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Fabrication of A Rotating Shaft Torque Sensor for Power Data Determination of Rotary Farm Implements

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ABSTRACT: A rotating shaft torque sensor so-called a torque transducer for power data determination of rotary farm implements was developed, fabricated, and calibrated. It built according to the working theory of the commercial power take-off (PTO) torque meter model of Lebow Model 1228-20k, Eaton Advanced Electronics, Troy, Michigan, USA using local materials. For a typical torque measuring design, resistance type strain gages were glued to a spline shaft surface similar to a PTO shaft and integrated into a Wheatstone bridge circuitry. A slip ring was used to interface the bridge circuitry on either side of the transducer to a data logger named Daytronic data PAC model 10k4. For a torque range of 0 to 5 kN.m, the fabricated torque transducer has been constructed. A 60 teeth gear was installed on the torque transducer to measure the rotational velocity. Laboratory static and dynamic calibration tests were conducted. The dynamic tests were accomplished during the full load varying speed tests using a hydraulic PTO dynamometer type AW NEB 400. In both dynamic and static calibration tests, the fabricated torque transducer confirmed high accuracy measurement with linear relationship addressed by determination coefficient (R2) in the range of 0.992 to 0.9994. The fabricated PTO torque transducer is less expensive considering the typical commercially available PTO torque transducer. For acquiring PTO torque data during field operations, particularly when using a rotary plow or similar implements, the fabricated PTO torque transducer can be installed on the tractor's PTO shaft easily.

Keywords PTO, tractor, torque, rotary plow, farm implements.

INTRODUCTION

Agricultural tractors are the most frequently power source for farm machines (Kumar et al., 2017). Moreover, an important percentage of the whole cost of crop production is borne by agricultural machinery. Maintaining high operating efficiency on the farm, requires careful matching of tractors and farm implements (Kumar and Tewari, 2013). Furthermore, with the development of knowledge, the managing of farm machinery tasks needs a considerate of power necessities so as to size tractors and farm implements for the most operative power allocation (Roeber et al., 2017; Çiftci and Çalişir, 2018). Additionally, the field reliability of tractors is directly impacted by the power take-off (PTO) driveline's dynamic performance (Shao et al., 2022). A tractor power take-off linked to a PTO brake torque dynamometer can be employed to measure torque and speed requirements of rotary farm implements for determining power later on. The PTO allows farm implements to use the tractor's engine for power (Yuvanarasimman and Rajeswari, 2014). Nonetheless, the optimal matching of tractor and rotating farm implements can result in reduced rotary power consumption and increased operating efficiency (Chethan et al., 2018). This can be done by monitoring PTO power data, which have attracted a lot of attention in research on the operation of farm machinery .

The measurement skill most often used in the typical commercially available PTO torque transducer today is based on a foil strain gage (Soundararajan, 2014). Moreover, PTO torque transducer is usually based on transit signal by a slip ring of strain gages material, as its resistance fluctuates with the instantaneous strain that develops over its surface since it is a strain-sensitive material (Yadav et al., 2020). On the other hand, PTO torque calculation is always crucial for determining power. Conversely, as PTO torque calculation has always an important for determination of power data, locally PTO torque transducers which are alternative of expensive PTO torque transducers are developed or fabricated (Dcruz et al., 2013; Muftah et al., 2013; Klaus, 2015; Zhang et al., 2015; Weidinger et al., 2018; Shuib et al., 2019). Hoki et al. (1988) employed a slip ring tool and foil strain gages to form a PTO torque transducer by placing the foil strain gages on the rounded section shaft's surface close to the universal joint that attaches to the tractor PTO. A reflection-type photo sensor was fixed in close proximity to the PTO torque meter so as to measure the shaft's rotation. Every time the tractor PTO shaft rotated, the reflector plate on it reflected light, creating a current pulse that a data recorder captured. Salokhe et al. (1994) built a PTO slip ring torsion torque transducer to measure the required power for a disk tiller in a clay soil .

