Abstract— This Paper describes the generalised structure of Force-Sensor-less Power assist control (FSPAC) which is an essential technology to design a feedback control system in a human friendly way. Paper clarifies regarding generalised structure of Force-Sensor-less power assist control using two force observer. The Force, which is used to assist the control system is estimated by using encoders instead of using force-sensors. This Paper also compares other FSPAC’s with the FSPAC using two observer methodology. Since, this Feedback control system uses positive feedback , the Force-sensor-less Power Assist control deals with weak robustness problem. To increase Robustness of the system , Control design based on disturbance observer with variable gain is also discussed in this paper. Finally paper concludes considering its advantages disadvantages and applications.

Keywords—Force Estimation, inner observer , Structure of FSPAC, two observer , variable gain .

I. INTRODUCTION

Now a days daily life is supported by power assistance using motors and it has drawn people’s attention to the greater extent. There are many researches and applications which uses power assistance system. Power steering system in vehicle is the typical example of power assistance system[5]. Beside that there are more conventional and daily life applications such as power assist wheel-chair[3],[4] wearable electro-mechanical suits , etc [4]. As the numbers of these power assistance applications increases, design methodology of the control part of that power assistance needs to be investigated. Force control is necessary because it is needed to accomplish a task where interaction between robot and user is present.

There are many researches that uses force sensors which can directly measure the force but have several disadvantages: cost, noise, weight, measurement-time delay, possibility to measure the force only if it is applied on the sensor itself, and others. To control power assist devices, such as wheel chair or wearable suits, the knowledge of user’s applied force on the device is a key aspect. Since the power assist control needs to measure the force to assist, force sensors such as strain sensors are used in power assistance system. However, there are researches on the power assist controls which do not use any force sensor and estimate the force using just encoders[6]. They use reaction force observer methodology which is based on the disturbance observer technology to estimate the force and have obtained successful experimental results in their researches[5].

However, the reaction force observer method has some disadvantages that it requires precise dynamic model and friction force values. To overcome this disadvantage, the dynamics learning methodology is developed to adapt the parameters in dynamic model to the precise dynamics [6] and even more there is model independent force observer approaches.Based on the analysis of the control structure, this paper clarifies the functions of the generalized force-sensor-less power assist control, particularly the functions of two force observers in FSPAC and FSPAC with variable gain are made clear.

This paper is Organised as follows Chapter II explains the Force-Sensor-less Power Assist Control system with two observer and also clarifies the same system using inner observer and explains the problem of robustness and describes in brief the FSPAC system with variable gain for increasing robustness. Finally Chapter III concludes this paper mentioning its advantages, disadvantages and application.

II. FSPAC SYSTEM

Figure 1 shows FSPAC system using disturbance two observer method [1]. There are two disturbance observers, model impedance, and feedback gain. Inner disturbance observer is the conventional disturbance observer which aims to reject all the external force.

The outer disturbance observer which is usually called a reaction force observer or force observer is for the estimation of the force to assist [5].
The model impedance decides the extent of power assistance. Since the feedback controller in FSPAC controls the system output $y_r$ to track the $y_{imp}$ of this model impedance, this model decides the impedance of the controlled system against external force [2]. If the impedance in the model is smaller than that of the original plant which means $JM < J$, $BM < B$, the model impedance achieves power assistance. This is how the FSPAC realizes power assistance. The feedback controller which produces the control input proportional to the error determines the tracking characteristics. The controller consists of the conventional PID controller. Higher the gain better is the tracking performance. This feedback controller determines the robustness and the gain margin of the system. The structure of Figure 1 has been used as the fundamental structure of the FSPAC in many researches.

Estimation of External Force to Assist:

There are different disturbance observer methods to estimate the force to assist, which can be used. One in which only one disturbance observer is used and inner disturbance observer is omitted and second in which two disturbance observer are used [2]. Usually, two disturbance observer method is adopted.

In both cases, a disturbance observer estimates the external force as a force observer. In force observer, differently from the inner disturbance observer, some premeasured disturbance information such as Coulomb friction is subtracted from the estimated force as they are not force to be assisted. This kind of force estimation is called Reaction force observer[3].

Some methodologies utilize a known model dynamic and system output and calculate the external force to the system based on them. The accuracy of the dynamic model determines the quality of the estimated force; if there is some modelling error in dynamic model or unknown dynamics, it will affect the estimation accuracy and result in inaccurate force estimation. There are many approaches that estimate the force[4], but this paper adopts the linear system analysis so that the robustness can be analysed in terms of linear system analysis.

Analysis Of The Generalized FSPAC:

Figure 1 can be more specifically characterised as figure 2. $Q$ filters in two disturbance observers are illustrated as $Q_i$ and $Q_o$, the inverse dynamics model is described as $P^{-1}$, the model impedance is described as $PM$, $P$ is the real plant and feedback controller is represented as $A$.

Function of 2 observer:

Figure 2 : Analysis of FSPAC

Figure 3 : Paths of External Force
Figure 3. is the analysis of the signal paths of external force in FSPAC. There are three signal paths:

1. Is the original path which affects the output through the plant itself,
2. Is through the inner disturbance observer, and
3. Is through the outer power assist control loop.

