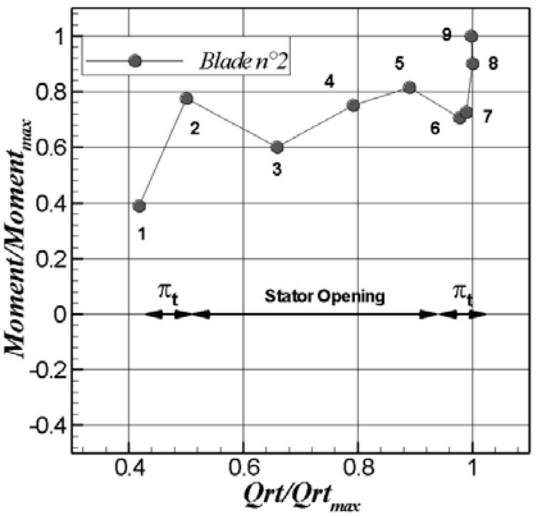

Figure 8: Evolution of the moment for blade n°2

This evolution is observed for most of the blades (blade n°1 to blade n°9). For the last blades before the tongue, the evolution of the moment is different from the others (cf. ***Figure 9***). The recirculation zone strongly influences the main flow. This affects the moment evolution.

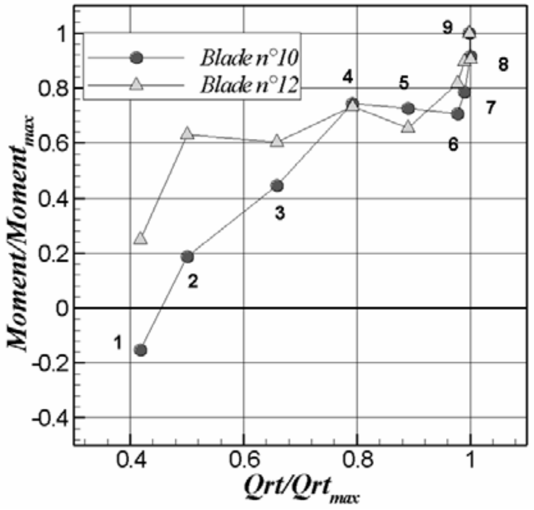

Figure 9: Evolution of the moment for blades n°10 and 12

Specific results are then presented on the controllability.

Controllability

The ***Figure 10*** presents the evolution of the moment of the blades downstream the spacers. There is an inversion of the blade moment for two operating points. This means that the blade n°1 and n°5 tend to pivot on the opposite direction of all the blades (cf. ***Figure 2***). The clearance contact for these two blades is inverted, changing their local orientation. The throat characteristics are no more precisely controlled for 4 channels. For instance, a stator angular variation of 1° induces an effect from 1 to 15 times stronger depending on stator opening.

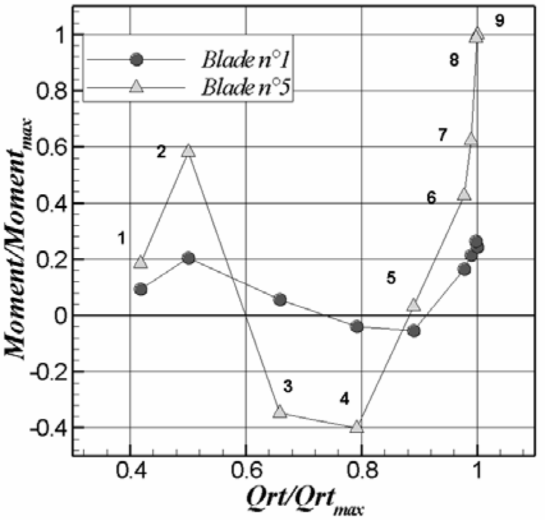

Figure 10: Evolution of the moment for blades n°1 and 5

The global moment will be affected and its transfer to the actuator has to be considered. In ***Figure 11*** is plotted the effort calculated by integration of all the moments of the blades and the real transmitted effort measured on the actuator.