Using measured PTO torque for a rotating agricultural implement, Kheiralla et al. (2001) developed a tractor instrumentation and data collecting system for power and energy demand mapping. Additionally, Elgwadi (2005) developed a slip ring PTO torque transducer for torque measurements. The transducer was composed of two shafts as sensing member, involved four isolated cuppers slip rings connected with four carbon brushes through a slip ring, involved a sixty toothed gear for rotational PTO speed measurement. Pexa et al. (2013) used a PTO hydraulic dynamometer type AW NEB 400 to determine engine performance metrics such as power and torque. Cho et al. (2016) installed a telemetry system on the tractor PTO shaft for torque measurements during tillage process. The torque was determined by employing a sensor that sense the torque by means of a four-element full-bridge strain gauge. Özbek and Al-Sammarraie (2020) used torque meter model Datum Brand Series 420 PTO 1800 N.m to measure the torque for applications in disk type silage machines. Hensh et al. (2021) developed a wireless system to collect torque data of a PTO-driven agricultural machinery .

It is useful for estimating performance data of rotary farm implements during field operation. However, sizing such implements and tractors are rest on power calculation. Instead, the commercial PTO torque transducer is expensive. Therefore, the main aim of the work offered in this research paper is to fabricate PTO torque transducer based on the concept of working principles of the typical commercially existing PTO torque transducer model Lebow Model 1228-20k, Eaton Advanced Electronics, Troy, Michigan, USA using local materials

MATERIALS AND METHODS

Description of the fabricated rotating shaft torque sensor

Many techniques for measuring the torque in rotating shafts exist (Norton, 1969). The commercial PTO torque transducer model of Lebow Model 1228-20k, Eaton Advanced Electronics, Troy, Michigan, USA as shown in Figure (1), measures torque and rotational speed to provide power data for rotary farm implements. It does this by producing an analog torque signal and a pulse output according to shaft speed.

In the present study, the fabricated PTO torque sensor was built according to the principle of working concept of the commercial power take-off (PTO) torque transducer (Figure 1) using local materials. A strain gage bridge installed on a spline shaft similar to a PTO shaft senses the torque (Figure 2). However, in Figure (2), different components were existing such as tractor PTO shaft, adapter shaft female side, adapter shaft male side, inner slip ring, outer slip ring, strain gage socket, rotary speed socket, speed sensing gear, and wiring rosette. Furthermore, a slip ring tool served as the link between the strain gage and the stationary transducer housing. A magnetic pick-up that senses every tooth on a 60-tooth gear positioned on the rotating shaft determines the rotating shaft speed. The fabricated PTO sensor can sense up to 1200 rpm and has a maximum torque measuring capability of 5 kN.m with a temperature coefficient of ±0.0036% of full scale/°C, the strain gages are temperature corrected across a range of 21-76°C.

As shown in Figure (2), on the male side, two circled Teflon parts slides on each other were engaged. The rotating down part engaged and rotates with the adapter, holds four isolated cuppers slip rings, while the upper stationary circled part slides around it. Eight holes were machined down from the top of the sliding upper stationary circled part; each hole contained carbon brusher touches one rotating cupper slip ring, each brusher compressed with a spring which in turn compressed with a screw cupper bolt fixed at the top of each hole. On opposite ends of the shaft, two sets of KFG-5-120-D16-11-LIM-2S Kyowa strain gages with 90° rosettes, 120±0.8 Ohm, and 2.1 gage factor were bonded at 45° shear planes. Wheatstone bridge circuitry was used to link the bonded strain gauges on the shaft in a complete bridge configuration through the appropriate slip ring, the data logger called Daytronic data PAC provided a 2.5 mA constant current excitation source. Electrical wire connected to each bolt; each four electrical wire formed a Wheatstone bridge two wires for the input voltage and two wires for output voltage, the bridge connected to the data acquisition systems (Daytronic) for torsion measuring as the adapter rotate under torsion load. Rotational speed sensor which located above 60 teeth (toothed wheel), fixed on the rotating down part at the male side. Electrical wire connected to the magnetic pick-up frequency sensor was connected to the data acquisition systems for rpm signal transmitting. The female side of the adapter connected to the tractor PTO while the male side can be connected to shaft of a rotary implement. Figure (3) shows a photo of disassembled adapter slip ring torsion transducer and Figure (4) displayed the Wheatstone strain gage bridge wiring diagram on the adapter.

