NEW APPROACH TO TORQUE MEASUREMENT UNIT DEVELOPMENT AND ITS CALIBRATION

NOWE PODEJŚCIE DO ROZKŁADU POMIARU MOMENTU OBROTOWEGO I JEGO KALIBRACJI

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Abstract. *The paper deals with the new approach to torque measurement in turboshafts. New construction of torque measurement is described with the highlighted advantages of the construction. The paper familiarizes the reader with the step-by-step algorithm of the torque measurement. As torque measurement units are not ideal, i.e. have manufacturing inaccuracies, so each unit has its own performance. The calibration algorithm to be in charge of obtaining the individual performance from the ideal one is described in the paper as well.*

Keywords: *torque-measurement unit, phase-shift measurement algorithm, calibration algorithm, measurement accuracy.*

Streszczenie: *Artykuł dotyczy nowego podejścia do pomiaru momentu obrotowego w turborowodach. Nowa konstrukcja pomiaru momentu obrotowego została opisana z wyróżnionymi zaletami konstrukcji. Artykuł przybliży czytelnikowi algorytm krok po kroku pomiaru momentu obrotowego. Ponieważ jednostki pomiaru momentu obrotowego nie są idealne, to jest mają niedokładności w produkcji, więc każda jednostka ma swoją własną wydajność. Algorytm kalibracji, który ma być odpowiedzialny za uzyskanie indywidualnej wydajności od idealnej, jest również opisany w artykule.*

Słowa kluczowe: *jednostka pomiaru momentu obrotowego, algorytm pomiaru przesunięcia fazowego, algorytm kalibracji, dokładność pomiaru.*

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1. Introduction

The global cost of the kerosene used by gas turbines has already broken the ambits of the end of the 2000s (IATA, 2017) for more than twice. It follows that improvements however small are still very well worthwhile.

According to (Anastasia Kharina, 2014) there are two ways in which fuel consumption can be reduced:

- The first way is to budget numerous R&D researches that will output the prototypes, which performances will have an improved fuel economy.
- The second way is to develop the control systems that will operate the existing and new gas turbines with the best possible fuel efficiency.

Definitely the best option is the simultaneous progress in both ways, however the results of the first way need a 10 year plus time period to give the first results.

Specific fuel consumption has already been cut dramatically over the last 4-6 decades, and the point has now been reached where further systematic progress is by steps so small that improvements can only be identified with certainty by instrumentation of the very highest accuracy, ideally 5-10 times better than the smallest effect sought.

The torque measurement has always been the best option to assess the power output of a gas turbine or a steam turbine in power generation operations.

Historically, torque measurement units were not widely used when fuel was cheap and the main requirement was to get new plant on stream at the earliest possible date. They have also had a poor reputation for reliability and credibility in gas turbine environments.

This may have been because measuring torque was seen as a pure instrumentation problem which could be solved by fitting strain gauges and their associated shaft-mounted electronics to the free turbine shafts with minor modifications (Kistler, 2017). Any faults tended to be in the transducer, and required the plant to be shut down while the shaft was returned to the electronics experts for repair.

The only other practical way of measuring torque accurately is to measure how much a drive shaft of known torsional stiffness twists under load. Phase shift torquemeters do this by measuring the phase displacement of signals produced in stationary pickups by toothed wheels, preferably formed integral with the drive shaft (Jean-Luc Charles Gilbert Frealle, 2013) and (Bodin, 2013). Making the strain gauges retire from the stage eliminated the problem with a transducer.

However, torque measurement units have nothing in common with the majority of the known measuring systems because they transmit torque as well measure it.

At gas turbine speeds and powers this presents considerable mechanical engineering problems, and calls for a multidisciplinary approach with a strong base in turbomachinery, electrical engineering, signal processing, algorithms development.

2. Motivation

The development of a new approach to torque measurement is not a destination point of the accomplished research, because the torque measurement is just an instrumentation tool that on our opinion has 5 main fields of application:

- Improvement confirmation. Components of modern gas turbines are quite perfect machines which improvements from engine to engine rarely breaks the 1% limit in fuel efficiency of the engine as a whole.
- Mating the driving machines and power consumers (lift rotors of helicopters, power generators etc.). It may turn a considerable problem to prove that to the customer that the power output of the gas turbine matches the power required for the consumer.
- Health management systems and diagnostics. In condition monitoring algorithms, they provide management information enabling plant to be operated at the best efficiency and output, and overhauled when performance starts to fall off. They also help to identify which machine requires maintenance or modification at planned shutdowns to increase efficiency or throughput.
- FADEC data source. The accurate torque and hence power measurement lets FADEC to govern the engine with minimum safety coefficients, i.e. with the maximum closeness to the limitations.
- Torque measurement in the systems where torque estimation is complex or impossible, for example, in complex petromechnical plant.