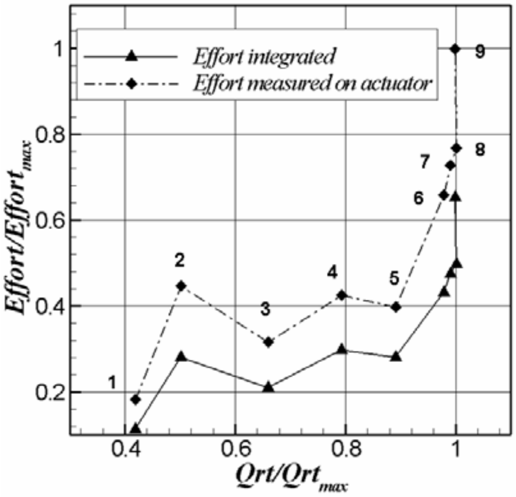

Figure 11: Evolution of the effort

First, the evolution of the two plotted efforts is quite similar to that observed on the blades but the gap between the values is important. This is due to the determination of the effort by integration which does not consider the mechanical clearances and the non-aligning of the arms between the nozzle ring and the actuator (cf. ***Figure 2***). Second, the effort is always positive which means that the stator always tends to open. The blades would never close freely which could increase the pressure upstream and endanger the integrity of the turbocharger in case of problems. Last, maximal effort (points 7-8-9) is much more important than those measured in intermediate positions (points 3-4-5). This means that the control strategy has to take account of global moment variations transferred to the actuator. Its displacement will require more or less energy to balance the global effort depending on the operating points.

Dynamic cycles

Some "dynamic" cycle tests of opening/closing stator have been carried out to compare the results with the static ones (cf. ***Figure 12***). The test protocol consists in fixing the mass flow rate and then quickly opening and closing the pneumatic actuator that controls the stator opening (1 cycle in 2 seconds). The engine functioning line cannot be reproduced but it enables us to observe the dynamic behaviour of the actuator.

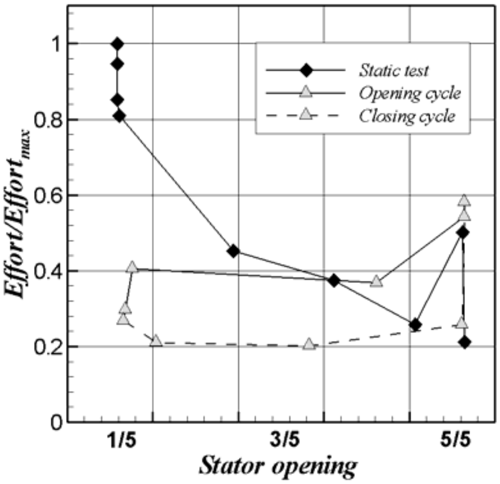

Figure 12: Opening/closing cycle

The static test measures previously presented are plotted with one dynamic cycle against the opening angle in ***Figure 12***. A hysteresis appears between opening and closing cycles. This hysteresis depending on the opening or closing of the stator was not observed in static conditions. At opened position of the stator, the difference between static and dynamic measurement is important. Mainly, the mass flow could not be rightly fitted to the pressure ratio for all the points. The experiments were then focused on closed positions of the stator where good agreement is observed. Negative incidences on the stator blades would be expected in closed configuration. Either in static or in dynamic test, no global moment inversion was observed. In this condition, the controllability strategy should not expect unstable points.

CONCLUSION

A simultaneous moment measurement was achieved in small radial turbine (diameter less than 60 mm) for real functioning points. This campaign of measurement completes the first one by fitting the engine operating conditions thanks to the description of the engine line. The first element is that the results allow determining the offset of the effort due to the mechanical system which has to be considered in the ECU settings. Then, in spite of a good understanding of the local effects, the global behavior presents some distortion, especially on a dynamic operating mode depending the operating points. This will modify the controllability and then the optimal functioning of the stage. However, no inversion has been shown which tends to prove that there would be no instable operating points in static tests. Finally, the amplitude of the effort has been quantified along the engine line. The values are very different which would supply a global level of the effort for each engine operating points. This would help to develop ECU settings that increase the efficiency of the turbocharger and permit to reduce the pollution.

The dynamic simulation of the engine line has to be improved. This would give better comparison between static and dynamic results to identify unsteady effects on the whole stator cycle. Finally, full dynamic tests would certainly give precious information on the real functioning.

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