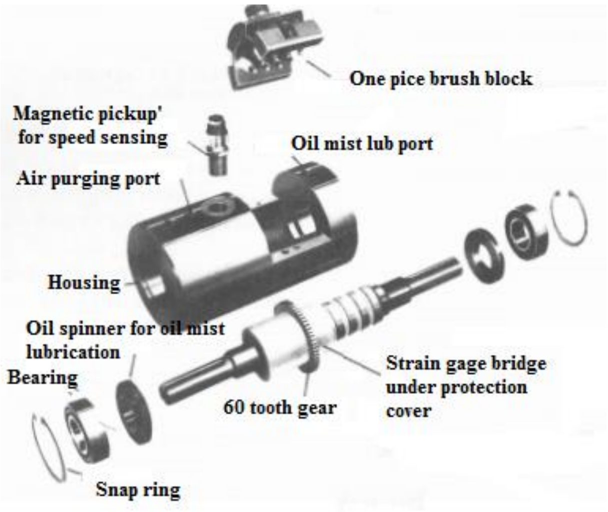

Figure (1). Components of the commercial power take-off (PTO) torque transducer Lebow products.

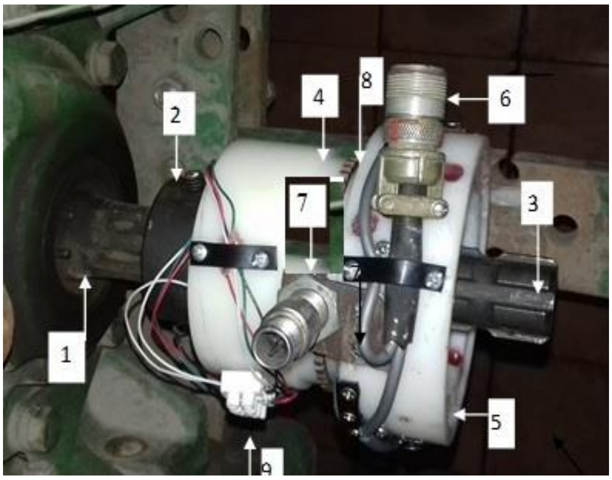

Figure (2). A rotating shaft PTO torque sensor for power data determination of rotary farm implements: (1) tractor PTO, (2) adapter shaft female side, (3) adapter shaft male side, (4) inner slip ring, (5) outer slip ring, (6) strain gauge socket, (7) rotary speed socket, (8) speed gear, and (9) wiring rosette.

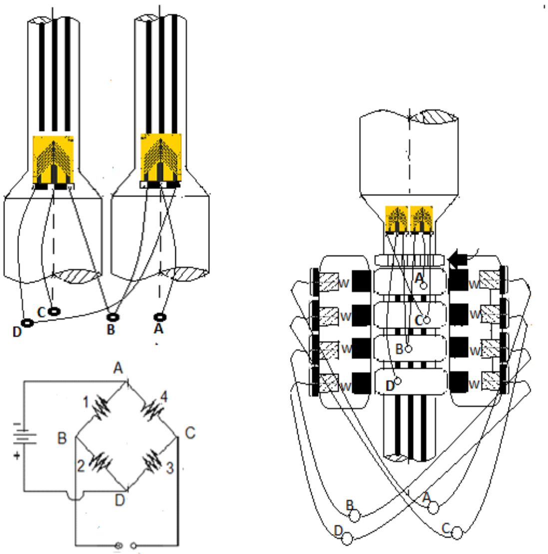

Figure (3). A photo of disassembled adapter slip ring torsion transducer.

(4) inner slip ring, (5) outer slip ring, and (6) strain gauge socket.

Figure (4). The displayed Wheatstone strain gage bridge wiring diagram on the spline shaft.

Appropriateness of shaft diameter to transmit power

Figure (5) shows a spline shaft adapter and strain gage location, Howevere, a 90-kW tractor transmit power through the modified shaft adapter (solid shaft). The tractor PTO and the shaft adapter rotate with 1000 rpm. Accordingly, the formula discribed by Equation (1) (Yahya et al., 2004) was used to determine the maximum torque delivered to the shaft.

$$P = \frac{2\pi nT}{60000}$$

………………………………….(1)

Where n is the rotational speed of the PTO (rpm), T denotes the torque (N.m), P states to the power output (kW), and 60000 is the conversion factor.