All five items of this list prove the relevance of the research made in deep cooperation by JSC “Motor Sich” and KhAI.

3. Phase shift measurement

Every torque measurement unit that implements the phase shift measuring principal measures the torsional “wind-up” experienced when the coupling is exposed to torque. This is done by comparing the relative displacement of one end of the coupling spacer to the other as it is shown in Fig. 1. Using sensors to detect teeth mounted to each of the coupling creates electrical impulses. By timing the pulses relative to each other, also known as their phase shift, the torsional deflection can be measured by electronic systems.

Fig. 1 Phase shift measuring illustration. Mechanical aspects

Each torque measurement unit is subjected to a factory calibration procedure. A measurement of its torsional stiffness is made so that the relationship of torsional deflection versus torque is accurately known. Also, a zero torque dynamic calibration is conducted so that the initial relative position of the teeth is known. This calibration data is programmed into the torque measurement unit electronics so that the torque being transmitted can be accurately calculated from the measurement of the torsional deflection.

4. Mechanical aspects of a torque measurement unit

The mechanical parts of the torque measurement unit are presented in Fig. 2. They are a shaft, which transfers the torque, a screen and an inducer. The screen is mounted on the shaft. It is fitted with a negative allowance and pinned to the shaft from side A. There is a small clearance between the shaft and the screen at the side B. The inducer is put on the shaft and pinned to it. Both inducer and screen have eight lugs equally spaced along the circumference. The assembling provides a mounting angle between the screen lug and the inducer lug being equal to φ_{20} .

Fig. 2 Torque measuring unit

When the torque is transmitted from a free turbine to a consumer through the shaft, the side A of the shaft is twisted against the side B at some angle that is proportional to the torque.

As the screen is not engaged in the torque transition, the screen lug is displaced relatively to the inducer lug at the same angle. In its turn, the twist angle is proportional to a time interval between the “wind-ups” from the inducer and screen lugs when they pass through the electromagnetic field of the TMU sensor. Thus, the torque is determined through this time interval.

This construction is will win a pole because of the following advantages:

- The length of the shaft is quite short to suffer from the bending or thrust, i.e. it means that there won't be any vertical and horizontal movements of the rotating unit relative to the non-rotating pick-ups. That means this unit will produce no additional phase shift because of this.
- The torque measurement unit can serve as a standalone device for torque measurement. It can be integrated in any engine with minor modifications.
- The torque measurement unit can operate as in cold part so in hot part of the gas turbine.
- The design is quite simple, consisting of three main parts: shaft, inducer and screen pinned together. It won't take much money to manufacture these parts, as they are manufacturable.

The special processing algorithm makes the measurements possible with a single RPM sensor, which prevents any sensors' synchronization problems.

5. Algorithmic aspects of torque measurements

Due to the shaft rotation, the inducer and screen lugs pass through the sensor magnetic field. The magnetic lines of force partially stretch in the air and partially – in the lug. The voltage grows with the number of magnetic lines of force stretching in the lug, reaching maximum magnitude when the sensor and the lug find themselves in a common plane. Upon further movement, the signal starts to decrease due to the sensor magnetic discharge. Roughly we can conclude that the signal of the sensor looks like a sinusoid.

Hence, the next algorithm can be used to evaluate the torque:

- Catch time moment t_1 when the voltage induced by the i^{th} screen lug breaks the boundary voltage, time moment t_2 when the voltage induced by the i^{th} inducer lug breaks the boundary voltage, time moment t_3 when the voltage induced by the $(i+1)^{\text{th}}$ screen lug breaks the same voltage boundary.
- Calculate three time intervals as

$$\begin{aligned}\Delta t_1 &= t_2 - t_1, \\ \Delta t_2 &= t_3 - t_2, \\ \Delta t_3 &= t_3 - t_1.\end{aligned}\tag{1}$$

In case of a zero torque, the time intervals and the corresponding mounting angles are proportional.

$$\frac{\Delta t_{10}}{\varphi_{10}} = \frac{\Delta t_{20}}{\varphi_{20}} = \frac{\Delta t_{30}}{\varphi_{30}} \quad (2)$$

where φ_{10} is an angle between the i^{th} screen lug and the i^{th} inducer lug at the zero torque, φ_{20} is an angle between the i^{th} inducer lug and the $(i+1)^{\text{th}}$ screen lug at the zero torque, φ_{30} is an angle between the i^{th} and the $(i+1)^{\text{th}}$ screen lug at the zero torque.