With these paths, the transfer function from f to yr is determined as,

\[ T_{cl} = \frac{P(1-Q_I+Q_0AP_M)}{1+Q_I(P^2+P-1)+(P+Q_0P_M)(1-P^{-1}P)} \] (1)

Three terms in the numerator represent three paths described above.

- The first term P corresponds to the first path (1) in Figure 3,
- the second term \(-PQ_i\) to the path (2) and,
- the last term \(PQ_0AP_M\) to the path (3).

The inner disturbance observer can improve model matching performance of the FSPAC. The second term \(-PQ_i\) can eliminate the effect of the first term \(P\), if \(Q_i = 1\). This is conventional usage of the disturbance observer; this elimination of the effect of the path (1) can help the controlled plant to follow the model impedance \(PM\).

Besides this model matching characteristics, two observers can distinguish the disturbances to be assisted and to be rejected by setting different processing between the two observers [3].

**FSPAC with One Disturbance Observer**

Figure 4 has only one disturbance observer as a force observer. This structure is motivated from the concern of the conflict between two disturbance observers. With \(Q_i = 0\) in Equation (1), the transfer function can be calculated as,

\[ T_{ct2} = \frac{P(1+Q_0AP_M)}{1+A(P+Q_0P_M(1-P^{-1}P))} \] (2)

Since the second \(Q_i\) term in Equation (1) is removed, the first term \(P\) remains in the numerator and affects the output, which may result in poor model matching performance. However, the controlled plant does not necessarily need to match the model impedance to achieve power assistance [3]. Even though the first term \(P\) is undesired unconsidered effect of the external force, it does not deteriorate assistance performance but merely worsens model matching performance. Additionally, regardless of the existence of the inner disturbance observer, if \(A >> 1\), the last term \(PQ_0AP_M\) plays dominant role in the system and the first term \(P\)'s effect decreases to negligible level. By removing the inner disturbance observer, the structure is simplified and consequently becomes more straightforward without deteriorating power assistance performance. One disadvantage is that it cannot reject undesirable external force. Although this structure also can cut out the undesirable external force in the control loop by subtracting the undesirable force from the estimated force, it does not reject it actively unlike the FSPAC with the inner disturbance observer [2].

**Robustness Limitation Of Fspac**

Let us discuss the design of a force-sensor-less controller using the structure in Figure 5 [1]. The plant is \(1/Js+B\) and we want control it so that the output \(y\) moves as if it has the impedance characteristic of \(1/JMs+BM\) against the external force \(f\) by the feedback controller \(C(s)\).

**FSPAC model Using Simple Feedback structure**

Under this problem formulation, the controller \(C(s)\) can be designed based on the model following control design. By substituting the general plant \(P(s)\) for \(1/Js+B\), the formulation can be generalized. The answer is,

\[ c(s) = (J_M - I_n)s + (B_M - B_n) = P_M^{-1}(S) - P_n^{-1}(S), \] (3)

Where \(Jn, Bn\) and \(Pn\) are the nominal parameters and plant for the real plant. If this model following control is designed for power assistance without force sensors, the model impedance should be smaller than that of real plant, that is, \(JM < Jn\) and \(BM < Bn\). This makes the feedback controller positive feedback and results in weak robustness caused by small stability margin [1].
Design based on disturbance observer with a variable gain (VG):

In order to increase robustness, safety as well as provide a better and smoother assistance to the user, a control design based on disturbance observer with a variable gain (VG) is used [3]. The design of the feedback variable gain is realized taking into account factors such as inertia as static/dynamic friction.

The structure of the proposed FSPAC with VG is shown in Figure 6.

![Figure 6: FSPAC system with variable gain](image)

In the proposed structure only one disturbance observer is used to reject the disturbances and to estimate the force to assist [2]. However, the main difference with the general FSPAC described before is in the design of the feedback gain. Variable gain is determined by using value of $V_G$.

**Variable Gain Design:**

Before describing in detail the VG’s design, it is opportune to consider how the reference torque is given to the motor by the controller. From the block diagram in Figure 6.

$$T_{ref} = (v_M - v_A) \cdot V_G$$

The VG was designed as a gain which value depends on the actual velocity in the way illustrated in Figure 7. On the x-axis there is the absolute value of the actual velocity while on the y-axis there is the value of the VG[4].

![Figure 7: Variable gain value in respect to actual velocity](image)
III. CONCLUSION

The need for power assist device is increasing due to always more aging society. Such devices require a new approach in both hardware and control design which can be referred as “human-friendly motion control”. This Paper proposes a Force Sensor-less Power Assist Control (FSPAC) with constant as well as variable gain. It also proposes the general form of force-sensor-less power assist control structure and compares with it other possible structures concluding the proposed general form has some advantage over others. It also clarifies the limit of robustness of FSPAC in terms of gain margin. A new concept of phase assist control is proposed and difficulty in guaranteeing the robustness in the phase assist control is explained. Some criterions are also proposed in order to develop the design discussing these problems in FSPAC.

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