The torque load that causes the solid shaft to experience its maximum shear stress is described below by Equation (2) (Allan, 1980; Loewenthal, 1984).

$$\tau = \frac{16T}{\pi D^3}$$

………………………………….(2)

Where τ symbolizes to the shear stress (MPa), T denotes the practical torque (N.m), and D represents the shaft diameter and was determined to be 25 mm. The designed shear stress (τ) was 280 MPa. However, the solid shaft's permissible shear stress is specified as described by Equation (3) (Yahya et al., 2004).

$$\tau_{allow} = \frac{0.57 S_{yt}}{f_s}$$

………………………………….(3)

Where τ_{allow} states the permissible shear stress (MN/m2), S_{yt} signifies the yield strength (MN/m2), and f_s indicates safety variable (dimensionless) and in this study it was determined to be 1.5 (Loewenthal, 1984). Steel with a Young's modulus of 193 N/mm2, a yield stress of 720 N/mm2, and a tensile ultimate strength of 784 N/mm2 is the material chosen for the solid shaft (Ahire and Munde, 2016). The shaft of the fabricated torque sensor is appropriate for the applied torque based on the provided shaft material strength.

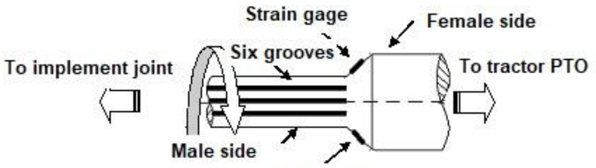

Figure (5). Strain gage on the spline shaft adapter with six grooves and male and female sides.

Static calibration

The specifically designed torque transducer underwent four replications of the static calibration tests. To examine the effects of hysteresis on the torque sensor, load applications that were both climbing and descending were considered. The torque arm, a 91.5 cm long and 2.3 kg weight pipe wrench clip tool that served as a component of the calibration platform, supported the opposite end of the PTO rotating shaft torque sensor with a spline shaft that was fitted on the tractor PTO shaft (Figure 6).

Two steel bars were joined vertically to a base plate and an adjustable horizontal beam to make up the calibration platform, which weighed a total of 5 kg. The PTO torque sensor was supported by the platform while it was being calibrated. As indicated in Figure (6), a sequence of dead weights, each weighing 20 kg, were added to the platform plate until the maximum torque was achieved, which was (2.3×9.81 + 0.915 m× (80+5) kg×9.81 = 786 N.m. The output strain from the PTO torque sensor is scanned and recorded using the signals program code for the Daytronic data PAC model 10k4. The torque sensor had a 0 to 5 kN.m, torque range in its design.

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Figure (6). A platform for static calibration of the torque for the fabricated torque sensor.

Dynamic tests

A PTO hydraulic dynamometer type AW Nebraska 200 with a torque rating of 1355 N.m and a range of engine and PTO speeds from 0 to 3600 rpm was used to deliver loads during the dynamic tests (Figure 7). However, the load supplied by the AW dynamometer was measured by two PTO torque meters, the first was an interface commercial PTO torque meter type Lebow Model 1228-20k, Eaton Advanced Electronics, Troy, Michigan, USA and the second was by the fabricated PTO torque transducer. Both fabricated PTO torque transducer and the commercial PTO torque transducer were connected in series with tractor PTO. Both transducers were connected to Daytronic data PAC model 10k4 via a slip rings to acquire and record the signals from the PTO torque meters. The signals were transferred to a laptop using a customized application in order to retrieve data from the testing area. Through calibration, the signals were translated from the voltage output to the corresponding torque and rotational speed in specific units.

Figure (7). The load produced by the AW PTO hydraulic dynamometer was stately by an interface commercial PTO torque meter and by the fabricated PTO torque transducer.

The calibration procedure

Following the tractor engine's start-up at maximum engine speed during no loading phase, the calibration process was initiated. The torque sensor and magnetic pick-up stately torque and rotary speed of the tractor PTO, which were then noted by the Daytronic data logger. The rotational speed of the PTO shaft was measured using a special arrangement on the fabricated PTO torque sensor by using a magnetic pick-up sensor and toothed wheel. The magnetic field of the magnetized cause was identified when the toothed wheel rotated and was shown as revaluations per minute (Emaish et al., 2021). AW PTO hydraulic dynamometer was employed to increase the load on the PTO shaft until a maximum load of 100% was grown, which resulted a minimum revaluations per minuets.