- Calculate the current angle φ_2 from the proportion:

$$\frac{\varphi_2}{\Delta t_2} = \frac{\varphi_{30}}{\Delta t_3}, \quad (3)$$

whence

$$\varphi_2 = \frac{\Delta t_2 \cdot \varphi_{30}}{\Delta t_3} = \frac{\Delta t_2 \cdot 45^\circ}{\Delta t_3}. \quad (4)$$

The angle φ_2 of an unloaded shaft is equal to the mounting angle φ_{20} . As the transferred torque increases, the angle also increases.

- Calculate the twist angle as

$$\alpha = \varphi_2 - \varphi_{20} \quad (5)$$

- Determine the torque according to a torque measurement unit performance:

$$\text{TORQ}_i = f(\alpha, T) \quad (6)$$

6. Torque measurement performance

As it was described in the previous section, the measuring algorithm must have the known individual performance of each torque measurement unit. Apparently each torque measurement unit has its own individual performance, because the manufacturing accuracy is always limited and its far too low to use some universal performance that suites every torque measurement unit. The individual performance of the torque measurement unit is derived from the universal one by a special procedure known as calibration. The calibration procedure will be described next.

Within the scope of this paper we will consider the universal performance to be a performance of torque measurement unit with the sizes from the drawing with zero allowances.

The universal performance was derived with the help of 3D modeling. The assembly of torque measurement unit was simplified in the way to have the same twisting as the real torque measurement unit. The pins were abolished and their functions were delegated to connections.

The assembly was loaded with the temperature in the expected range of operating conditions, centrifugal forces and transmitted torque. Torque and constraining of the assembly were made by two different sides of the shaft. The design scheme of analysis is shown in Fig. 3.

Fig. 3 Design scheme of strength analysis

Each simulation aimed to obtain the angle between the i^{th} inducer lug and the $(i+1)^{\text{th}}$ screen lug for each combination of TORQ and T. Finally, referring φ_2 we determined the twisting, which is a final parameter of interest.

The performance identification is a two stage procedure that includes structural and parametric identification.

The parametric identification goes in the structure of the performance that is next used for parametric identification.

As φ_2 is a result of the elastic straining caused by twisting, then it is reasonable to use the following formula

$$\alpha = \frac{L}{G \cdot I_p} \text{TORQ} \quad (7)$$

where L is a measuring base (the distance between the centers of two pins), G is a shear modulus, I_p is polar inertia

As you may noticed from eq. (7), the torsional deformation depends on shear modulus which is temperature dependent. In the standard case, the relation between the shear modulus and the temperature can be described by a parabola

$$G = a_2 T^2 + a_1 T + a_0. \quad (8)$$

If the expected temperature range of the torque measurement unit is quite narrow, the simpler equation will be used, which is

$$G = a_1 T + a_0. \quad (9)$$

Considering $\text{TORQ} = \frac{\alpha \cdot G \cdot I_p}{L} = \frac{\alpha \cdot I_p}{L} (a_1 T + a_0)$, the suggested structure for parametric identification is

$$\text{TORQ} = A \cdot \alpha + B \cdot T + C \cdot \alpha \cdot T + D, \quad (10)$$

where A, B, C, D are the parameters to be calibrated.

All parameters may fall into four categories:

A parameter: The factors that change the resistance to torsion ($G \cdot J_p$), which are the inner and outer radii of the shaft. The factors of this group depend only on the change in the geometrical parameters of the section.

B parameter: The factors that depend only on the temperature state of the torque measurement unit parts: the radial, circumferential and axial temperature strains of the parts..

C parameter: The factors that depend on the temperature state of the torque measurement parts and their resistance to torsion ($G \cdot J_p$): the material properties.

D parameter: The factors of the manufacturing and assembling errors: the pin mounting, the lug width etc.

7. Experimental checkout of torque measurement accuracy

The proposed method of torque measurement was experimentally checked on the certified test bed of JSC “Motor Sich”. The test bed was equipped with hydraulic brake that played a role of a power consumer of a free turbine. The control system of the test bed was able to set any power of the hydraulic brake within the power range of the tested engine.