RESULTS AND DISCUSSION

The accuracy of the fabricated torque transducer was evaluated via static and dynamic calibrations. In static calibration, the torque load was varied from 0 to 786 N.m according to the specifications, applied by hanging weights. The calibration curve that is presented in Figure (8) demonstrates the strong correlation between the measured and applied torques. The theoretical values derived from the hanging weight results were compared with the torque data acquired from the torque sensor. The data collected using both procedures are directly proportionate, it was noticed. Additionally, it was found that there was a maximum discrepancy of 9.51 N.m between the torque detected by the created torque sensor and the torque applied. Moreover, torque measurements from the torque sensor were found to be higher than the applied torque in every instance. This observation is consistent with the findings of Kumar et al. (2017) and could be caused by vibrations, hysteresis, and internal stresses and strains. Equation (4) expresses the linearity relationship for torque measurements during static calibration.

$Y = 1.029\ X\ -6.9033$ with $R2 = 0.9992$ ………………………………….(4)

Where Y signifies the stately torque (recorded or measured torque by the fabricated torque transducer (N.m) and X is referred to the practical torque (calculated torque) during static calibration (N.m).

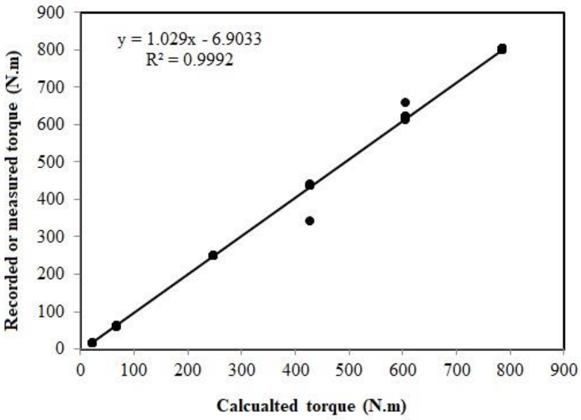

Figure (8). Relationship between calculated torque and recorded or measured torque during static calibration for the fabricated torque transducer.

In the dynamic calibration, torque transducer was connected to both of the tractor PTO shaft and the AW PTO hydraulic dynamometer. For rotary motion, the rotational speed and torque were measured and power was calculated by Equation (1). It was detected a precise linearity (Figure 9) of power data. For increased accuracy, each test was repeated three times.

The analysis presented that the average difference in power data by means of the fabricated torque transducer and that with the AW PTO hydraulic dynamometer data was initiated to -7.02 kW, however, the change was due to gain multiplier effect that was set automatically during auto ranging by the data logger. Additionally, Table (1) shows statistical criteria for performance parameters during dynamic tractor PTO tests. The suitability of the present PTO torque transducer to provide dynamic driving torque and PTO speed in actual time is depicted in Table (1). The linearity equation for power calculation from dynamic calibration is expressed by Equation (5).

Y =1.1969X+1.7249 with R2 = 0.9778 ………………………………….(5)

Where Y represents the calculated power form the data obtained by fabricated torque transducer (kW) and X is calculated power form the data obtained by AW PTO hydraulic dynamometer (kW).

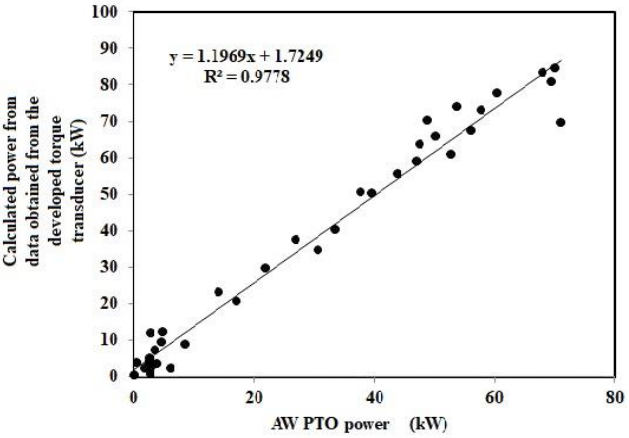

Figure (9). Relationship between calculated power from data obtained from the fabricated torque transducer and power calculated from data obtained from AW dynamometer.

Table (1). Statistical criteria for performance parameters during dynamic tractor PTO test.

Parameters	Unit	Minimum	Maximum	Standard deviation	Mean
Rotational speed of tractor PTO	(rpm)	69	1055	±267.75	925.33
Torque measured by fabricated PTO torque transducer	(N.m)	6	816	±278.50	325.70
Torque measured by AW PTO hydraulic dynamometer	(N.m)	2	676	±232.59	256.55
Calculated power based on data measured by fabricated PTO torque transducer	(kW)	0.24	84.64	±30.40	33.94
Calculated power based on data measured by AW PTO hydraulic dynamometer	(kW)	0.01	71.07	±25.12	26.92

CONCLUSION

A rotating shaft torque sensor called torque transducer for power data determination of rotary farm implements had been successfully fabricated, developed, and calibrated. The fabricated torque transducer was able to obtain data for both torque and rotational speed of a power take-off of a tractor. Excellent linearity relationship with a coefficient of determination (R2) of 0.9992 was occurred between the applied (calculated) torque and the recorded or measured torque by the fabricated torque transducer during static calibration. The dynamic response of the fabricated torque transducer was checked through laboratory tests with AW PTO hydraulic dynamometer. The average difference in power values using data measured by the fabricated torque transducer and that with the calculated power using data by AW PTO hydraulic dynamometer values was itemized to be -7.02 kW. Thus, the fabricated torque transducer was reliable and generally applicable to many farms implements which require power from power take-off of a tractor.

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الملخص العربي

تصنيع مجس عزم على عمود دوار لتحديد بيانات القدرة لمعدات المزرعة الدورانية

عادل أحمد الجوادي، عبد الواحد محمد أبو كريمة، سامي جمعة حميده، وليد مرسي

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تم تطوير وتصنيع ومعايرة مجس عزم على عمود دوار لتحديد بيانات القدرة لمعدات المزرعة الدورانية (محول عزم الدوران). تم التطوير والتصنيع لمحول عزم الدوران وفقًا لنظرية العمل لمحول عزم الدوران التجاري والذي يركب على عمود الإدارة الخلفي للجرار من طراز Lebow Model 1228-20k، Eaton Advanced Electronics، Troy، Michigan، USA باستخدام مواد محلية. وللحصول على تصميم نموذجي لقياس عزم الدوران، تم لصق أجهزة قياس الانفعال على سطح عمود يشبه عمود الإدارة الخلفي للجرار ودمجها في دائرة ويتستون. تم استخدام حلقة منزلقة لربط دائرة ويتستون على جانبي محول عزم الدوران بمسجل بيانات يسمى Daytronic data PAC model 10k4. وبالنسبة لنطاق عزم الدوران كان المحول المصنع قادر على قياس العزم على عمود الإدارة الخلفي للجرار من 0 إلى 5 كيلو نيوتن. متر، ولقياس السرعة الدورانية لعمود الإدارة الخلفي للجرار تم تركيب ترس حديد ذو 60 سنه على محول العزم المصنع. وأجريت اختبارات المعايرة الثابتة المعملية وأثناء التشغيل (ديناميكي) للحمل الكامل باستخدام دينامومتر هيدروليكي من نوع AW NEB 400. لقياس العزوم على عمود الإدارة الخلفي للجرار. وأظهرت النتائج في كل من الاختبارات الثابتة والديناميكية، أن محول عزم الدوران المصنع أعطى دقة قياس عالية بصورة خطيه، بمعامل تحديد (R^2) في حدود 0.992 إلى 0.9994. كما يعد محول عزم الدوران المصنع أقل تكلفة، بالنظر إلى محول عزم الدوران النموذجي المتوفر تجاريًا. ولجمع بيانات عن عزم الدوران أثناء العمليات الحقلية، خاصة عند استخدام المحراث الدوراني أو أي من المعدات الزراعية المشابهة، يمكن تركيب محول عزم الدوران المصنع على عمود الإدارة الخلفي لجرار ما (PTO).