The testing covered all steady operational modes and did not consider the transients. The test loop is shown in Fig. 4.

Fig. 4 Test loop

The torque itself was measured by a developed torque meter with the embedded measurement algorithm as well as by the certified torque meter of the test bed with known 99.9% confidence. The temperature of parts used in the performance of the torque measurement unit was not measured directly, because of complexity. Instead, the temperature of gas streamlining the parts was used. The thermocouple was inserted in the wall of the cavity with torque measurement unit. The readings of the torque were averaged every 20 measurements. The results are shown in Fig. 5

Fig. 5 Theoretical performance (—) vs experimentally obtained measurements (×) with trend line(---)

The analysis of the performances from Fig. 5 clearly shows that the tested torque measurement unit is considerably different from the ideal one or the temperature state of the parts was not measured precisely, or the effect of temperature was underestimated. To find the true reason of the problem one subjected the torque measurement unit to precision analysis. The analysis aimed to answer two questions, which are what is the worst confidence level of the torque measurement unit and is it possible to reach the desired accuracy without individual calibration of every torque measurement unit.

In the analysis the total error was decomposed into sources and the impact of each source was estimated. The results of the analysis are shown in Fig. 6.

Fig. 6 Components of the total error

The total error according to the made error analysis is 11.6%. The major sources of the error are the errors of the external and internal shaft machining and errors caused by temperature straining of the measurement base and the temperature effect on material properties(especially Elasticity modulus).

Hence, answering the first question one can claim that the worst confidence level is 89.4%. This physically means that the control system engineers must set the power limit 11.6% lower than they could in case of 100% confidence in the measurements, or in the other words they must pay 11.6% power for the safety, which is far too much.

No matter how precise the production facilities are, the error of measuring base will always remain. Moreover, the steep demands to the precision of the torque measurement unit will make it noncompetitive.

Concluding the considered above, the individual calibration of each torque measurement unit sounds a reasonable price to get the 98-99% confidence in the measured torque, keeping the engine price at the same level.

8. Torque measurement unit calibration aspects

The stages of the calibration algorithm are presented next.

- 1) Start the engine and accelerate up to an idle mode. The angle φ_{2k} is determined according to the measurement algorithm presented above. At the same time, a rig bed torque meter measures the torque ($TORQ_{BEDk}$). All measured parameters are then averaged. Calculate the twist angle by the equation

$$\alpha_{exp} = \varphi_2 - \varphi_{20}, \quad (11)$$

where α_{exp} is an experimental twist angle at the mounting angle being equal to φ_{20}

- 2) Evaluate the residual between the calculated twist angle and the measured twist angle

$$RES = \alpha_{calc} - \alpha_{exp}, \quad (12)$$

where α_{calc} is a twist angle obtained from the inverse performance of the measurement unit ($\alpha_{calc} = \frac{TORQ_{BED} - B \cdot T - D}{A + C \cdot T}$). The performance had been obtained by the finite element analysis of the torque measurement unit 3D model.

- 3) Generate the adjustment to eliminate the residual calculated at the previous step. The adjustment reduces experimental twist angle to calculated twist angle:

$$ADD = RES. \quad (13)$$

- 4) Introduce the adjustment to the φ_{20} angle. The adjustment is introduced by the change of the mounting angle. New φ_{20} becomes equal to

$$\varphi_{20 \text{ calibrated}} = \varphi_{20} - ADD. \quad (14)$$

Measure the α_{exp} by the considered algorithm and $TORQ_{BEDk}$ by the rig bed torque meter at all available modes. The φ_{20} must be equal to $\varphi_{20 \text{ calibrated}}$.

- 5) Identify performance parameters using least squares method.

The result of the torque measurement unit calibration is an individual performance of the each produced unit.

9. Conclusions

The introduction of the calibration procedure into the adjustment of the torque measurement unit gave a considerable profit in the measurement accuracy providing the 98.5 confidence in the measurements (see Fig. 7).

Fig. 7 Theoretical performance (—) vs experimentally obtained measurements (x) with trend line(---)

The algorithms of calibration and torque determination were implemented in the electronic block of the engine automatic control system. They were verified during the engine rig testing comparing values of the torque determined by the algorithms and directly measured by the rig measuring system.

Good results of rig testing shown the torque measuring system ability to be implemented in gas turbines.

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